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Hydrographic-hydrochemical assessment of the Baltic Sea 2018

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Content

Kurzfassung

Die Arbeit beschreibt die hydrographisch-hydrochemischen Bedingungen in der westlichen und zentralen Ostsee für das Jahr 2018. 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 67,7 Kd. Im Vergleich belegt der Winter 2017/18 den 34. Platz der wärmsten Winter seit Beginn der Aufzeichnungen im Jahr 1948 und wird als mild klassifiziert. Mit einer Wärmesumme von 394,5 Kd setzt der Sommer 2018 einen neuen Rekordwert in der 71jährigen Datenreihe. Das Langzeitmittel liegt bei 153,5 Kd.

Auf der Grundlage von satellitengestützten Meeresoberflächentemperaturen (SST) war 2018 ebenfalls das wärmste Jahr seit 1990 und mit 1,19 K weit über dem langfristigen SST-Mittel. Mai bis August trugen durch ihre stark positiven Anomalien von bis zu +4-5 K dazu bei. März und April waren aufgrund des späten Wintereinbruchs (Februar-März) durch negative Anomalien gekennzeichnet.

Die Situation in den Tiefenbecken der Ostsee war im Wesentlichen geprägt durch stagnierende Bedingungen. Die Auswirkungen der intensiven Einströme zwischen 2014-2017 klingen allmählich aus und die Konzentrationen von Phosphat und Ammonium steigen im Tiefenwasser wieder kontinuierlich an. Zwei barotrope Einstromereignisse von schwacher Intensität wurden Ende September und Anfang Dezember erfasst. Dabei strömten Gesamtvolumen von 233 km³ und 215 km³ in die Ostsee hinein. Das Einstromwasser umfasste jedoch nur niedrige mittlere Salzgehalte von etwa 15 g/kg. In den windarmen Sommermonaten stellten sich mehrere Phasen von baroklinen Einströmen ein und sehr warmes Oberflächenwasser aus dem Kattegat wurde in das Tiefenwasser der Ostsee importiert. Die Temperatur stieg in den tiefen Becken um 3-5 K an.

Abstract

The article summarizes the hydrographic-hydrochemical conditions in the western and central Baltic Sea in 2018. 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 67.7 Kd in Warnemünde amounted to a mild winter in 2017/18 and ranks as 34th warmest winter since the beginning of the record in 1948. The summer “heat sum” of 394.5 Kd ranks on 1st position setting a new record as warmest summer over the past 71 years and is nearly twice as high as the long-term average of 153.5 Kd.

Based on satellite derived Sea Surface Temperature (SST) 2018 was as well the warmest year since 1990 and with 1.19 K far above the long-term SST average. May to August contributed to the record by their high positive anomalies of +4-5 K. March and April were characterized by negative anomalies due to the late winter cold spell in February and March.

The situation in the deep basins of the Baltic Sea was characterized by mainly anoxic to euxinic conditions. The influence of several inflows during 2014-2017 was fading away and phosphate and ammonium concentration were increasing again. Two weak barotropic inflows occurred during September and December transporting volumes of 233 km³ and 215 km³ into the Baltic Sea, showing a relatively low mean salinity of around 15 g/kg. Calm summer weather induced several phases of baroclinic inflow events, importing very warm saline surface water of the Kattegat area into the deep basins. A temperature increase of 3-5 K was registered.

1. Introduction

This assessment of hydrographic and hydrochemical conditions in the Baltic Sea in 2018 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 since then continued the measurements outside the EEZ on its own account. 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 2018 covering 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, July and November were performed by 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 after maintenance. DARSS SILL (DS) station was also overhauled, and went back into operation in August 2013. The ODER BANK (OB) station was in operation from end-April to mid-December 2018; it was taken out of service for a break over the winter of 2018/2019. A second system of a new buoy construction more resistant against damages caused by ice 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 in some two hundred metres distance 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). 2018 was assessed in relation to the mean values for 1990-2018 as the warmest year since 1990. The results were also summarized in a HELCOM environmental fact sheet (SIEGEL & GERTH, 2019).

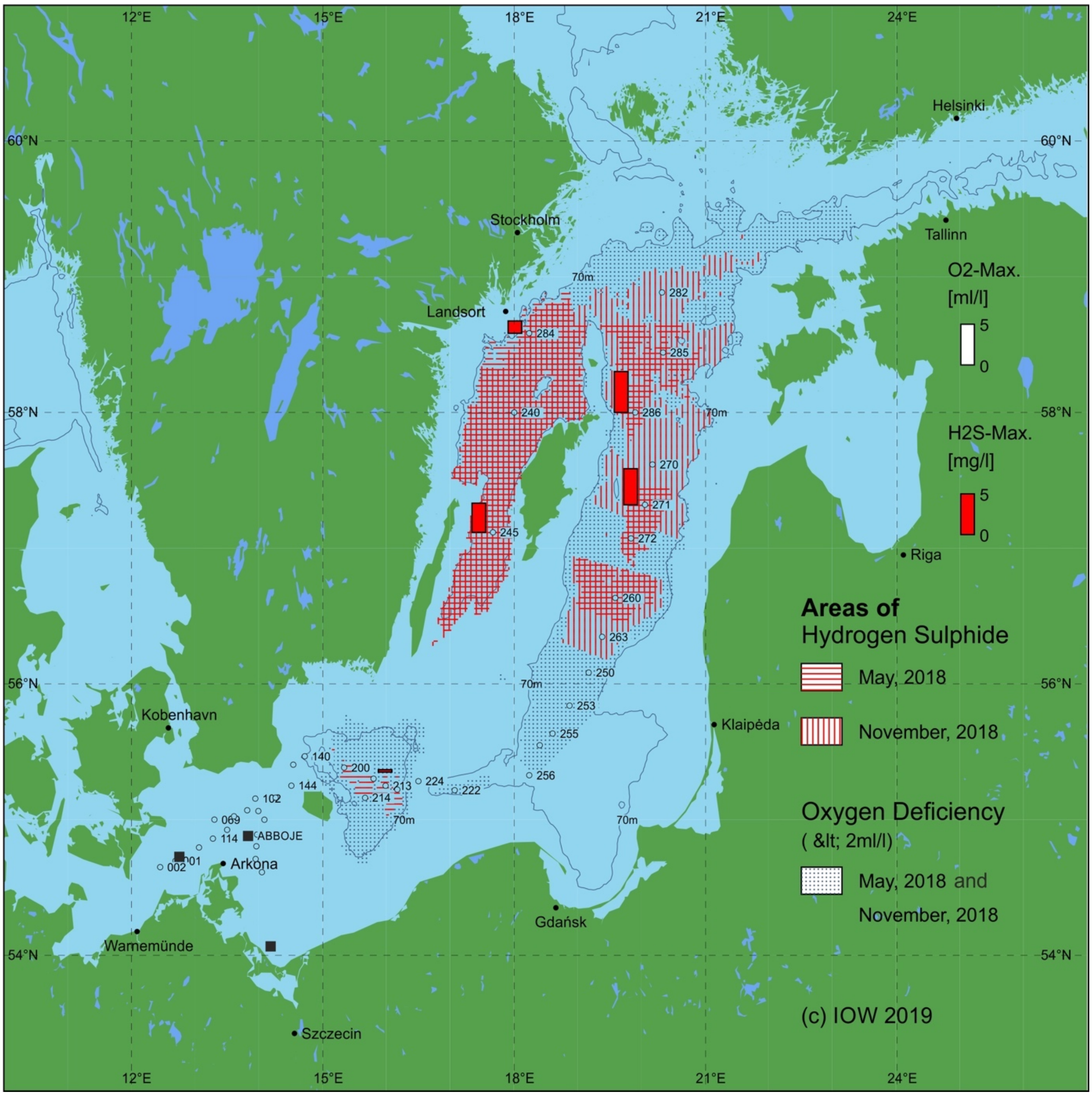


Fig. 1: Location of stations (■ MARNET- stations) and areas of oxygen deficiency and hydrogen sulphide in the near bottom layer of the Baltic Sea. Bars show the maximum oxygen and hydrogen sulphide concentrations of this layer in 2018; the figure additionally contains the 70 m -depth line

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, sunshine duration, precipitation as well as the number of days of frost and ice at Arkona weather station. Solar radiation at Gdynia weather station is given in addition. The warm and cold sums at Warnemünde weather station, and in comparison with Arkona, are listed in tables 2 and 3.

According to the analysis of DWD (DWD, 2018), 2018 was the sunniest and warmest year since the beginning of continuous measurements in 1881. In addition, it was as well one of the driest years on national and European scale. April and May 2018 were the warmest one's ever recorded. The mean annual temperature of 10.4 °C was about 2.2 K higher than the international reference period 1961-1990 and 1.8 K warmer than the national 30-year reference period 1981-2010. It was 0.1 K higher than the previous record in the time span since 1881, the year 2014. The year began with mild temperatures in January throughout Germany showing monthly mean anomalies up to 4.8 K in the south (Munich) and around 2 K in the north along coastal stations compared to 1981-2010. In February and March the winter situation changed to cold temperatures by two long lasting cold spells. Temperature anomalies ranged from -1.2 K to -3.3 K, at the Baltic Sea coast. March was around -2.8 K at coastal stations and a snow period occurred at the coast until Easter. In the beginning of April the winter situation changed immediately to summer-like weather. Until the end of the year, all months showed positive anomalies between 1.3 K to 2.7 K at station Arkona (c.f. Table 1).

Across Germany, the annual amount of precipitation was 590 l/m², only 75 % of the long-term mean of 789 l/m². A period of 10 dry months in a row lasted from February to November. In the coastal states along Germany's Baltic Sea coast ranged precipitation from 520 l/m² in Schleswig-Holstein to a very low value of 440 l/m² in Mecklenburg-Vorpommern.

The average annual sum of 2,020 hours of sunshine set a new record in the long-term series since 1951. Hamburg registered 1,895 hours (1,507 hours long-term mean), but showed the lowest value of all German states. Mecklenburg-Vorpommern sets a new record with 2,085 hours (mean: 1,648 hours) and Berlin showed the national maximum of 2,180 hours (mean: 1,634 hours).

2.1 Ice winter 2017/18

For the southern Baltic Sea area, the cold sum of 67.7 Kd at Warnemünde station amounted to a warm winter in 2017/18 (Table 2) like the latest winter seasons 2016/17 (31.7 Kd) and 2015/2016 (63.5 Kd). Since the year 2012 all values are below the long-term average of 100.8 Kd. The winter 2017/18 ranks in comparative data from 1948 onwards as 34th warmest winter in this time series of the last 70 years. In comparison, Arkona station at 53.8 (Table 3) is slightly lower, but represents a higher value than the previous winters 2016/17 (27.2 Kd), 2015/2016 (36.1 Kd), 2014/2015 (8.1 Kd) and 2013/2014 (42.1 Kd). Given the exposed location of the north of the island of Rügen (surrounded by large water masses), 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.

The winter season started generally warm at the coast and the months November 2017 to January 2018 showed positive air temperature anomalies between 1.0-1.7 K. Only some short periods of frost occurred in December (4 days) and January (8 days). Afterwards the weather situation changed to continuously winterly temperatures and snow cover in February (22 frost days, 7 ice days) and March (16 frost days, 5 ice days). Overall, 50 days of slight frost and 13 days of ice were recorded at Arkona compared to 43 days of frost and 7 days of ice in the previous mild winter of 2016/17 (NAUMANN et al., 2018). The winter's warm temperature profile was also reflected in icing rates. One continuous period of ice formation occurred from February 6 to March 22 with highest formation rates between March 2-7 (SCHWEGMANN & HOLFORT, 2018). According to SCHWEGMANN & HOLFORT (2018), this ice season in the Baltic Sea is classified as average. Given warm weather conditions up to end of January, the maximum extent of ice was reached late at March 5, 2018, with an area of 182 005 km². This ice coverage is ranked on 156th place since the year 1720, starting at the lowest value of 49 000 km² (year 2008) in this time series of 299 years.

The maximum extent of ice corresponded to 44 % of the Baltic Sea's area (415 266 km²), and was largely centred in the Gulf of Bothnia with only some ice-free area left in the southern part, the Gulf of Finland as well as the Gulf of Riga and 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 182 005 km² is much higher than in the previous year 2016/2017 (104 000 km²) and recent years show the maximum ice coverages of 114 000 km² in 2015/16, 51 000 km² in 2014/15, 95 000 km² in 2013/14 and 187 000 km² in 2012/13. At 86 %, the ice coverage 2017/18 fell lower than the long-term average of 212 000 km² in the time series from 1720 onwards (Figure 2). The 30-year average of the last decades accounts for 140 000 km².

Along Germany's Baltic Sea coast, local conditions were assessed as a weak, but on the edge to a moderate ice winter on the basis of an accumulated areal ice volume of 0.49 m (SCHWEGMANN & HOLFORT, 2018). After lower values in previous years of 0.16 m (2016/17) and 0.35 m of the season 2015/16 (SCHWEGMANN & HOLFORT, 2016, 2017), it is the sixth weak ice winter in a row (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). Besides various other indices, this index is used to describe the extent of ice formation, 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 ice formation 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: 26.83m in 1942; 26.71m in 1940; 25.26m in 1947; and 23.07m in 1963. In all other winters, values were well below 20 m (KOSLOWSKI, 1989).

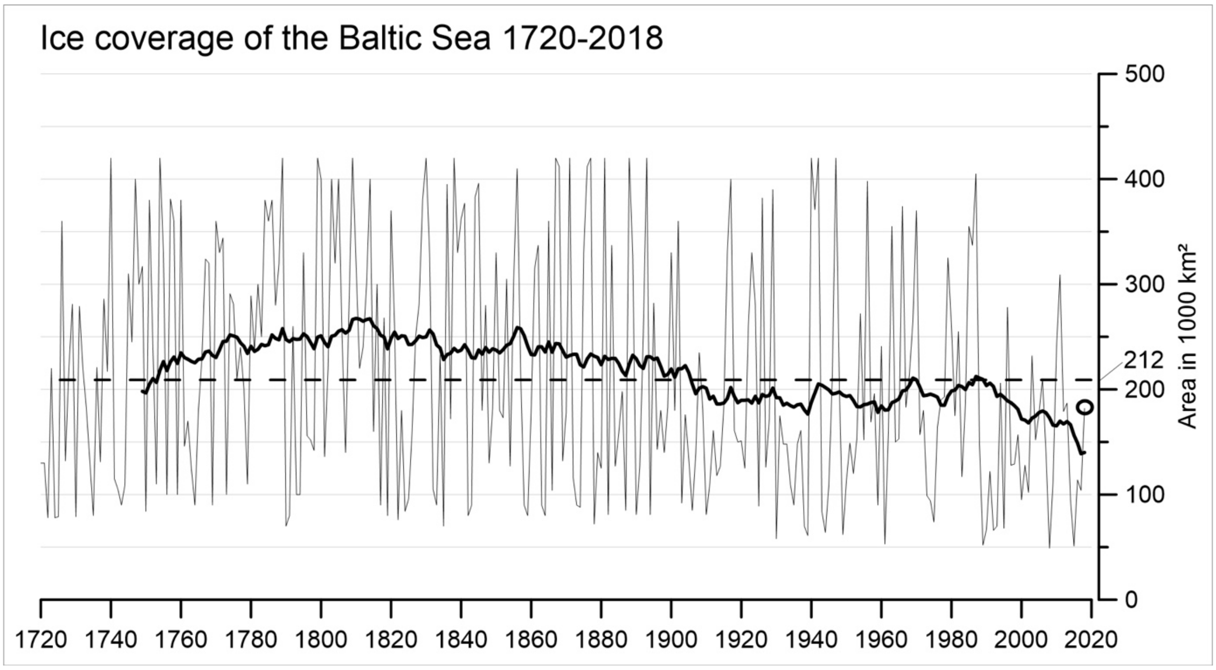


Fig. 2: Maximum ice covered area in 1000 km² of the Baltic Sea in the years 1720 to 2017 (from data of SCHMELZER *et al., 2008,* SCHWEGMANN *&* HOLFORT*, 2018). The long-term average of 212 000 km² is shown as dashed line. The bold line is a running mean value over the past 30 years. The ice coverage in the winter 2017/2018 with 182 005 km² is encircled.*

A first ice formation was observed in December at the Schlei estuary, at that time still followed by melting during daytime by warmer temperatures. From January 8 to mid of the month slight ice coverage occurred at several stations along the German Baltic Sea coast. A continuous icing period started at February 6. Maximum ice thicknesses of up to 15-30 cm was observed around Rügen Island, but along the chain of coastal lagoons and bays, an average of 5-15 cm prevailed.

Along the Western Pomeranian lagoon chain, the longest duration of ice formation was registered at the Dänische Wiek (inner Greifswald lagoon) during a period of up to 57 days. At other areas, the number of recorded ice days was 53 days at Schlei estuary, 39-47 days at Darss-Zingst lagoon chain and 36-42 days at lagoons west of Rügen island and up to 30 days at the Warnow river mouth (Rostock harbour). In contrast to previous years even more open German sea areas showed ice coverage, for example the Mecklenburg Bight of up to 20 days (SCHWEGMANN & HOLFORT, 2018). In the winter of 2017/18, an accumulated areal ice volume for the coast of Mecklenburg-Vorpommern of 0.45 m and Schleswig-Holstein of 0.54 m was calculated, which is much higher than the previous winter season of 0.22 m and 0.09 m. Surprisingly, Schleswig-Holstein showed a larger value which is normally reverse. At farther east lagoons at the southern Baltic Sea first ice formation started in mid-January. A maximum ice thickness of 20 cm was observed in these subareas. In the northern part of the Baltic Sea ice formation started in the beginning of December (Bothnian Bay). Up to end of January the ice coverage was more or less constant, increased rapidly since beginning of February and reached its maximum at March 6. The maximum areal extent was 43 % larger compared to the previous wintertime and at May 24, the last icing was registered in the Bothnian Bay (SCHWEGMANN & HOLFORT, 2018).

2.2 Weather developments in 2018

In the course of the year 2018, pressure systems and air currents changed often between westerly to south-westerly and easterly directions (cf. Figures 3a, 4b, 5). Westerly winds account for about 50 % of the annual sum and easterly directions to another 25 %. The progressive wind vector curve of 2018 is dominated by easterly wind conditions during spring and early summer months not following the climatic mean situation of usually southwesterly to westerly directions (cf. 3a, b). The Institute of Meteorology at FU Berlin has given names to areas of high pressure and low pressure since 1954, which are used in the following descriptions.

The year 2018 started very mild. In **January** a mean temperature across Germany of 3.7 °C was registered, which is 3.3 K above the long-term mean. At the Baltic Sea coast anomalies of 1.6 to 2.5 K and in central Germany 4-5 K were measured. The wind situation started with westerly winds, changed to easterly direction at the mid of the month and, since January 21, turned back to west (Figure 4b). At January 29, low-pressures "Imke" and "Jira" crossed northern Europe as wind event of the month and third windiest day of the year, showing a daily mean of 15.1 m/s and gusts up to 24.5 m/s. The mean sea level of the Baltic Sea, described by the tide-gauge station Landsort (Figure 6a), showed a high stand of 42 cm MSL at the beginning of January, dropped due to easterly winds to -20.9 cm (February 25) and increased rapidly to the end to of the month. Beside mild temperatures it was generally too wet. The mean precipitation of 99 mm across Germany was 51 % above the long-term mean of 65 mm. Weather stations at the Baltic Sea coast showed anomalies of 67 % (Schleswig), 52 % (Rostock) and 55 % in Ückermünde. Sunshine duration in most areas of Germany was below average, showing a mean of 33 hours (-35 %) and the phase of low intensity continued since September 2017.

In **February** the situation changed to cold, snowy winter weather in Germany. The mean temperature of -1.9 °C was 2.8 K below average. Large high-pressure cells across central and northern Europe ("Dino" and "Hartmut") controlled the weather during the month. Relatively calm easterly winds with daily means between 2-6 m/s (2-3 Bft) were dominating. Only three days showed values above 10 m/s (February 4, 12, 16). After a highstand of 26.1 cm MSL (February 3) a long-lasting outflow period occurred (Figure 6a). At the end of the month a sea level of -29 cm MSL was reached at station Landsort Norra. At the Baltic Sea coast temperature anomalies of -1.9 K (Schleswig and Rostock) to -2.5 K (Ückermünde) were registered. Precipitation was generally low. The mean value of 17 mm was far below the average of 54 mm (-68 %) and at the coast anomalies up to -80 % (Ückermünde) were registered. The sun shone longer than usual and the mean value of 114 hours was far above the average of 75 hours (51 %). In northern Germany it was the sunniest February since the beginning of the record in 1951.

The cold spell continued in **March**, showing an anomaly of -1.9 K (nationwide). High-pressures "Hartmut", later "Irenäus" and "Jost", dominated the weather situation and were only shortly interrupted by low-pressures. Mainly low to moderate easterly winds occurred with daily means of 2-8 m/s. Low pressure "Zsuzsa" crossed from March 16th to 17th the North Atlantic inducing the storm event of the year showing gusts up to 29.8 m/s from eastern direction. Daily means of 18.8 m/s and 17.7 m/s were registered (Figure 4a). The outflow period which has started in February continued, reaching the lowstand of the year of -48.6 cm MSL at March 18 (Figure 6a). Along the coast temperature anomalies of -2.2 K (Schleswig), -2.9 K (Rostock) and -3.4 K in Ückermünde were registered. Precipitation varied from too dry values in the western part (Schleswig -16 %) to very wet conditions as snowfall at Rostock (73 %) and Ueckermünde (34 %). Due to cold temperatures the snow cover stayed up to the end of the month. Sunshine duration was nationwide balanced and with 113 hours only 1 % below the average, but locally in the northern part much less than average. At Arkona in the north of Rügen island the lowest value of 85 hours (65 %) were registered, as well as Schleswig with 78 hours (69 %).

At the beginning of **April** the situation changed mediately to warm temperatures. A mean temperature of 12.3 °C (4 K) was the highest ever registered in April since begin of the record in 1881. The high-pressures "Leo", "Martin", "Norbert" and "Onni" dominated central Europe and sunny, mild weather occurred. Wind directions changed a lot between east and west during the month (Figure 4b) and the sea level fluctuated at the beginning of the month around -30 cm MSL. At the end of the month west winds raised the sea level to -7 cm MSL (Figure 6a). Temperature anomalies of 2.4 K to 3.0 K occurred along the Baltic Sea coast. Too wet precipitation values of 38 % (Schleswig) and 26 % (Rostock) as well as too dry values of -41 % at Ückermünde were registered. The nationwide mean sunshine duration of 226 hours was 30 % above the average and is ranked on 4^{th} place since the beginning of the record. The highest value occurred at station Hohenpeißenberg in the south of Bavaria (277 hours, 164 %) and Arkona registered an anomaly of 135 %.

In **May**, the mild sunny weather continued and again the nationwide mean temperature of 16 °C (3 K) set a new monthly record since 1881. High-pressure dominance across northern and central Europe was going on (high pressures "Peter", "Quinlan", "Roland", "Tews", "Uwe") and very calm easterly wind conditions occurred (Figure 4a, 4b). Beside May 1 with a daily mean wind speed of 10.1 m/s all other days recorded values below 8 m/s (4 Bft). The sea level at Landsort slowly lowered from 4 cm MSL to -34.5 cm MSL at the end of the month (Figure 6a). Along the German Baltic Sea coast, the air temperatures showed as well warm values of 3.6 K at Schleswig, 2.8 K at Rostock and 3.0 K at Ückermünde. Arkona showed a monthly mean of 12.9 °C (+2.5 K). Amounts of precipitation varied locally, but were generally too dry. For example Schleswig recorded -23 %, Rostock -91 %, Arkona -84 % and Ückermünde -49 % compared to the long-term average. The sunshine duration was with 288 hours in mean, 37 % above the long-term mean of 210 hours. Germany's northern part recorded with up to 388 hours (List at Sylt island) the sunniest May in the record. Arkona registered 373 hours (137 %).

High-pressure influence and the warm, dry as well as sunny summer weather continued during **June** 2018. Low-pressures "Bigi" and "Cathy" of colder air masses from the North Atlantic crossed northern Europe from June 21^{st}-23^{rd}, inducing strong northwesterly winds of gusts up to 21.4 m/s (9 Bft). In June, mainly weak to moderate southwestern to western wind conditions occurred, shortly interrupted by weak easterly winds. The sea level raised stepwise from -38.6 cm MSL to 8.8 cm MSL (June 24). The nationwide mean air temperature of 17.7 °C was 2 K above the average. An anomaly of maximum 2.8 K was reached in Magdeburg in the central part and the minimum of 0.6 K (Freiburg) was reached in southern Germany. At the Baltic Sea anomalies varied between 2 K (Rostock), 2.1 K (Schleswig), 2.2 K (Ückermünde) and 2.5 K at Arkona. Overall, June was too dry with a mean of 46 mm precipitation compared to the long-term average of 77 mm (-40 %). Only a small area of southern Germany spanning from Stuttgart to Munich showed too wet values of 12-13 %. The coastal stations at the Baltic Sea showed too dry anomalies from -27 %

(Schleswig) to -88 % (Ückermünde). At 218 hours, sunshine duration was about 7 % above the average of 204 hours, but at the coast the sun shone longer compared to southern Germany. Arkona registered the national record of 327 hours (130 %).

At the beginning of **July** high-pressure "Ekkehard" across Scandinavia influenced the situation and moved slowly northwards. Then low-pressure cells "Fabiola" and "Gislinde" crossed the Baltic Sea area up to July 12. Afterwards high-pressures "Falk", "Gottfried" and "Ingolf" dominated the weather situation. The trend of warm, dry and calm weather was going on. Only low to moderate winds of daily means mainly between 2-5 m/s (1-3 Bft) occurred. A maximum of 8.4 m/s (5 Bft) with maximum gusts of 15.2 m/s was reached at July 6th (Figure 4a). The sea level fluctuated only slightly around the mean level due to this calm wind situation. The monthly mean temperature accounts nationwide 20.3 °C (2.3 K) and at the Baltic around 1.8-2.7 K above the mean temperature. Anomalies more than 3 K were registered in central Germany and the drought continued. The mean precipitation of 40 mm was 52 % below the long-term average of 83 mm. A lowest value of 3 mm (-96 %) was registered in Emden, the stations at the Baltic Sea showed anomalies of -69 % to -70 %. Low-Pressure "Gislinde" at the beginning of July brought locally some rain locally and the stations northeastwards of Berlin showed slightly wet values, for example at Ückermünde with 64 mm (+10 %). The sun shone 311 hours in average and was 41 % above the reference period 1981-2010. Longest sunshine duration was measured at the isle of Fehmarn (356 hours, 140 %) and Arkona recorded 326 hours (118 %).

In **August** the series of warm, dry and sunny weather continued for a next month. High-pressure dominated again and daily means of the wind stayed below 10 m/s. The direction changed between southerly and westerly winds (positive eastern component). As a result, the sea level fluctuated again and increased only slightly to 16 cm MSL at August 27 (Figure 6a). Nationwide warm mean temperature anomalies between 1.2 K (Emden) to 3.1 K (Nürnberg) occurred, the mean value of 19.9 °C was 2.4 K above the long-term average. At the German Baltic Sea coast values varied from 1.5 K at Schleswig, 2.3 K at Rostock, 2.2 K at Arkona and 2.2 K at Ückermünde. The amount of precipitation was with 42 mm at the level of July and 45 % below the average of 78 mm. Along the Baltic Sea coast anomalies ranged from -1 % at Schleswig to -37 % at Ückermünde in the eastern part. Across Germany as a whole, sunshine duration of 249 hours was 21 % above the average (206 hours). The station Zugspitze in the Alpes registered the nationwide minimum of 176 hours (101 %) and Fürstenzell, as well located in Bavaria, the maximum of 295 hours (133 %). 245 hours were registered at Arkona (101 %).

The summer weather continued up to **September** 20 with light to moderate easterly to southerly winds. Afterwards several westerly cyclones crossed northern Europe and the situation changed to colder temperatures and more windy weather up to the end of the month. Daily means of wind speed increased to more than 7 m/s and the maximum was registered at September 26 (low-pressure "Gertraud") with 12.7 m/s, gusts up to 25.9 m/s (10 Bft). At the beginning of September, outflow occurred and the sea level lowered to -23.6 cm MSL. The change to stronger westerly winds induced a rapid rise to 25 cm MSL to the end of the months. The monthly mean temperature showed a nationwide average of 15.1 °C, 1.6 K above the long-term average. At Arkona a monthly temperature of 15.8 °C was reached, which is 1.7 K above the long-term average. The stations Schleswig showed an anomaly of 1 K and Rostock as well as Ückermünde 1.8 K. Rainfall of 43 mm was again far below the average of 67 mm (-36 %). Stations at the Baltic Sea registered low values of -32 % at Schleswig, -57 % at Rostock, -52 % at Arkona and -65 % at Ückermünde. Sunshine duration of 207 hours was 39 % above the long-term average 1981-2010 and the 4th sunniest September in the record. Arkona registered 208 hours (122 %) and Lahr in southwestern Germany a maximum of 254 hours (149 %).

The influence of westerly cyclones crossing northern Europe continued at the beginning of **October**. Strong northwesterly winds at October 2 and 3 (daily mean 12.3 m/s, gusts 27 m/s) led to a continuation of the inflow period, reaching a maximum sea level of 44.8 cm MSL at Landsort Norra (annual top level). An inflow volume of in total 233 km^3 was calculated. Later on, late summer weather returned due to the extensive high-pressure cell "Viktor" up to October 23rd. The end of the month was again dominated by low-pressures crossing Scandinavia and westerly winds. During the warm weather period the sea level lowered to 3.2 cm MSL (October 22nd) and increased again rapidly to 43.6 cm MSL at October 27th (Figure 6a). The nationwide average temperature was 10.7 °C, 1.5 K above the long-term mean. Stations along the Baltic Sea coast recorded monthly temperatures anomalies off 1.7 K (Schleswig) up to 2.3 K (Rostock). At 28 mm, precipitation was 55 % below the average value of 63 mm; at 157 hours, sunshine duration was 46 % above average of 108 hours. Along the Baltic Sea coast precipitation was again low and varied between -24 % at Schleswig, -31 % at Rostock, -32 % at Arkona and -49 % at Ückermünde. The sun shone at Arkona station 167 hours (143 %) and 219 hours at the Zugspitze in the Alpes (nationwide maximum).

The generally mild weather continued during **November** with dominance of extensive high-pressure across eastern and central Europe. During the whole month, cyclones were blocked at the Scandinavian coast and diverted northwards. Easterly winds occurred most of the time, leading to a rapid lowering of the sea level from above 40 cm MSL to a lowstand of -44.4 cm MSL at November 30 (Figure 6a). The nationwide mean temperature was 0.8 K generally too mild (5.2 °C). Only Freiburg in southwestern Germany showed a negative anomaly of -0.5 K. At the German Baltic Sea coast the anomalies of mean temperatures decreased from west to east (Schleswig +1.2 K, Rostock +0.9 K, Ückermünde 0.7 K). Precipitation varied between -62 % (30 mm) at Schleswig, -80 % (10 mm) at Rostock, -81 % (9 mm) at Arkona and -58 % (19 mm) at Ückermünde. Generally, too dry conditions occurred in Germany with a mean of 20 mm (-70 %). The mean sunshine duration of 75 hours was 40 % above the long-term mean (1981-2010) and shone from 46 hours at Kiel to 171 hours at the Zugspitze (Alpes). Arkona registered 70 hours (130 %).

In **December** the mild weather conditions continued across Germany. At the beginning, a typical influence of westerly cyclones crossing northern Europe occurred. In the period December 12 to 20 again high-pressure dominated Scandinavia and Eastern Europe. Afterwards several low-pressure cells crossed the Baltic Sea. During the first third of December strong southwesterly to westerly winds occurred up to daily means of 12 m/s and the sea level increased rapidly from -44.4 cm MSL to a top level of 16.3 cm MSL at December 11th. The rise of 60.7 cm comprises a total volume of 215 km^3 (Figure 6a). Following easterly winds lowered the level to -23 cm MSL at Christmas. To the end of the month the sea level rose again to the mean sea level at Landsort Norra. Generally mild temperatures across Germany account for a mean temperature of 3.9 °C, which is 2.7 K above the long-term average. At the Baltic Sea coast, station Arkona showed a mean temperature of 4.4 °C (+2.1 K) and Warnemünde 5.2 °C (+2.9 K). At 102 mm, precipitation was too high compared to the average of 72 mm (+41 %) and along the Baltic Sea coast the following values were measured: Schleswig +23 % (97 mm), Rostock +10 % (54 mm), Arkona 37 % (59 mm) and Ückermünde 27 % (52 mm). The sunshine duration was nationwide at 25 hours (-37 %). Arkona registered a sunshine duration of 26 hours (-32 %), but in the south of Germany at the mountain Zugspitze in the Alpes the national maximum of 83 hours was measured. The lowest value was registered with 9 hours at Weiden in southeast Germany.

2.3 Summary of some of the year's significant parameters

An annual sum of 409 391 J/m² of **solar radiation** was recorded at Gdynia station (Gdansk Bight). This value is the second highest in a series of comparative data gathered since 1956 (compilated by Feistel et al., 2008). It is much lower than the long-term maximum of the sunniest year 1959 (457 751 J/m²), but well above the mean of 374 803 J/m². Like in the previous year, the sunniest month were by far May (Table 1). At 74984 J/m², Mai comes at the first 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. The year's lowest value was 3344 J/m² in December, lying in 57th place below the long-term average of 4348 J/m² as the fifth darkest December. The other months took the following ranks in the list of the solar radiation in the last 63 years: January 44th; February 13th, March 53rd; April 16th; June 10th; July 17th; August 22nd; Sept 15th; Oct 5th; Nov 38th.

With a **warm sum** of 394.5 Kd (Table 2), recorded at Warnemünde, the summer 2018 set a new record over the past 71 years and was far above the previous record of 355.1 Kd in 2006. In third position the years 1997 and 2002 with 239.9 Kd are following. The extreme 2018 value is nearly twice as high as the long-term average of 153.5 Kd.

Average monthly temperatures show the following values and rankings in the time-series since 1948: May 29.5 Kd (2nd), June (49.4 Kd (3rd), July 137.8 Kd (4th), August 130.7 Kd (2nd), September 38.1 Kd (5th) and October 9 Kd (1st). All months recorded warm sums in the "top five" and prove a constantly extreme warm summer in the Baltic Sea area.

With a **cold sum** of 67.7 Kd in Warnemünde, the winter of 2017/18 is ranked in the midrange as 34th warmest winter in the long-term data series. The winter showed sporadic days of light frost in December and January but the cold sums of zero Kd and 2.2 Kd were far below the average (cf. Table 2), but in February to March three cold periods of permanent frost occurred from February 2-10, February 23 to March 4 and March 16-19. The cold sums of February (33.3 Kd) were slightly above average, but March recorded 32.2 Kd which is much colder than usual. Compared to the long-term average of 100.8 Kd, the winter was a slightly warm one.

*Table 1: Monthly averaged weather data at Arkona station (Rügen island, 42 m MSL) from DWD (2018). t: air temperature, **Δ**t: air temperature anomaly (reference period 1981-2010), 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 (2019). Percentages are given with respect to the long-term mean. Maxima and minima are shown in bold.*

Month	*t*/°C	Δ*t*/K	*s*/%	*r*/%	Frost	Ice	Solar
Jan	2.9	1.7	71	**177**	8	0	5100
Feb	**-0.3**	-1.7	135	70	22	7	13093
Mar	0.4	**-2.5**	**65**	155	16	5	21726
Apr	8.2	2.2	117	135	-	-	45113
May	12.9	2.5	137	**16**	-	-	**74984**
Jun	16.7	2.5	130	41	-	-	67951
Jul	**19.8**	**2.7**	118	31	-	-	63541
Aug	19.2	2.2	101	90	-	-	51589
Sep	15.8	1.7	122	48	-	-	34701
Oct	11.6	1.6	**143**	68	-	-	21481
Nov	6.8	1.3	130	19	-	-	6768
Dec	4.4	2.1	68	137	4	-	**3344**

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 1948–2017 are given.

Monat	CS 2017/18	Mean	Month	HS 2018	Mean
Nov	0	2.5 ± 6.1	Apr	0	1.0 ± 2.4
Dec	0	21.1 ± 27.9	May	29.5	5.9 ± 7.0
Jan	2.2	38.8 ± 39.2	Jun	49.4	23.4 ± 14.5
Feb	33.3	30.4 ± 37.6	Jul	137.8	57.4 ± 35.8
Mar	32.2	8.1 ± 11.9	Aug	130.7	53.4 ± 31.8
Apr	0	0 ± 0.2	Sep	38.1	12.0 ± 13.1
			Oct	9	0.4 ± 1.1
Σ 2017/2018	67.7	100.8 ± 84.8	Σ 2018	394.5	153.5 ± 68.9

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.*

Month	CS 2017/18	Month	HS 2018
Nov	0	Apr	1
Dec	0	May	1.5
Jan	2.2	Jun	28.9
Feb	28.7	Jul	117.1
Mrz	22.9	Aug	112.3
Apr	0	Sep	33.2
		Oct	1.7
Σ 2017/2018	53.8	Σ 2018	295.7

Figures 3 to 6 illustrate the **wind conditions** at Arkona throughout 2018. Figure 3 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 2018 assessment (Figure 3a), the long-term climatic wind curve is shown by way of comparison (Figure 3b); it was derived from the 1951-2002 time series. The 2018 curve (37 000 km eastwards, 31 000 km northwards) differs from the curve for the climatic mean (52 000 km eastwards, 25 000 km northwards) and showed in the months February to July often dominance of easterly winds instead of the typical southwestern to western directions. The trend towards prevailing SW winds that began in 1981 and continues until today (HAGEN & FEISTEL, 2008) is not so evident over the year like in the previous year 2017 (Naumann et al., 2018). Only the months January, July to October and December show their typical pattern. The curves of February and June show a strong vector compensation of south-western and north-eastern winds and low intensity. In March, April and November phases of easterly winds were dominant (Figure 3a). According to the wind-rose diagram (Figure 5), northwestern to southwestern directed winds account for about 50 % of the annual sum, which is a low percentage compared to the previous year 2017 (75 %). Easterly to northeasterly account for another 25 % and registered the most high-wind days of over 15 m/s during the year. The mean wind speed of 6.5 m/s (Figure 4a) is much lower than the long-term average of 7.1 m/s (HAGEN & FEISTEL, 2008). Compared to long-term data since 1980, it is the lowest annual wind intensity followed by the year 2016 (6.52 m/s). The windiest year in this period of 8.41 m/s was 1990 (based on DWD data, 2019b). Comparing the east component of the wind (positive westwards) with an average of 1.2 m/s (Figure 4b) with the climatic mean of 1.7 m/s (HAGEN & FEISTEL, 2008), westerly winds were in 2018 lower than the mean. For example Figure 3a shows an eastward movement of 37 000 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 smoother 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).

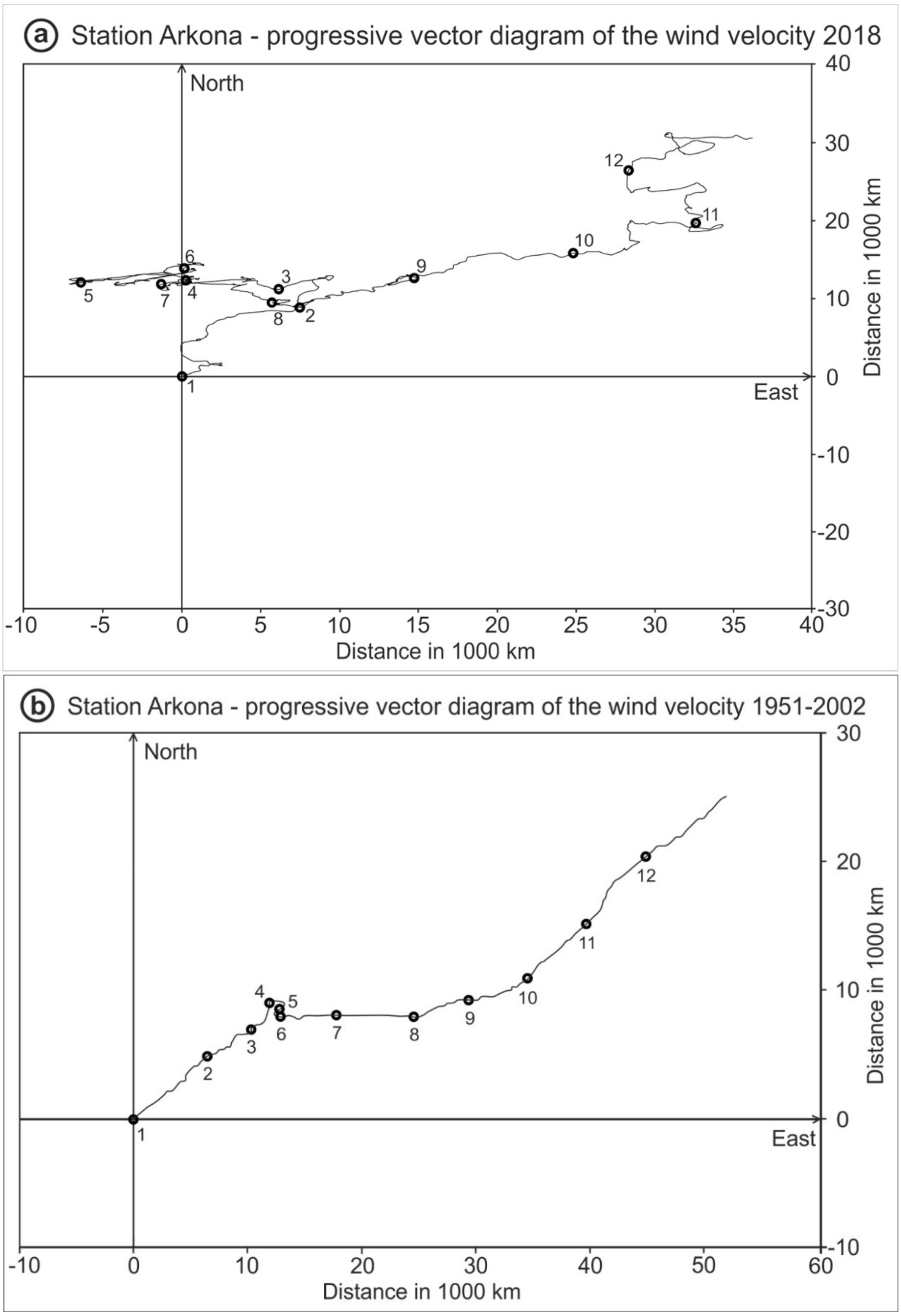


Fig. 3: Progressive vector diagram of the wind velocity at the weather station Arkona, distance in 1000 km, positive in northerly and easterly directions. The first day of each month is encircled. a) the year 2018 (from data of DWD, 2019a). b) long-term average.

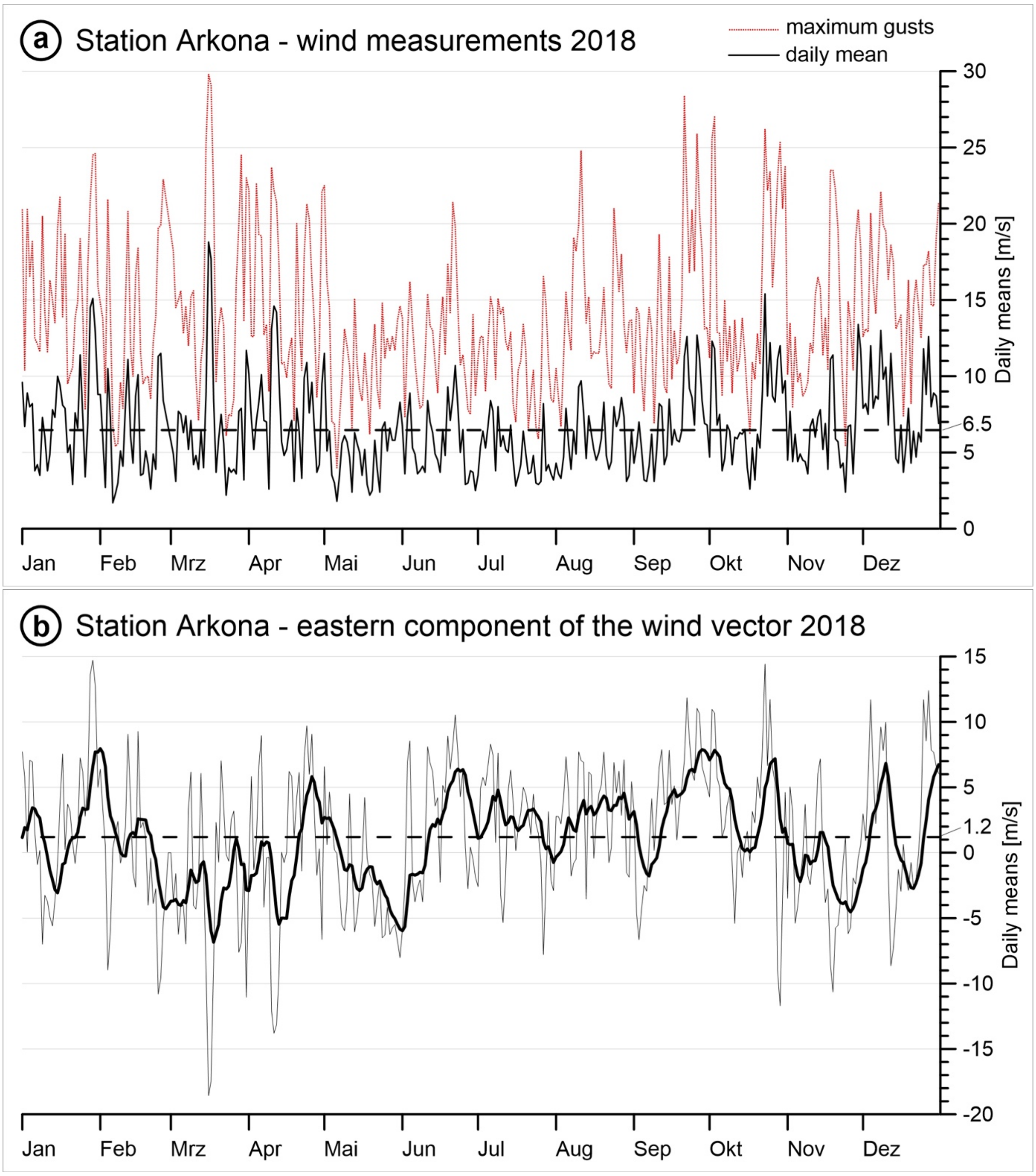


Fig. 4: Wind measurements at the weather station Arkona (from data of DWD, 2019a). a) Daily means and maximum gusts of wind speed, in m/s, the dashed black line depicts the annual average of 6.5 m/s. b) Daily means of the eastern component (westerly wind positive). The dashed line depicts the annual average of 1.2 m/s. The line in bold is filtered with a 10-days exponential memory.

Wind development in the course of the year shows a typical distribution of stronger winds, as daily averages of more than 10 m/s (>5 Bft) were often exceeded in the winter half year (Figure 4a). On March 16 a storm from eastern direction (low-pressure “Zsuzsa” of 970 hPA crossing the North Atlantic and high pressure “Irenäus” of 1040 hPa across Scandinavia) occurred in the Baltic Sea as strongest wind event of the year, showing the highest daily average of 18.8 m/s and gusts up to 29.8 m/s (Figure 4a). Other storm events occurred from western direction on October

23 (low pressures "Siglinde" across Scandinavia) with daily means of 15.4 m/s and gusts up to 26.2 m/s as well as on January 29 (low pressures "Imke" and "Jira", daily mean of 15.1 m/s, gusts 24.5 m/s). The annual mean wind speed of 6.5 m/s is much lower than 2017's 7.2 m/s (NAUMANN et al., 2018). Previous years showed annual mean values of 6.5 m/s (2016), 7.2 m/s (2015), 6.7 m/s (2014) and 7.0 m/s in the year 2013 (NAUSCH et al., 2014, 2015, 2016, NAUMANN et al., 2017, 2018). Maximum wind speeds in excess of 20 m/s (>8 Bft) were recorded as hourly means at March 16 (22.3 m/s) and March 17 (20.9 m/s). In 2017, a similar maximum value of 21.9 m/s was reached on December 24 (NAUMANN et al., 2018). 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 5) in which orange and red colour signatures indicating values greater than 20 m/s. They did only slightly occur from easterly direction in 2018.

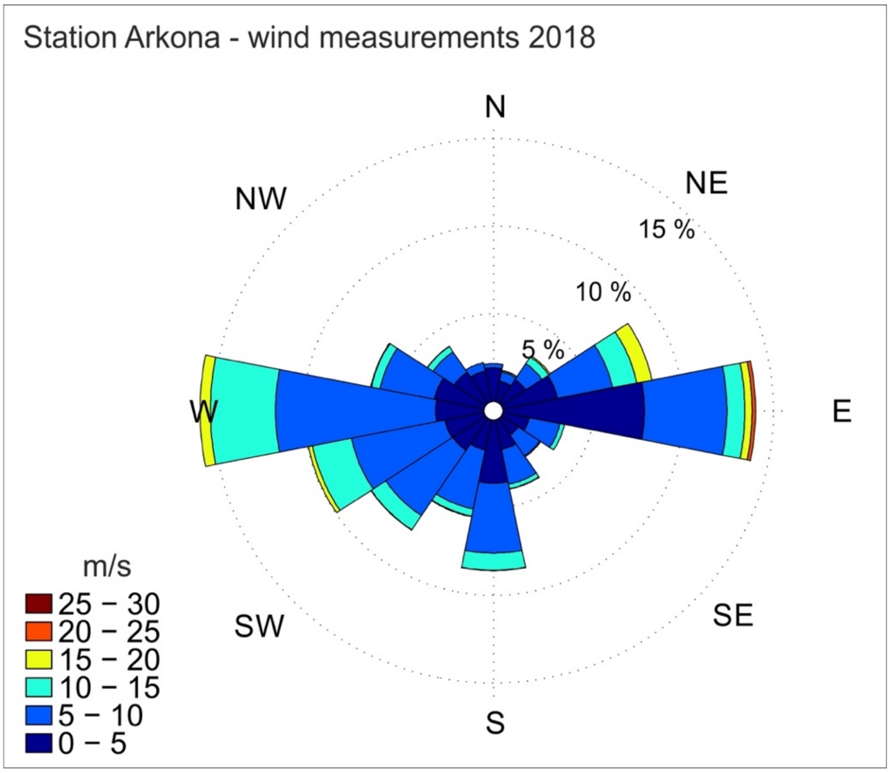


Fig. 5: Wind measurements at the weather station Arkona (from data of DWD, 2019a) as windrose plot. Distribution of wind direction and strength based on hourly means of the year 2018.

The Swedish tide gauge station at Landsort Norra provides a good description of the general **water level** in the Baltic Sea (Figure 6a). 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 land lift (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 2018, the Baltic Sea experienced two barotropic inflow phases with total volumes estimated between 233 km³ and 215 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 4b, 6b). 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).

At the beginning of the year, on January 1, the gauge at Landsort Norra recorded the highstand of 42 cm MSL (Figure 6a) as a result of preceding strong westerly to northwesterly winds. A short system shift to moderate to strong easterly winds caused a sea level drop to -20.9 cm (February 25). Afterwards a rapid sea level rise to 26.1 cm MSL (February 3) occurred due to prevailing westerly winds, before a longer outflow period started. At the end of this phase the lowstand of the year of -48.6 cm MSL was reached at March 18. Up to mid of June a negative eastern and southeastern component of the wind dominated (Figure 4b, 6b) and the sea level fluctuated below the mean sea level (-35 cm to -3 cm MSL). Afterwards the general wind situation turned to westerly winds, but of low intensity (Figure 4a). Up to mid-September, the sea level was oscillating around the mean level. Since September 12 to the end of the month a phase of moderate to strong westerly to northwesterly winds rapidly raised the sea level. The annual top level of 44.8 cm MSL was registered at October 2nd and the resulting inflow volume of 233 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 to use 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 share of around 50 km³ propagated through the Öresound (Figure 7) and another 183 km³ crossed the Darss Sill. The bottom salinity at the Darss Sill exceeded 17 g/kg only for a short time and the stratification was too high to classify this event as a Major Baltic Inflow. A short period of southern to southeastern winds lowered the level at Landsort to 10 cm MSL (October 18th) before a next short period of westerly winds raised the level again to 43.8 cm MSL (October 27th). In November, long lasting easterly winds led to continuous outflow and a lowstand of -44.4 cm MSL (November 30th) was reached (Figure 6a). Afterwards a next rapid sea level rise of 60.7 cm to a top level of 16.3 cm MSL occurred up to December 11th. A total volume of 215 km³ was calculated, whereof 45 km³ crossed the Öresund (Figure 7). To the end of the year a balanced level was reached (Figure 6a).

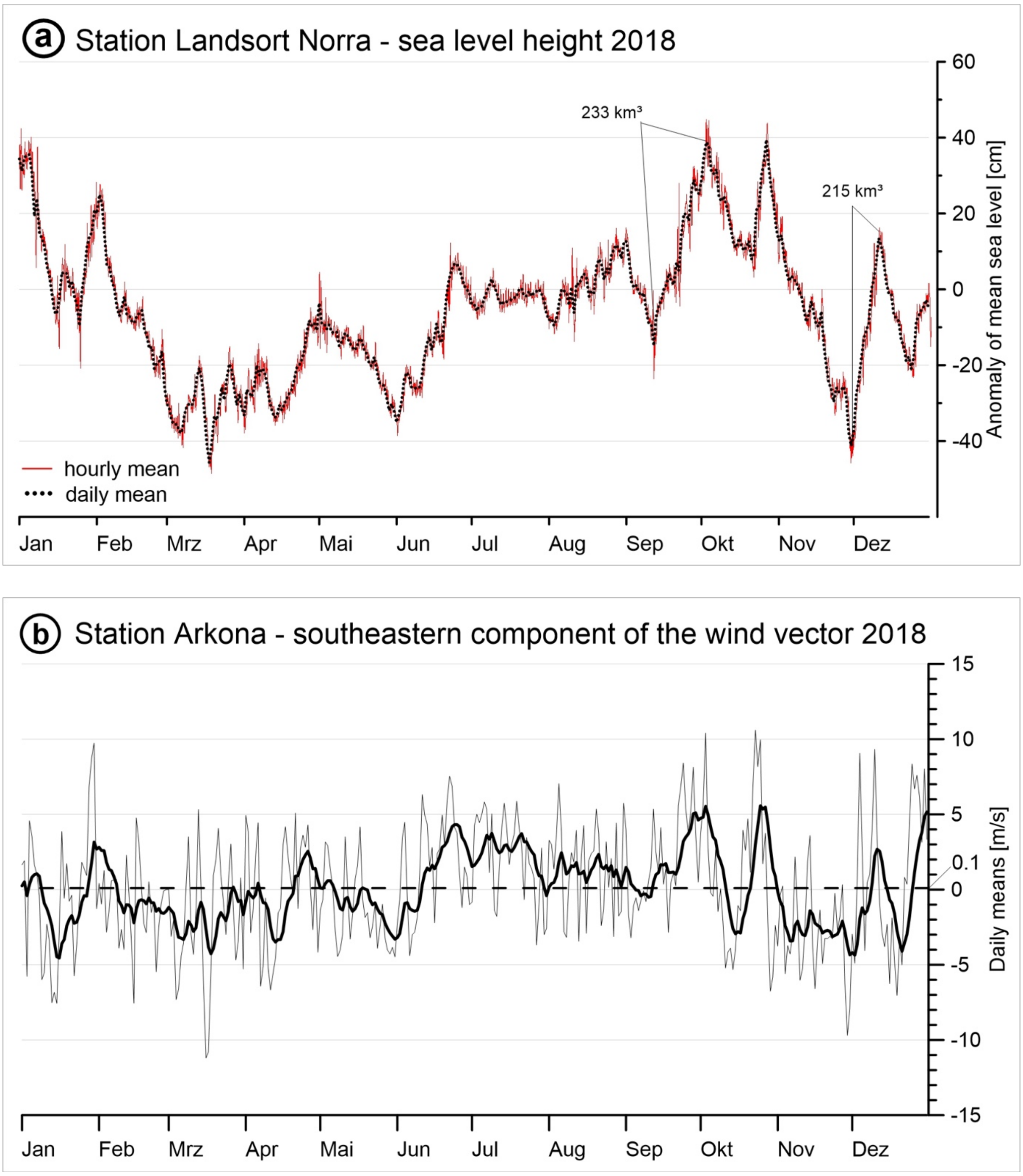


Fig. 6: a) Sea level at Landsort as a measure of the Baltic Sea fill factor (from data of SMHI, 2019a). b) Strength of the southeastern component of the wind vector (northwesterly wind positive) at the weather station Arkona (from data of DWD, 2019a). The bold curve appeared by filtering with an exponential 10-days memory. The dashed line depicts the annual average of 0.1 m/s.

Compared to previous years of high inflow activity of four MBIs and various smaller events (2014-2017), the year 2018 is characterized a weak to moderate inflow year. This is visualized in Figure 7 by the accumulated inflow volume through the Öresund (SMHI, 2014-2018), where the inflow curve of 2018 runs below the average of the reference period 1977-2016.

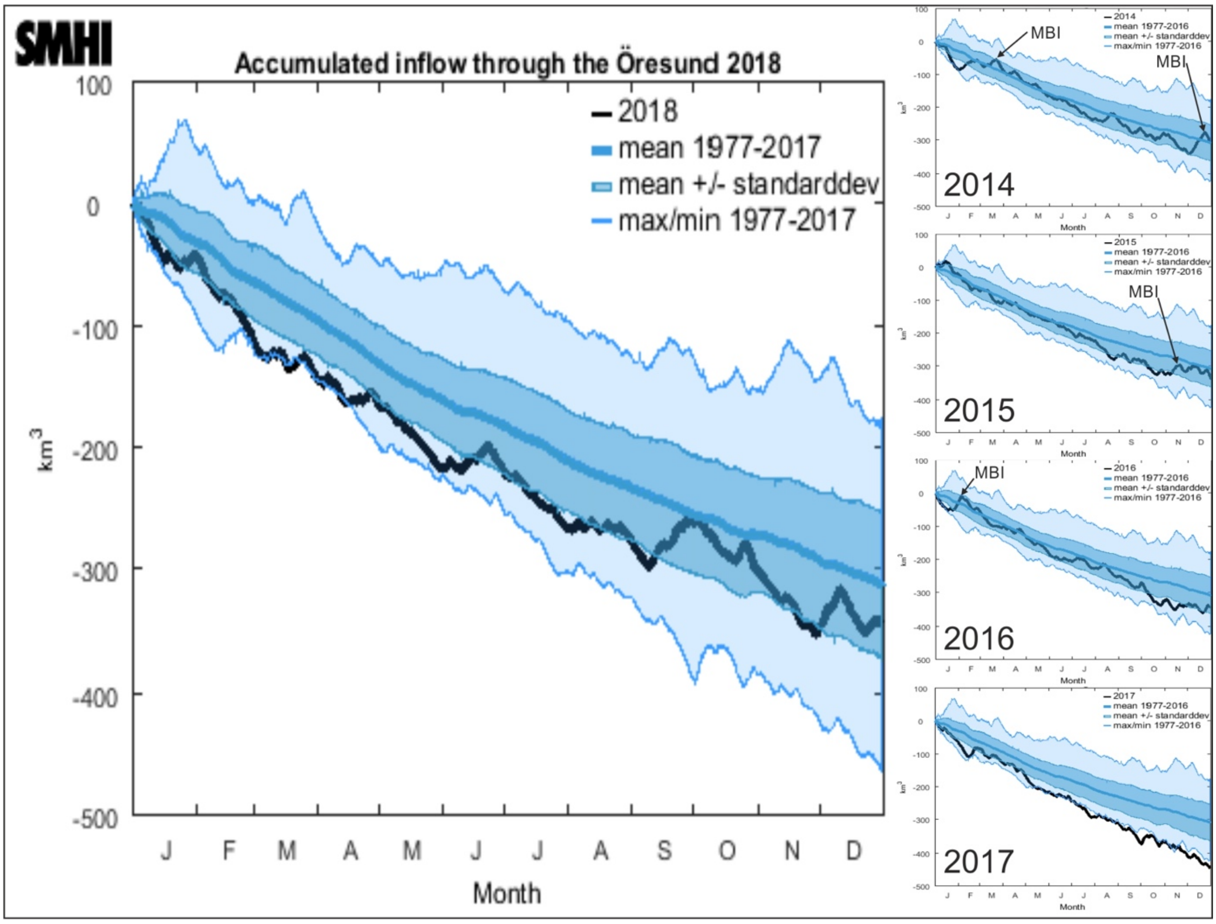


Fig. 7: Accumulated inflow (volume transport) through the Öresund during 2018 in comparison to previous years 2014-2017 (SMHI 2019b).

3. Water exchange through the straits / observations at the monitoring platform "Darss Sill"

The monitoring station at the Darss Sill supplied nearly complete records during the year 2018, except for the last 9 days of December due to a broken wind turbine. This resulted in a complete loss of sensor data in all depths during this period. The ADCP provided full data records throughout the observation period. The oxygen sensors showed in the first half of January and in April multiple short data gaps. 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 of 9 days at the end of December did not bias the annual statistics.

The temperature recordings of 2018 were close to those of the record-setting year 2014. The yearly mean temperatures (Table 4) for the year 2018 were with 10.54 °C slightly lower than in 2014. Annual mean surface-layer temperatures are found on rank 2 of the entire record since 1992 (i.e. in the upper quartile), which is consistent with the climatic characterization of 2018 as a year with the warmest summer (see chapter 2). Due to the unusual cold spring, but the long, hot and dry summer, the standard deviation of the surface-layer temperatures shows the largest value since the beginning of recordings in 1992. This large annual variability can also be seen in Figure 9. Here, we show the anomaly of the near surface temperature. The climatology was based on the data set of REYNOLDS et al., 2007 and covers the period 1982-2011. This period can be regarded as close to the national reference period (1981-2010). In spring, the water was up to 2 K colder than the long-term mean. However, during summer the station recorded elevated values of up to 5 K above average. The temperature values at 17m and 19m are well below the recordings in 2014. Nevertheless, they are still placed in the upper quartile of all recordings. As already discussed for the near surface temperatures, also the annual variability of the temperature at the two lowest sensors was largest in 2018.

The mean salinities and their standard deviations at the station are given in Table 4. 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 years 2014 and 2016, both characterized by strong inflow activity, the year 2018 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 m depth, and only 3 years in 19 m depth. The standard deviations at the 17 m depth level can be considered as average. However, the variability at the 19 m sensor can be ranked as the third largest so far observed. In contrast, the near surface salinity was well below the long-term mean and shows the second lowest variability, since the start of recordings in 1992. These first findings already indicate a lack of barotropic inflow activity in 2018, but suggest some baroclinic inflow activity.

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 large standard variations in 2018 discussed above, Table 5 shows that also the amplitudes of the annual cycle at different depths are well above the long-term average, and close to 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 0.5 months between the surface and near-bottom temperatures that is also evident from Table 5. Due to the low wind speeds in early summer, a strong thermal stratification could build up, isolating the lower layers from direct atmospheric forcing. Still, due to the large temperature amplitude in the atmosphere, the near bottom water at 17m finally reached a new long-term maximum. The temperature amplitude at the bottom (19m) is ranked as the second largest since 1992.

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
2018	10.54 ±**6.62**	8.76 ± 1.16	9.24 ± **5.41**	11.58 ±3.23	9.16 ± **5.27**	12.56 ± 3.56

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
2018	8.82	4.53	**7.31**	4.08	7.18	4.01

To provide a final statistical measure, we evaluated the minimum and maximum temperatures recorded at 7m water depth at Darss Sill. Table 6 indicates that in 2018 the highest temperature since 1995 was recorded. In the beginning of August, the water temperature reached 23.10 °C. Additionally, the annual temperature range is ranked as the third largest since 1995. Similar conclusions can be drawn from the amplitude of the annual cycle, given in Table 5.

Table 6: Minimum and maximum temperatures measured at 7m water depth at Darss Sill. Time indicates the date of occurrence. The column Range provides the difference between minimum and maximum temperature. Minima and maxima are highlighted in bold face. For the occurrence of the annual maximum, we indicated in bold face the first ever recording.

	Minimum		Maximum		
Year	Temperature °C	Time	Temperature °C	Time	Range °C
1995	0.98	30.12	20.54	05.08	19.56
1996	0.37	27.01	17.65	09.08	17.28
1997	0.16	21.01	22.50	19.08	22.34
1998	2.59	16.12	16.61	10.08	14.02
1999	1.55	18.02	19.84	31.07	18.29
2000	2.65	25.01	17.87	14.08	15.22
2001	2.33	28.03	20.65	29.07	18.32
2002	2.03	13.01	20.24	30.08	18.21
2003	0.09	11.01	21.92	13.08	21.83
2004	1.45	28.02	19.11	20.08	17.66
2005	1.50	13.03	19.79	13.07	18.29
2006	0.40	30.01	22.80	21.07	**22.40**
2007	3.36	25.02	18.70	14.08	15.34
2008	3.12	17.02	19.67	29.07	16.55
2009	1.65	25.02	19.62	10.08	17.97
2010	**-0.44**	05.02	20.33	21.07	20.77
2011	-0.12	05.01	17.94	12.07	18.06
2012	–	–	–	–	-
2013	–	–	–	–	
2014	1.54	09.02	21.61	09.08	20.07
2015	2.95	04.02	18.14	13.08	15.19
2016	1.81	23.01	20.42	28.07	18.61
2017	2.09	19.02	18.61	30.08	16.52
2018	1.11	18.03	**23.10**	04.08	21.99

3.2 Warming phase and buildup of stratification

Figure 8 shows the development of water temperature and salinity in 2018 in the surface layer (7 m depth) and the near-bottom region (19 m depth). As in the previous years, the currents in the surface and bottom layers, observed by the bottom-mounted ADCP, were integrated in time, respectively, in order to emphasize the low-frequency baroclinic (depth-variable) component, plotted in Figure 10 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 10, using the convention that positive slopes reflect inflow events.

The year 2018 started with well-mixed conditions in temperature and salinity that lasted until the beginning of April. The lowest temperature of 1.11 °C at Darss Sill was recorded at 18.03. (Table 6). Due to the low air temperatures in March, the situation did not change significantly during that time. Moreover, the lowering of the sea level at Landsort (Figure 6) and the induced outflow of water through the Danish straits, further suppressed the development of stratification at Darss Sill. The warming in April (Table 1) led to a first build-up of stratification in temperature, accompanied by a slight stratification in salinity. The low easterly wind speeds supported this tendency. At the end of April, the wind turned to a westerly direction with wind speeds peaking at 10 m/s, homogenising again the entire water column. With the start of May, the wind turned again to easterly winds of low intensity (wind speed < 5 m/s, Figure 4). This induced an outflow of water over the entire water column (Figure 10). The bottom salinity dropped to values well below 10 g/kg.

3.3 Baroclinic inflow activities during summer

At the end of May, the wind turned again to westerly winds and remained calm (wind speeds <5m/s) for the following months, until the first week of September. The low wind speed supported the build-up of stratification at Darss Sill. Due to the positive air temperature anomaly of +2.5 K (Table 1), the warming of the surface waters set in. The water temperature anomaly in early summer reached +3.5 K (Figure 9), and the temperature difference between surface and bottom waters at Darss Sill showed peak values of +8 K. The low wind speed in combination with the build up of thermal stratification set the stage for pronounced baroclinic inflow activity (FEISTEL et al., 2006). These baroclinic inflows can only be established during persistently calm wind conditions (usually in late summer). They import salt into the Baltic along with water volume export. In contrast to barotropic inflows (MOHRHOLZ et al., 2015), these baroclinic inflows import oxygen-deficient waters, but ventilate the deep Baltic basins by entrainment.

From mid-May on, the salinity continuously increased from 10 g/kg to peak values of 16 g/kg at the end of June (Figure 8). With the start of June, a stable stratification in temperature and salinity developed at Darss Sill. Moreover, the progressive vector diagrams (Figure 10) indicate the divergence of the flow tendency near the bottom and at the surface. At the bottom, we see a continuous inflow of water, whereas surface waters were leaving the Baltic Sea. The ongoing inflow lead to a further increase in the near-bottom salinities, increasing to 17 g/kg (Figure 8). On the 25.6. a short wind event led to a collapse of the stratification, nearly homogenising the salinity over the entire water column. However, due to the high positive air temperature anomalies and the re-establishing of the baroclinic inflow situation, the near-bottom salinities further increased to 18-19 g/kg.

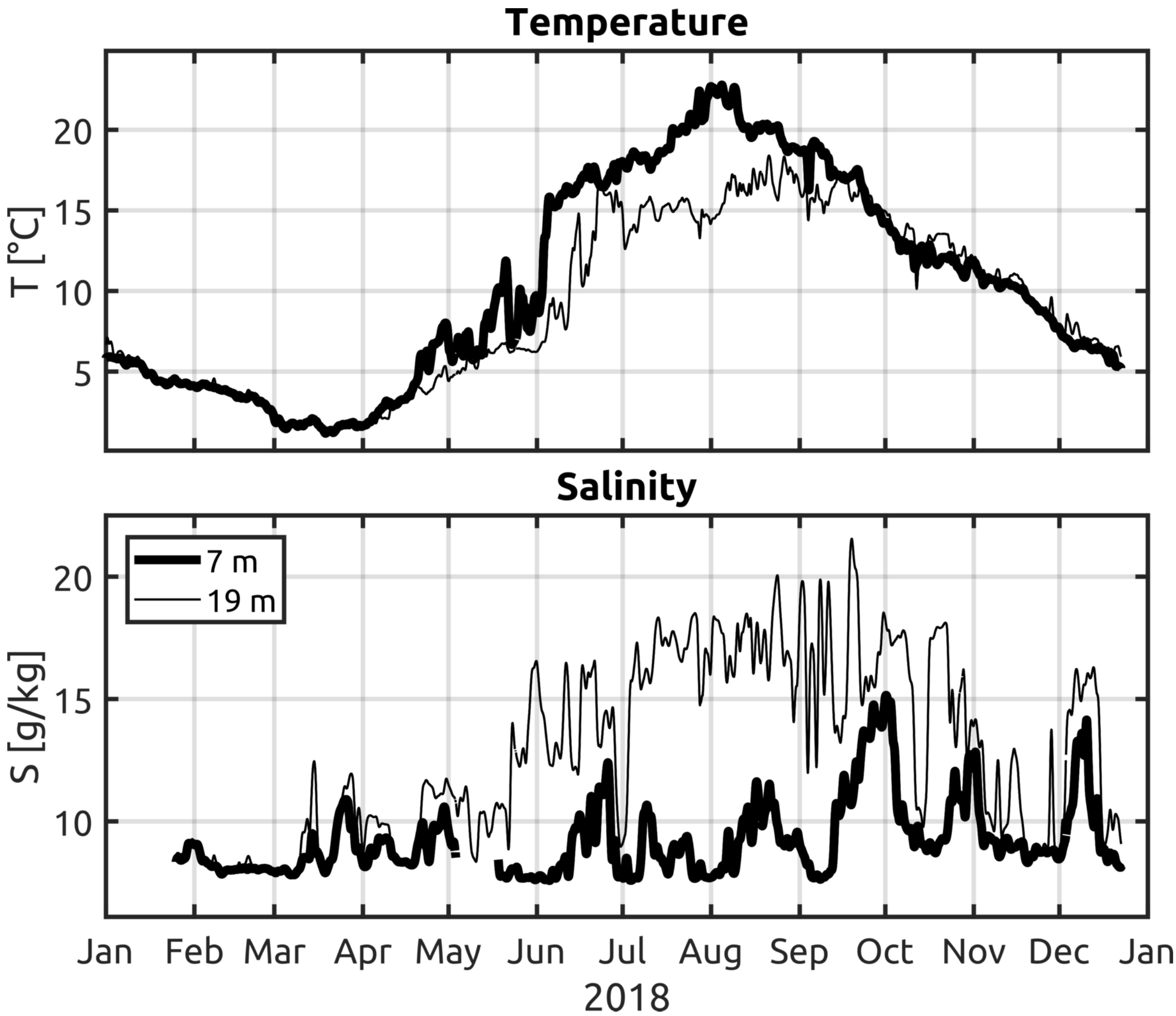


Fig. 8: Water temperature (above) and salinity (below) measured in the surface layer and the near-bottom layer at Darss Sill in 2018

Although the bottom salinity shows some variability during July and August, the values stayed nearly always above 16 g/kg. The baroclinic inflow activity was further supported by the high positive air temperature anomalies. At the end of July, the surface waters at Darss Sill showed a maximum temperature anomaly of +5 K. At the first days of August the highest temperature of 23.1 K (during the period 1995-2018) was recorded. Along with this record-breaking value, the temperature difference between surface and bottom layer reached a peak value of 12.4 K. This large temperature gradient, in combination with the haline stratification (Figure 8), provided a very effective shielding and decoupling of the surface dynamics from the flow activity at the seafloor. Thus, the baroclinic pressure gradient between the high saline Kattegat waters and the low salinity Bornholm Basin waters controlled the inflow dynamics (LASS et al., 1987). The barotropic pressure gradient could only balance an outflow of brackish, low saline water. The strong stratification further enhanced and maintained the estuarine circulation: inflow of saline water at the bottom and outflow of low saline water at the surface.

The progressive vector diagrams (Figure 10) show that in mid-August positive values were reached. This indicates that in August the total inflow water budget was positive, compared with the long-term outflow of 15500 m^3/s through the Danish straits (FEISTEL et al., 2008).

The strong stratification, at Darss Sill and in the Belt Sea, had negative consequence for the oxygen dynamics. The oxygen data (Figure 11) reflect typical baroclinic inflow conditions. With the onset of stratification at Darss Sill, first week of March, oxygen saturation in the bottom layers was well below the surface values. Due to the shielding effect of the double stratification (halocline and thermocline), the bottom layers could not be oxygenised. Thus, a reduction in oxygen saturation took place. Furthermore, the end of the spring bloom in early April lead to a sinking of organic material, causing a strong oxygen demand due to remineralisation in the near-bottom layers. Since baroclinic inflows import oxygen-deficient waters, the oxygen situation could not be improved during these inflow events. It is therefore not surprising that the lowest oxygen concentrations of the year were observed at the end of September with 12% of the saturation. Thus, the oxygen in the near bottom layers was nearly depleted.

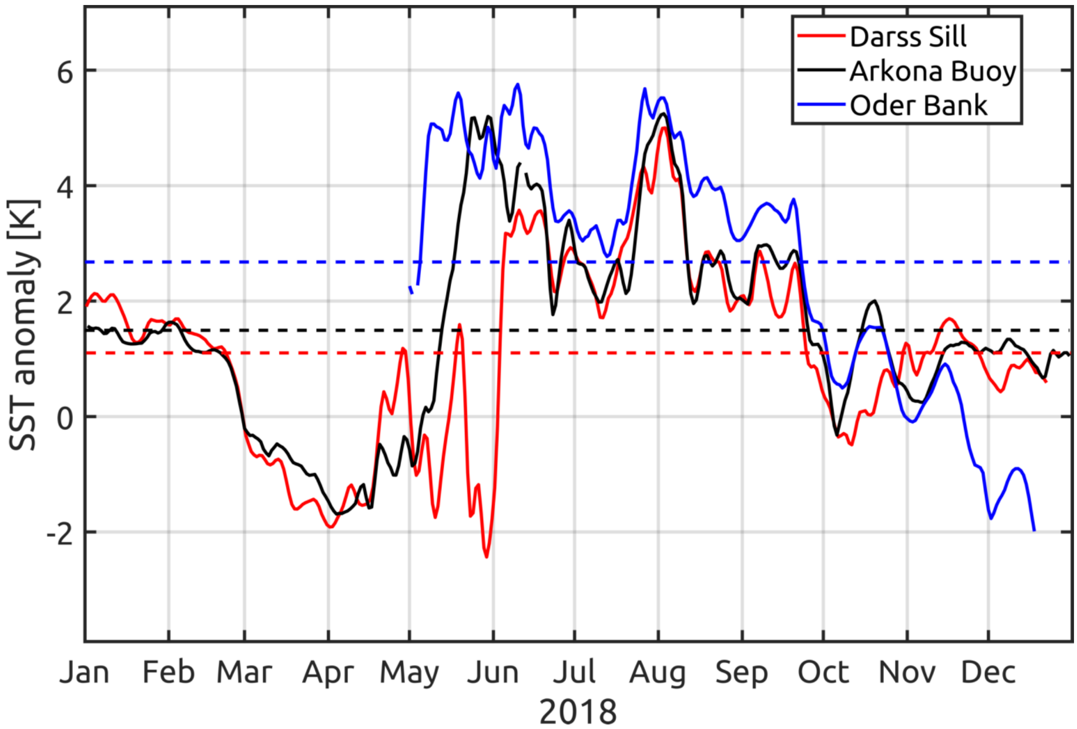


Fig. 9: Deviation of near surface temperature from the climatology at the three stations in 2018. The climatology was built for the national reference period 1981-2010 and is based on the dataset of Renolds et al., 2007. The full lines show the anomaly, the dashed lines indicate the annual means.

3.4 Cooling phase with small inflow events in October and December

The oxygen conditions near the sea floor improved at the end of September. After two weeks of westerly winds, with peak wind speeds of 25 m/s, a nearly full breakdown of the stratification could be observed. The water column at Darss Sill did not show any significant thermal stratification anymore. Furthermore, the wind induced mixing increased the salinity of the surface layers to values of 14 g/kg. Thus, the wind nearly homogenised the entire water column. As already indicated by the gauge data of Landsort (Figure 6a), a barotropic inflow took place. Based on the sea level change at Landsort, an inflow volume of 230 km^3 was estimated. Although the sensors recorded elevated salinities of up to 18 g/kg, haline stratification at Darss Sill was still present.

From November 2 on, the wind turned to easterly directions and an outflow of water through the Danish Straits took place. During November, the near-bottom salinities reached the near-surface values of 9 g/kg. Besides the low bottom salinities, the nearly linear drop in the progressive vector diagrams (Figure 10) confirms the finding of an outflow event. At the first days of December, the wind direction returned to the climatological mean (south-westerly direction) and reached for two weeks average values of 10-12 m/s, with peak speeds of 20 m/s (Figure 3b). This induced a further barotropic inflow event. Based on the change in the gauge Landsort, the inflow volume was estimated with 215 km^3. However, the bottom salinities at Darss Sill did not exceeded 16 g/kg.

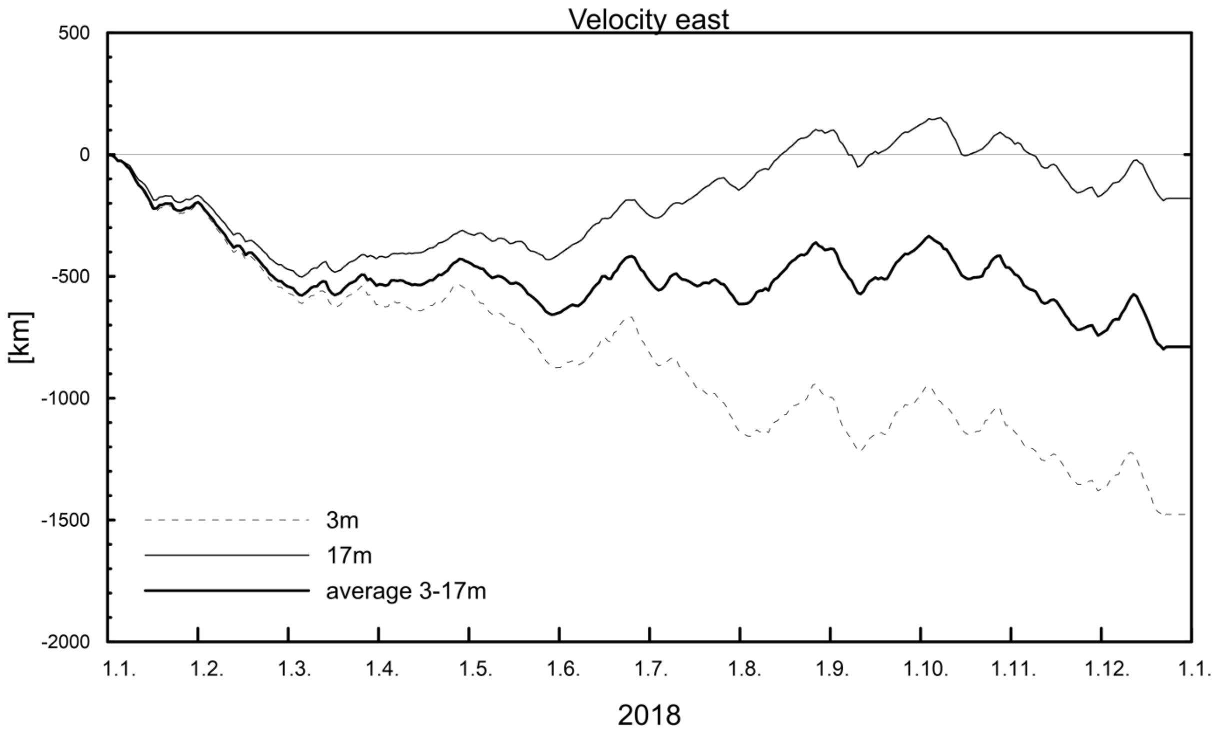


Fig. 10: East component of the progressive vector diagrams of the current in 3 m depth (solid line), the vertical averaged current (thick line) and the current in 17 m depth (dashed line) at the Darss Sill in 2018

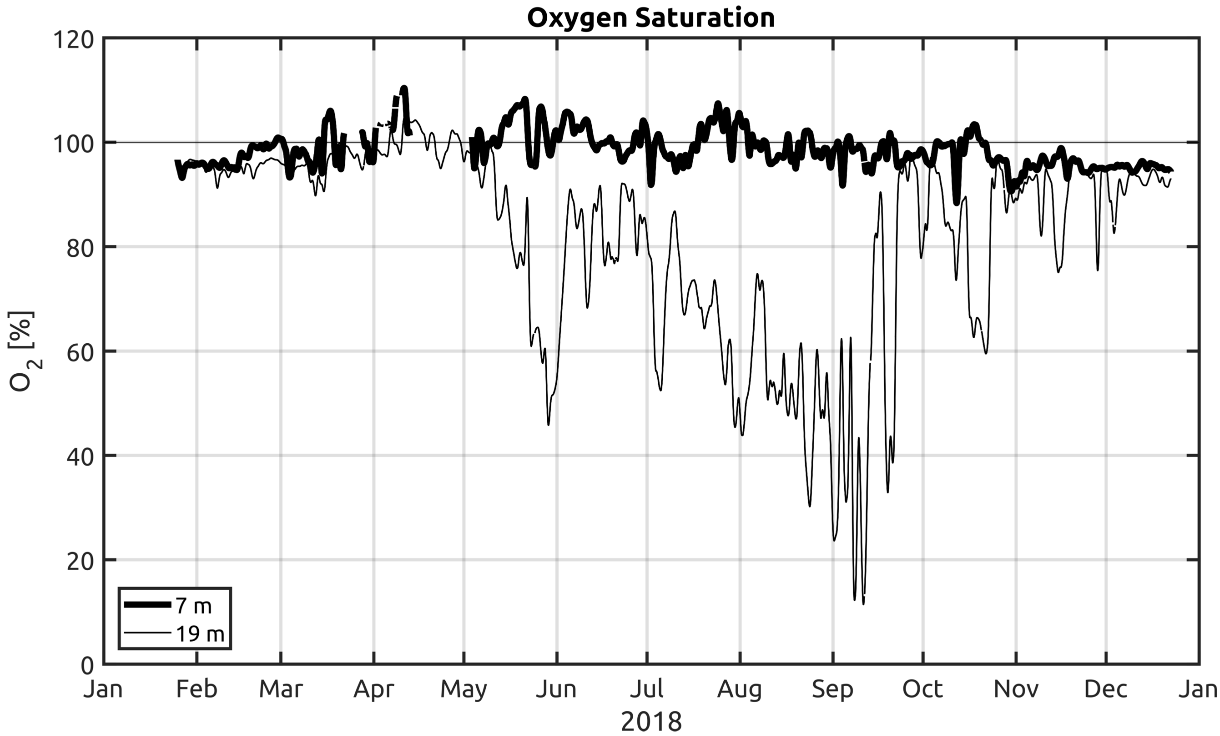


Fig. 11: Oxygen saturation measured in the surface and bottom layer at the Darss Sill in 2018

4. Observations at the buoy "Arkona Basin"

The dynamics of saline bottom currents in the Arkona Basin were 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 a 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. The monitoring station in the Arkona Basin supplied nearly complete records during the year 2018. During 3.9.-19.12., a broken internal battery of the T/S sensors in 25 m depth led to a gap in the recordings. Additionally, due to air bubbles in the conductivity sensor at 7 m depth, the measured salinity data did not pass the validation check. 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 12 shows the time series of water temperature and salinity at depths of 7 m and 40 m, representing the surface and bottom layer properties. Corresponding oxygen concentrations, plotted as saturation values as in the previous chapter, are shown in Figure 13.

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 lowest daily mean temperatures of the year, approximately 1.3 °C, were reached on 24.03. (Figure 12), approximately 0.2 °C warmer than the minimum temperatures measured 5 days earlier 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.

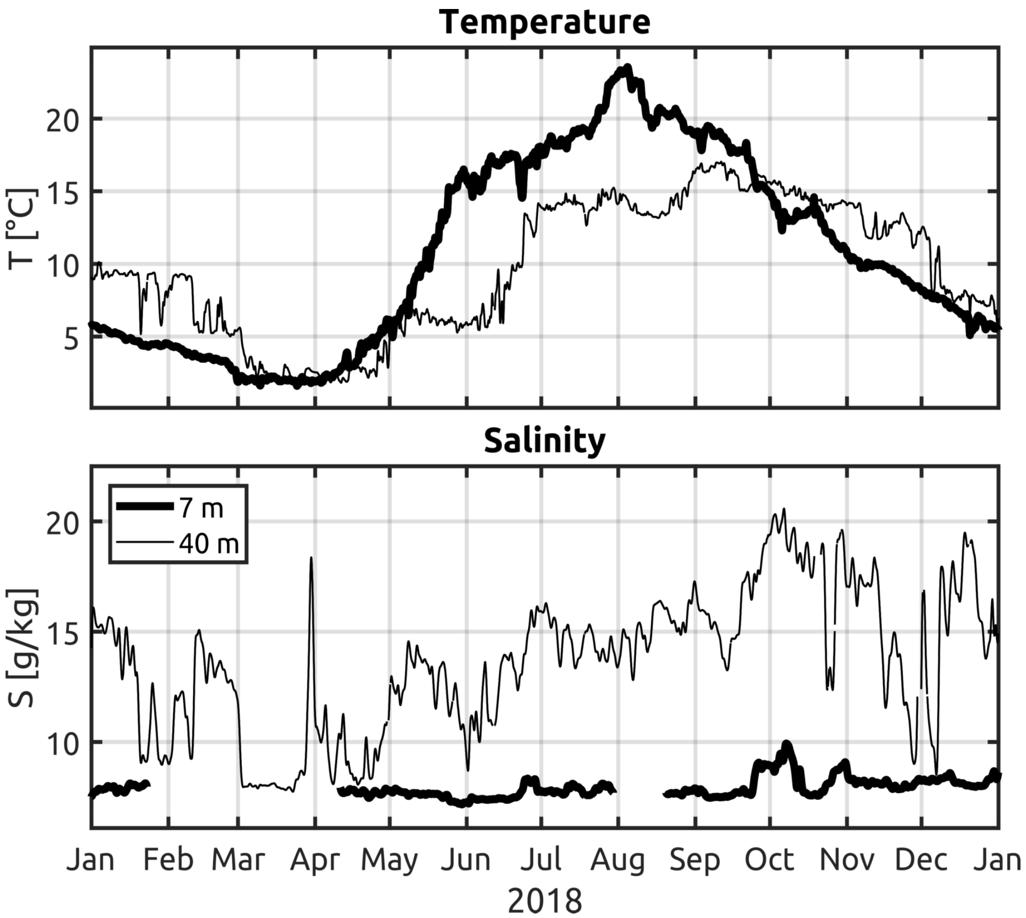


Fig. 12: Water temperature (above) and salinity (below) measured in the surface layer and near bottom layer at the station AB in the Arkona Basin in 2017

During the first two weeks of 2018, the water mass properties in the bottom layer were determined by the aftermath of a small inflow event that had occurred in the second half of December of 2017 (see Figure 8 and Figure 6a). Nearly stagnant temperatures around 8 °C suggest that the near-bottom region was decoupled from direct atmospheric cooling. The slowly decaying salinities indicate the draining of the bottom pool of salty and dense inflow waters through the Bornholm Channel (Figure 12). 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 60 % of the saturation threshold (Figure 13).

Beginning in the 3rd week of January, the near bottom variability in temperature and salinity increased, indicating a small inflow event. During this time, 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 15 g/kg (Figure 12). During this event, also the bottom temperatures dropped by 4 K, but still showed a declining tendency. Additionally, a combination of reversible downwelling on the southern slope of the Arkona Basin, and the arrival of the cold and salty inflow waters from the Darss Sill, lead to a recovery of the oxygen values to roughly 95 %.

At the beginning of March, some gale winds of 20 m/s homogenised the water column in temperature and salinity. The bottom oxygen values reached near surface figures. During a further gale with easterly winds during 17/18 March 2018, the water levels in the Baltic Sea decreased (see Figure 6a). In its aftermath, and with the refilling of the Baltic Sea, highly saline waters, with salinities of 19.4 g/kg, were recorded at March 19. Since the measurements at Darss Sill simultaneously showed low values of only 14 g/kg (Figure 8), the origin of the water masses was the Sound. The short inflow via Drogden Sill can also be seen from the accumulated inflow through the Öresund (Figure 7).

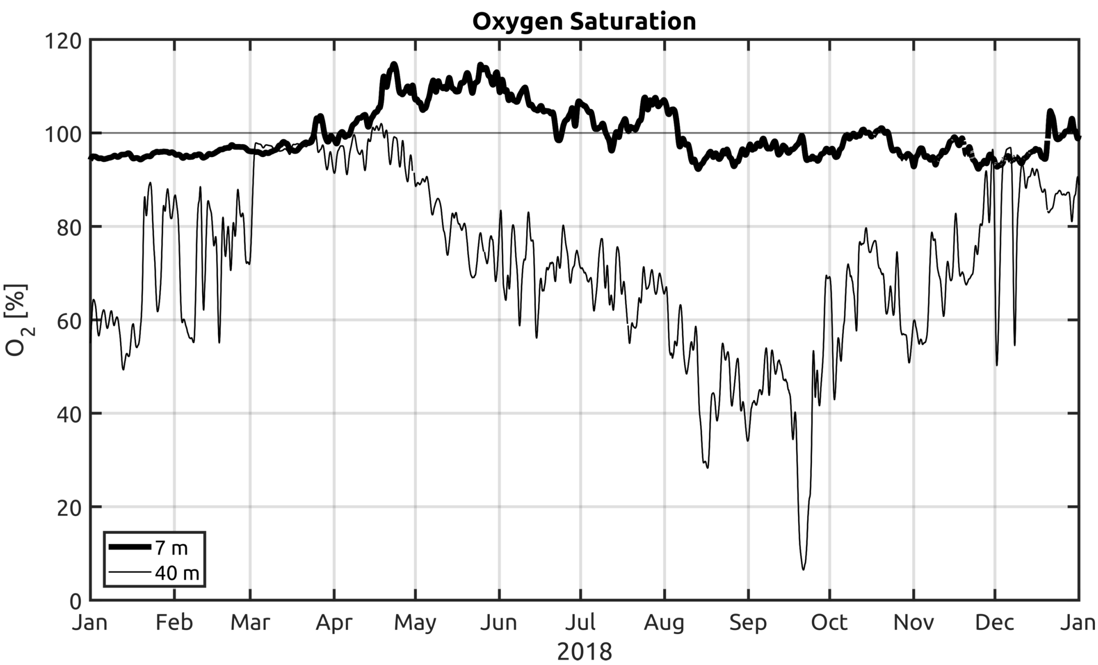


Fig. 13: Oxygen saturation measured in the surface and bottom layer at the station AB in the Arkona Basin in 2017

To present a slightly different view of the near-bottom dynamics in the Arkona Basin, we applied the numerical model of GRÄWE et al., (2015), and extended the simulation to the year 2018. Beside temperature and salinity as active tracers, we coupled an age tracer to the model. As age we define the time elapsed since last contact with the sea surface (DELHEZ & DELEERSNIJDER, 2002). The age tracer therefore provides a good estimate of the deep-water ventilation.

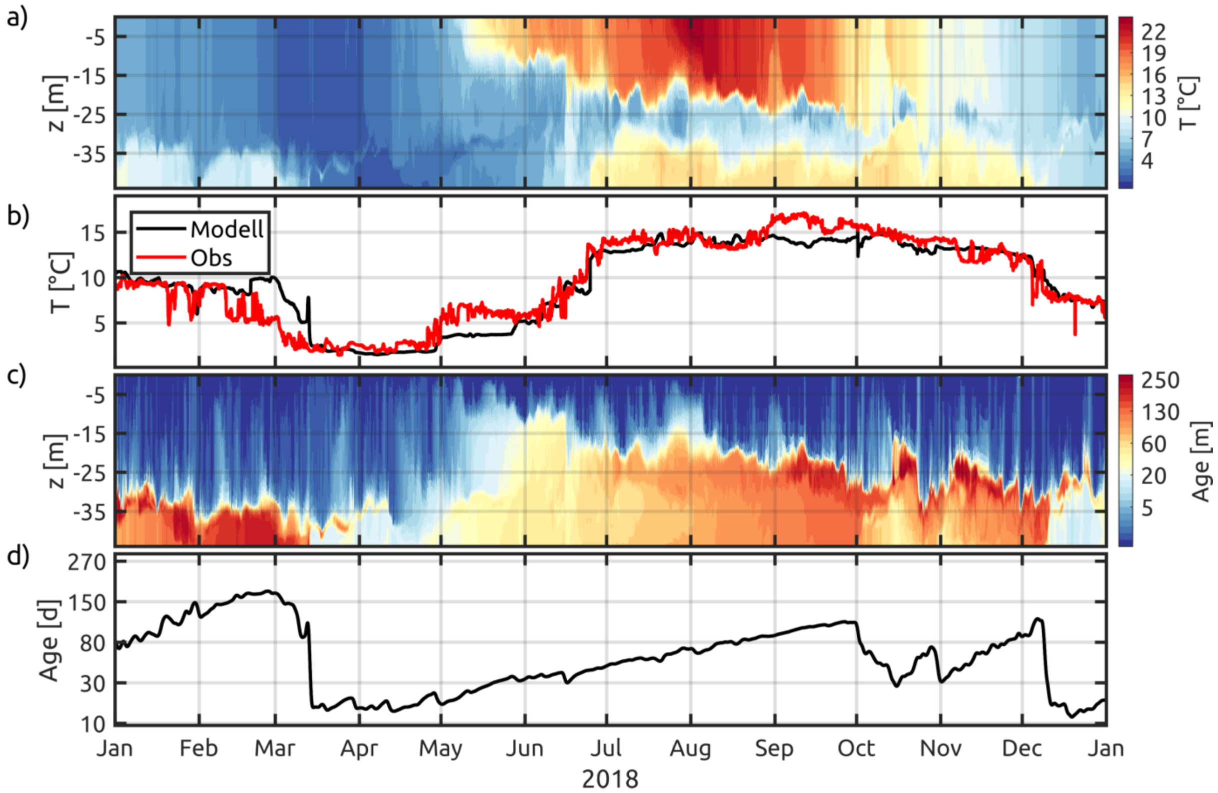


Fig. 14: a) Vertically resolved modelled temperature at the station AB in the Arkona Basin in 2018. b) Comparison of measured and modelled temperatures at 40 m depth. c) Vertically resolved modelled water age. d) Time series of the near bottom water age. Please note in c) and d) the non-linear scaling of the water age.

In Figure 14c, we show the vertically resolved profile of water age at the station AB in the Arkona Basin. The water age was computed using the numerical model of GRÄWE et al. (2015). The inflow through the Öresund can clearly been seen from mid-March on. The water occupies the lower 3-5 m of the water column and is sandwiched between the sea floor and the old bottom water. Moreover, the time series of the near-bottom water age (Figure 14d), shows the clear drop of age from 150 days to 15 days, consistent with the increase in near-bottom oxygen values (Figure 13).

From beginning of May on, the salinity in the bottom pool of the Arkona Basin started to increase, caused by the baroclinic inflows via Darss Sill. As a result of the baroclinic inflow activities, bottom salinities further increased to 20 g/kg in the following summer months until September. Parallel to the increase in near-bottom temperature and salinity, the oxygen conditions slowly degraded. On 21 September, a daily mean of only 5 % of the saturation value was found, and the minimum hourly values were as small as 4 %. These nearly anoxic conditions in the deepest layers of the Arkona Basin are the combined result of the low-oxygen baroclinic intrusions, the high biological production in the surface layers and the resulting high remineralisation in the fluffy bottom layers. The nearly permanent thermal stratification in the Danish Straits and in the Belt Sea limited the oxygenation of the inflowing waters. The low wind speeds in combination with the high air temperatures and the baroclinic inflows build up a 3-layer thermal stratification in the Arkona Basin (Figure 14a). During summer, the surface mixed layer could penetrate to a depth of 25 m. The inflowing waters could build up a 8-10 m thick bottom pool. In between, the cold intermediate layer, consisting of the water from March, was sandwiched. This structure lasted until mid-November.

The maximum temperature was 23.6 °C, observed on 4 August in the surface layer of Arkona Basin. This temperature was slightly higher than the maximum temperature at the station Darss Sill, measured on the same day. After this date, surface layer temperatures showed a rapid decline for the next two weeks, and then gradually dropped down to approximately 4 °C at the end of the year. The temperature anomaly in the surface waters reached peak values of +5 K at the end of July (Figure 9), similar to the observations at Darss Sill.

The situation changed slightly with the arrival of the barotropic inflow waters during the September/October inflow (Figure 6a). Bottom temperatures still declined, but salinities increased to peak values of 22 g/kg and oxygen concentrations recovered to 80 % (Figures 12 and 13). The arrival of the inflow waters can also be detected in the water age. During October, the water age dropped from 95 days to 30 days.

At the beginning of December, the inflow event (as indicated in Figure 6b) led to a recovery of the near-bottom oxygen concentrations in the Arkona Basin (Figure 13). The inflowing water masses elevated the near-bottom salinities to 21-22 g/kg. Since at Darss Sill only salinities of 16 g/kg were observed, a significant amount of highly saline water must have entered through the Öresund (Figure 7). The arrival of the inflow water can also nicely be seen in the water age (Figure 14c, d). The water age dropped to 10 days, increasing the likelihood that large parts of this new water originated from Drogden Sill.

To track the fate of the inflows, we also used the numerical model to analyse the situation in the Bornholm Basin (Figure 15). Due to the cold temperature anomalies in February and March (Table 1) in combination with high wind speeds due to the low/high pressure system "Zsusza"/"Irenäus" (see chapter 2.3), the water in the Bornholm Basin was completely mixed, down to 40-45 m. These water masses formed the cold intermediate layer, which lasted until October. The gale "Sieglinde" (23.10.) could extend the surface mixed layer down to 40 m, but could not eradicate the cold winter water in 50 m depth. The fate of the 4 °C cold spring water can be tracked until the end of the year.

An imprint of the refreshing of the bottom water in the Arkona Basin in March 2018 (Figure 14c and 14d) can hardly be found in the Bornholm Basin. From the start of the year on, the bottom water was stagnant and age increased with a nearly linear constant rate of 1 day/day until the start of November. Only in a water depth of 70 m (Figure 14d), we see a signature of the short inflow event. The water age drops from 360 days to 250 days. This indicates that the water was interleaved in 60-80 m depth. We see a similar behaviour for the baroclinic inflows during summer (chapter 3.3). The oxygen deficient waters did not reach the bottom waters in the Bornholm Basin, but interleaved in 55-75 m. However, water age in August showed minimum values of 120 days. A decrease in age in the bottom water can be seen due to the barotropic inflow during the September/October (Figure 6a). The arrival of these inflow pulses is most clearly seen by the spikes in the near-bottom water age (Figure 15d) and the warming in the near-bottom temperatures (Figure 15d) from November on. The bottom pool shows a warming of up to 12 °C, which corresponds to the surface temperature at Darss Sill (Figure 8) at the start of the inflow.

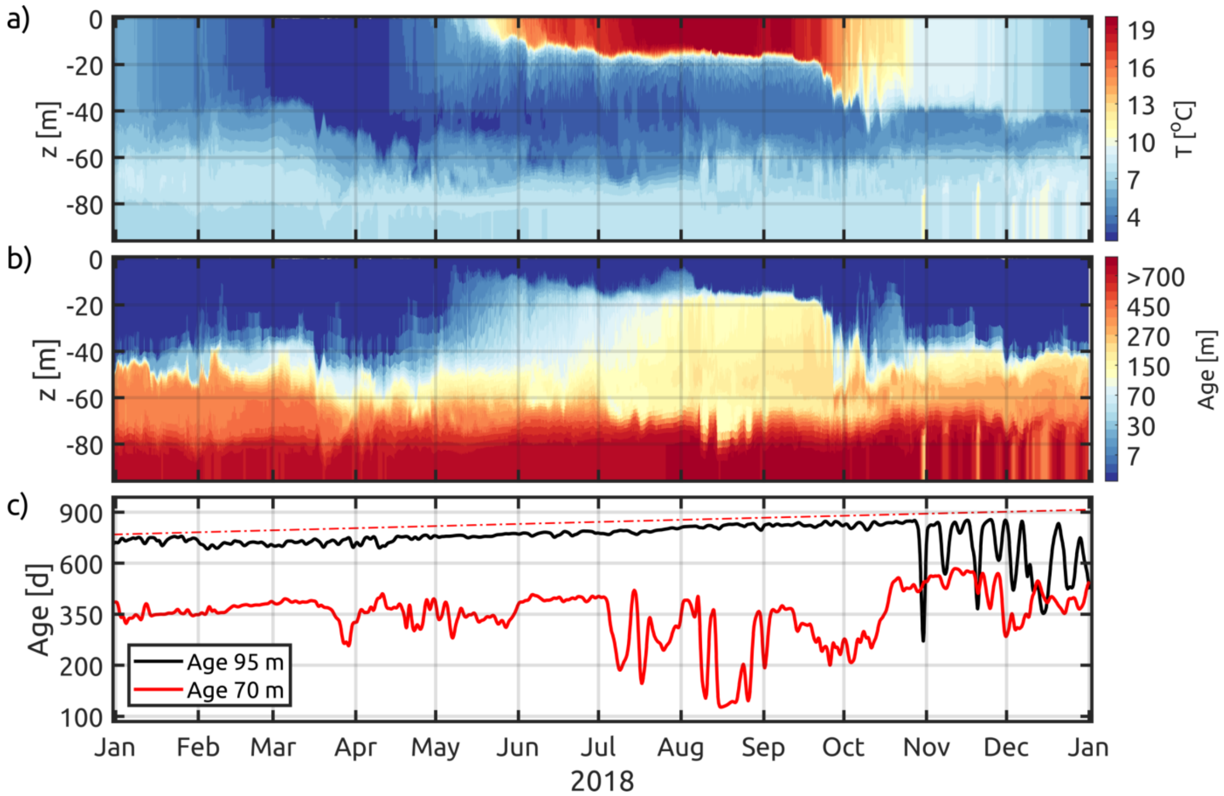


Fig. 15: a) Vertically resolved modelled temperature at a central station in the Bornholm Basin in 2018. b) Vertically resolved modelled water age. c) Time series of the water age at the sea floor (95m) and at 70 m depth. The red dashed-dotted line indicate stagnant water. Please note in b) and c) the non-linear scaling of the water age.

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. The 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 April 28, 2017, approximately three weeks later than in the previous year. Starting from that date, the station provided a continuous time series of all parameters until December 18, when it was again demobilized to avoid damage from floating ice.

Temperature and salinity at OB are plotted in Figure 16; associated oxygen readings are shown in Figure 17. Similar to the other MARNET stations, the maximum temperatures reached during the summer period were higher than 2017, and comparable or even larger to the record-setting years 2010, 2013, and 2014, when temperatures of up to 23 °C were observed at station OB. In 2018, the maximum daily mean temperatures in the surface layer exceeded the threshold of 24 °C in late July. The maximum hourly mean temperature, reached on July 26, was 24.8 °C. As in the previous years, surface temperatures at the monitoring station OB were significantly higher compared to those at the deeper and more energetic stations in the Arkona Basin and the Darss Sill (see Figures 9 and 12), which reflects the shallower and more protected location of this station. This is also well illustrated in the plot of the temperature anomalies (Figure 9). The anomalies started at OB already at the beginning of May, two weeks earlier than for the other two stations. Moreover, maximum positive anomalies, with + 5.5 K were recorded in the second week of June and at the end of July.

On average years, 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 saltier bottom waters (e.g. LASS et al.,2001). However, during 2018 the precipitation over most of the Oder catchment was record setting low (see chapter 2). The missing rain lead to low water levels in the Oder and a nearly full stop of the inland water transportation until late autumn. Thus, the impact of the Oder plume in the Pomeranian Bight was of less dynamical importance in 2018.

Directly after the start of service at the end of April, a temperature and haline stratification developed. The temperature gradient between the surface and bottom layers varied around 5 K. In mid-June peak values of 9 K were reached. Along with the further increase of the air temperature and the related lowering of the thermocline, the thickness of the warm surface layer reached depths of 15-20 m (see Figure 14a) and finally touched the seafloor at OB. The breakdown of the thermal stratification also induced the collapse of the haline stratification.

From an ecological perspective, the most important consequences of the build-up of stratification and the suppression of turbulent mixing during May and June were the decrease in near-bottom oxygen concentrations due to the de-coupling of the bottom layer from direct atmospheric ventilation. Their impact on the oxygen budget of the Pomeranian Bight becomes evident from Figure 17, showing oxygen concentrations at depths of 3 and 12 m. For May and June, 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 remineralisation, respectively.

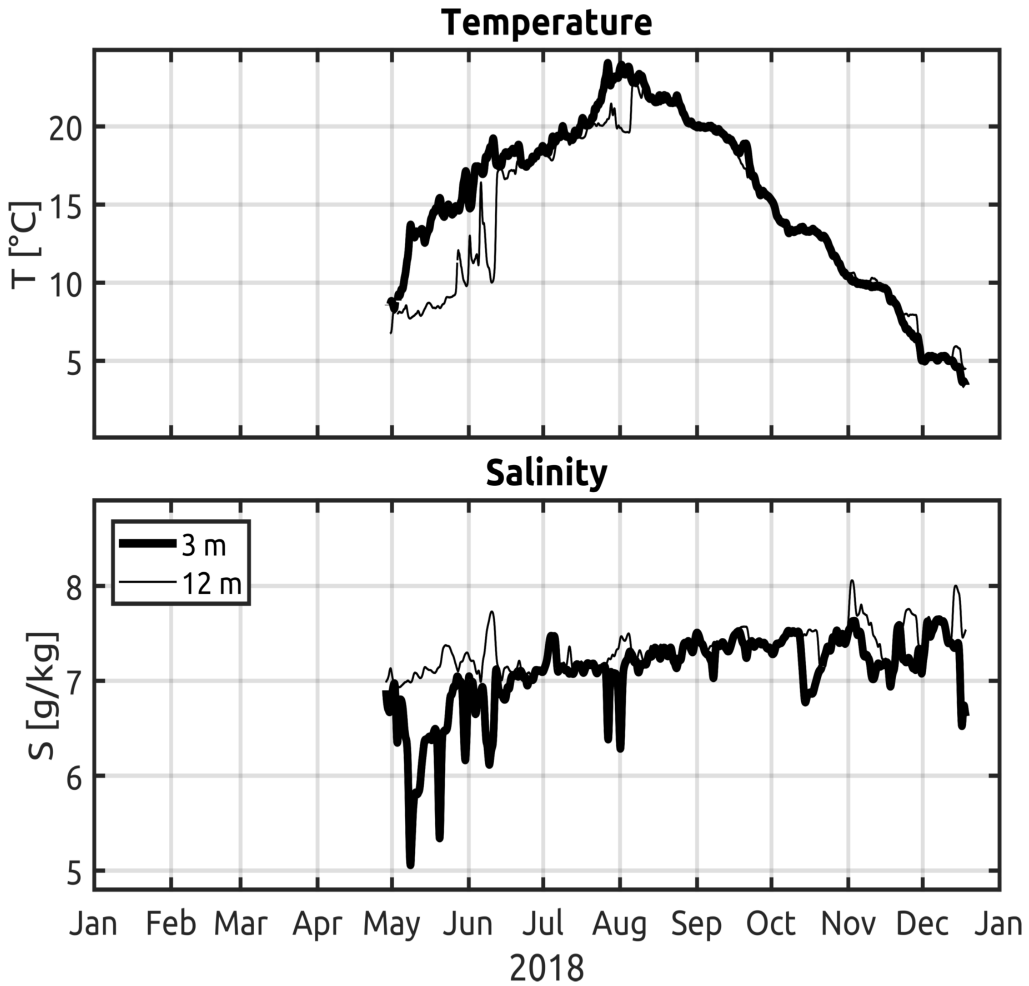


Fig. 16: Water temperature (above) and salinity (below) measured in the surface layer and near bottom layer at the station OB in the Pomeranian Bight in 2017

Lowest near-bottom oxygen concentrations (see Figure 17) in 2017 were observed at the start of June, with hourly saturation values as low as 31 % (4 June). A second stratification event around the start of August resulted in minimum oxygen saturations of 28.9 % (3 August). This event was caused by a two week calm wind period (Figure 3a), that helped to establish a thermocline in the already 21 °C warm water. The near bottom waters stayed at this temperature level, while the sea surface heated up for additional 3 K. With the onset of a slow atmospheric cooling and stronger winds at the start of August, the thermal stratification vanished and near bottom oxygen levels recovered to 90 % saturation.

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 at the beginning of June. 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").

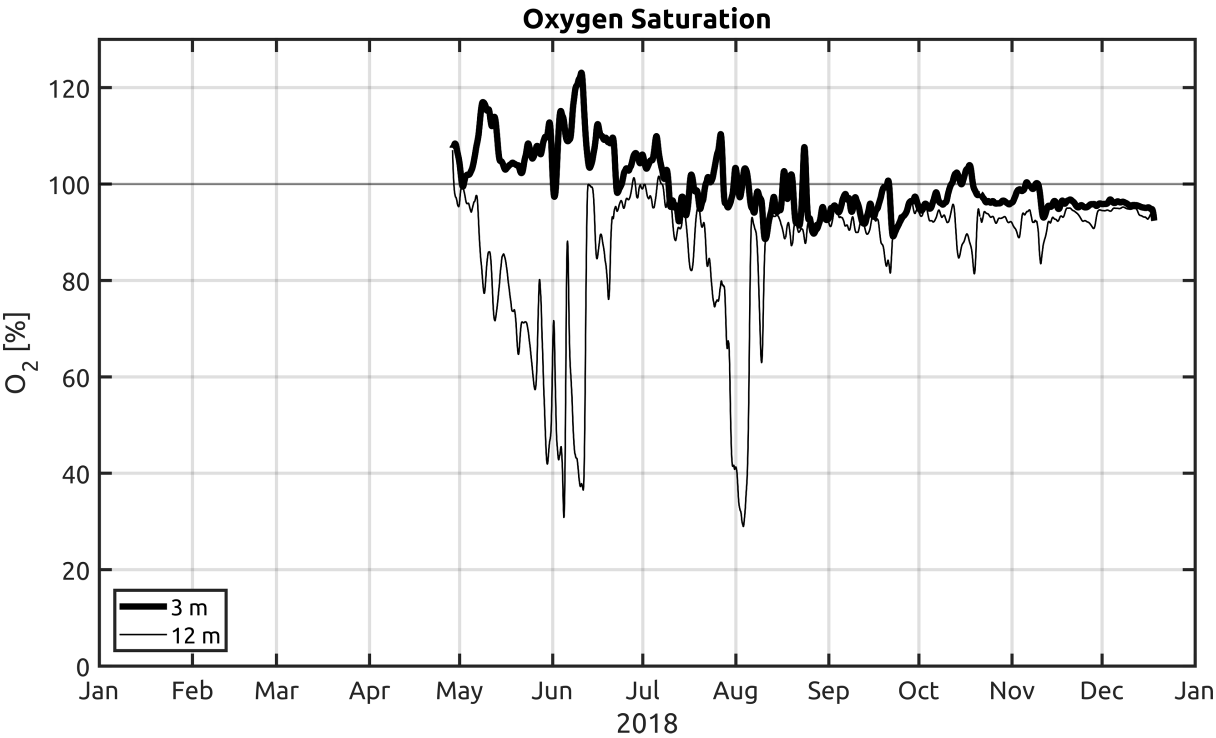


Fig. 17: Oxygen saturation measured in the surface and bottom layer at the station OB in the Pomeranian Bight in 2017.

6. Hydrographic and hydrochemical conditions

6.1 Water temperature

6.1.1 The sea surface temperature of the Baltic in 2018 derived from satellite data

The development of Sea Surface Temperature (SST) of the Baltic Sea in 2018 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 for example in NAUMANN et al. 2018 and in HELCOM Environment Fact Sheets (SIEGEL & GERTH, 2018). Reflections on the 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 the air temperature in Warnemünde (Chapter 2, Table 2) as well as the data from the MARNET stations (BSH/IOW) were included for the interpretation of the detailed SST development. The map of maximum ice coverage was provided by the BSH (Schwegmann, Holfort 2018).

The year 2018 was the warmest year since 1990 in terms of SST (with 1.19 K above the long-term average) as well as in air temperature (0.05 K above 2014, the latest very warm year before 2018). May to August mainly contributed to the average by their positive anomalies of up to +4-5 K. The

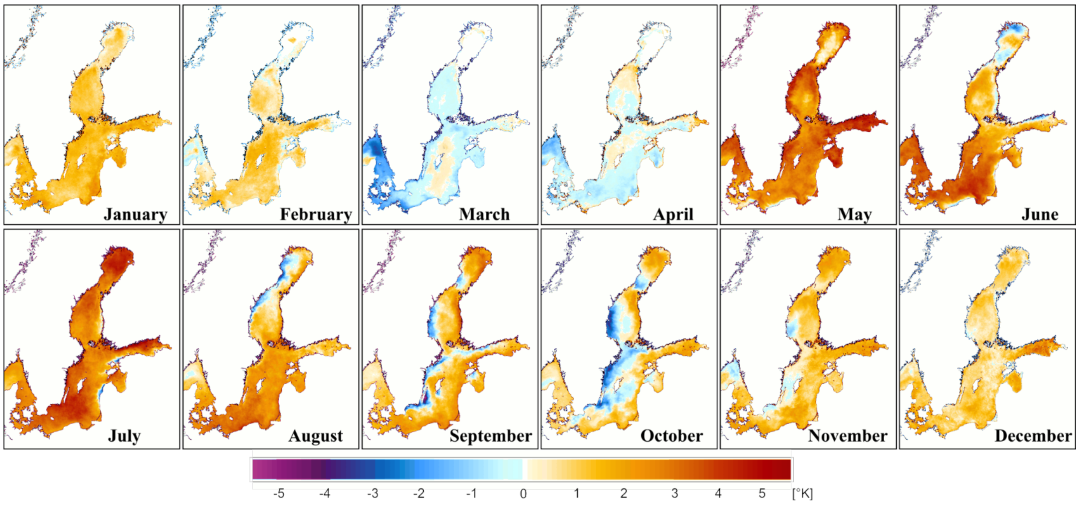


Fig. 18: Anomalies of the monthly mean sea surface temperature of the Baltic Sea in 2018 referring to the long-term means (1990-2018)

late winter conditions led to negative anomalies in March and April. The winter of 2017/2018 was comparatively warm, as shown in the cold sum of air temperature of Warnemünde but also in the SST. March was the coldest month. The coldest day and the day of maximum ice coverage was in the first week of March. The warming started in May and strongly continued in June due to high solar radiation and low wind conditions. The conditions led to special development of phytoplankton. The monthly mean SST in May to August determined particularly in the western and central Baltic the upper limit of the variation range in the period since 1990. The warmest day was around 1 August with up to 27 °C in large areas of the central Baltic. A further particularity was a stronger upwelling along the Swedish coast in autumn due to abnormal westerly winds.

Cold and heat sums of air temperature of Warnemünde (Table 2, Chapter 2) deliver information about the severity of winter and the course of the summer. With a cold sum of 67.7 Kd, the winter 2017/18 was below the long-term average (100.8 Kd), which means the 34th warmest winter since 1948. February and March contributed with 33.3 Kd and 32.2 Kd mainly to this value (long-term averages 30.4 Kd and 8.1 Kd). March 2018 was the 5th coldest since 1948. The heat sum of the summer 2018 was 394.5 Kd, more than 2.5 times as high as the long-term average of 153.5 Kd and the warmest summer since 1948. The second warmest summer was 2006 with 355.1 Kd. All months from May to October exceeded the long-term averages of each month and contributed to the summer value. 2018 was the warmest year since 1881 (Chapter 2).

Anomalies of monthly mean SST for the entire Baltic Sea in Fig. 18 referring to the long-term means (1990-2018) are the basis for the discussion of the overall thermal development in 2018. The seasonal development of monthly mean temperatures in the central areas of the Arkona Sea,

Gotland Sea, and Bothnian Sea are presented in Fig. 19 in comparison to the long-term monthly means (1990-2018). Daily and weekly mean SSTs were the basis for the detailed description of temperature development.

Mild temperatures in January and February with sea surface temperatures slightly above the long-term averages led to positive anomalies less than +1-2 K. In March and April, cold weather prevented the normal warming in spring. Thus, the monthly means were in the range of the long term averages or below. The anomalies reached partly values to – 2 K. May, June, July, and August are characterized by positive anomalies with up to +5 K. May 2018 was the warmest since 1990 (second 2016), June was together with June 2002 the warmest except in the Bothnian Bay. July was the warmest followed by 2014 and August belonged to the warmest in the central Baltic together with a few of other years. In November and December, most areas of the Baltic are characterized by positive anomalies between 0 and +2 K. In September and October, unusually long lasting westerly to northwesterly winds led to upwelling along the western coasts and negative anomalies in temperature there.

The annual temperature cycles in the central parts of the Arkona Sea (AS), Gotland Sea (GS) and Bothnian Sea (BoS) in Fig. 19 show that March was the coldest month in all regions. The months January and February were warmer than in average. In March and April, the central parts were in the range or below the long-term average due to the later winter, before a strong warming took place in May and June with positive anomalies of up to 4 K. The warming was more pronounced in the western and central than in the northern Baltic Sea. The highest temperatures of the year occurred in the northern Baltic in July, in the central in August and in the western Baltic the averages of July and August were rather similar. In July, the anomalies were up to +4 K in all regions but in August only in the western and central Baltic. In October, the central stations were between the areas of positive and negative anomalies means in the range of the long-term averages. In September, November and December, the central stations are characterised by slightly positive anomalies.

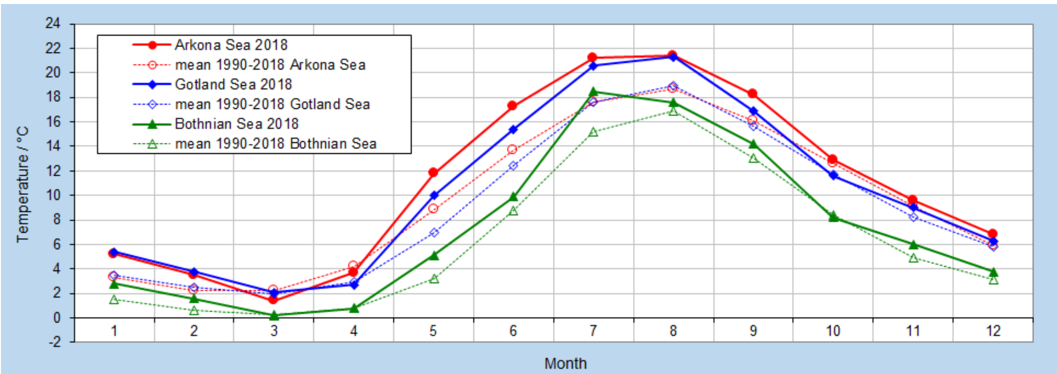
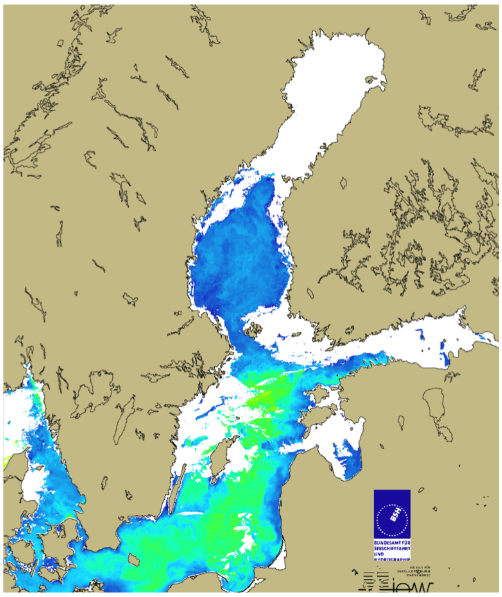


Fig. 19: Seasonal cycle of SST in the central Arkona-, Gotland- and Bothnian Sea in 2018 in comparison to the mean values (1990-2018)

The year 2018 started with temperatures between 3 and 7 °C in the western and central Baltic Sea which remained at that level during the first decade of January before the typical cooling began. By the end of January, the SST was between 3 and 5 °C. The cooling continued in February, thus, the first week of March became the coldest week of the year (Fig. 20, left image) with around 0 °C in the shallow Pomeranian Bight and in the northern Baltic, 1-2.5 °C in the western and central Baltic Sea.



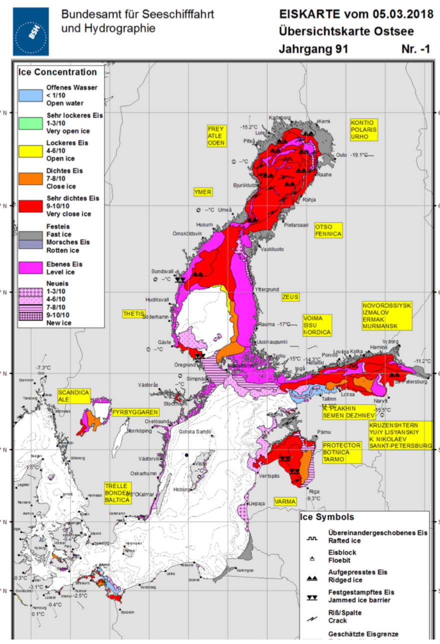


Fig. 20: The first week of March included the coldest day, and maximum ice coverage in the winter 2017/2018 on 05 March (Schwegmann, Holfort, 2018)

This period matched with the maximum ice coverage (Fig. 20, right image) on 5 March (Schwegmann, Holfort 2018). Because of the cold weather in the Baltic region until the end of March, the temperatures differed only slightly from the coldest week. Therefore, March was the coldest month in all regions. The transect of monthly mean SST through the entire Baltic in March is presented in relation to the long-term average (1990-2018), the previous year, and the variation range in Fig. 21 (upper panel). SST of the entire Baltic was mainly in the range or below the long-term average except in the western Baltic, where the SST was below the average. Particularly in the westernmost parts, the Bay of Mecklenburg, the anomalies reached values of -1.5 K. The situation remained until mid-April. Warm air masses, transported from the Atlantic Ocean into the Baltic region by westerly winds, initiated a warming phase particularly along the south coasts which started in the west by mid-April. Slight warming in April led to monthly mean SST in the range of the long-term averages as seen in Fig. 21 mid panel showing the transect of mean monthly mean SST through the entire Baltic in April in relation to the long-term average (1990-2018), the previous year, and the variation range.

The warming continued until 16 May and after a stagnation a further warming took place. This situation with 14-17 °C in the central parts did not change until the end of the month. From about

May 20 on, easterly winds initiated upwelling of cold water along the east and south coasts of the Baltic Proper. However, due to the long ongoing warming, the upwelling patterns are not reflected in the anomalies of the monthly averages of SST. The monthly mean temperature distribution along the transect through the central basins of the Baltic Sea in May 2018 determined the upper limit of the variation range from the Arkona Sea to the Bothnian Sea (Fig. 21 lower panel). These conditions were a strong basis for phytoplankton development.

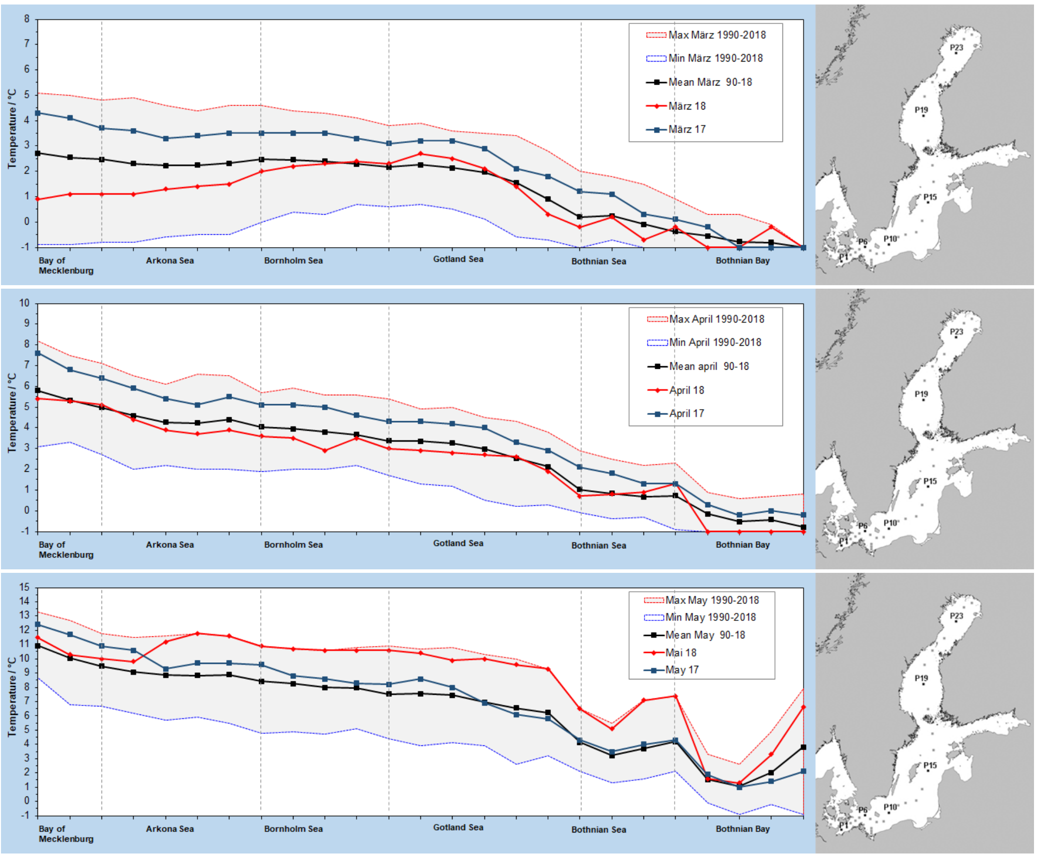


Fig. 21: Monthly mean temperature distribution along the transect through the central basins of the Baltic Sea in March, April and May 2018 in comparison to the previous year, the long-term mean value of 1990-2018 and the variation range

This continued and, particularly by the end of May, low wind speed led to temperatures of 15-17 °C in the eastern Gotland Sea and 18-20 °C by the beginning of June in the central part of the Gotland Sea. This induced an early development of cyanobacteria already at the beginning of June. June is characterised by changing conditions with warmer and colder phases in the Bothnian Sea and central Baltic, but on a generally high level leading to the positive anomalies of the monthly averages particularly from the western Baltic to the central Gotland Sea. By the end of the month, SST of 18-21 °C was reached in the western Baltic, 13-17 °C in the Gotland Sea and 8-13 °C in the Gulf of Bothnia. This situation remained unchanged until July 5, before a strong warming occurred due to warm air masses from the Atlantic Ocean in the entire Baltic region. Already on July 12, the North-South gradient was balanced. In the following days, a further warming took place in the entire Baltic with only slight regional differences. On July 19, the highest SST with up to approximately 25 °C was determined in the Gulf of Bothnia. In the

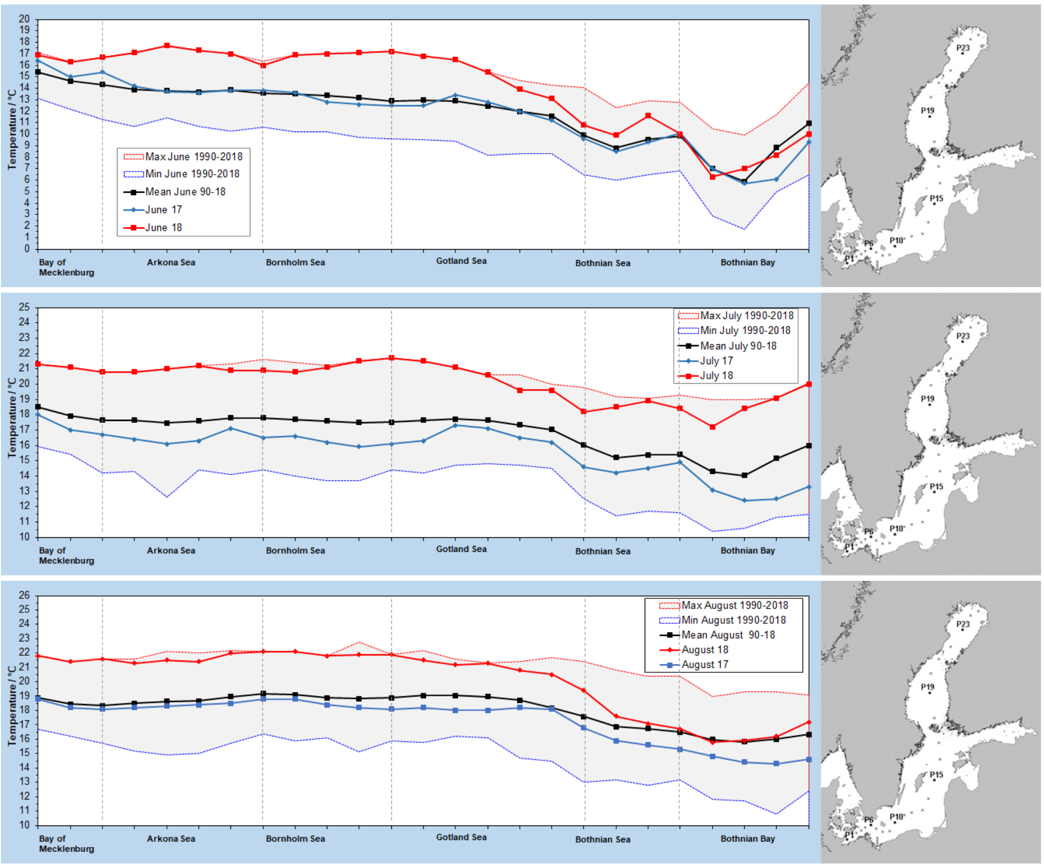


Fig. 22: Temperature distribution along the transect through the central basins of the Baltic Sea in June, July and August 2018 in comparison to the previous year, the long-term mean value of 1990-2018 and the variation range

following days until the end of the month, the SST decreased slightly in the northern Baltic and increased particularly in the Baltic Proper. The highest SST was determined on August 1, with up to 27 °C from the Bornholm Sea to the central eastern and western Gotland Sea, 22-25 °C in the Gulf of Bothnia, 23-25 °C in the western parts (Fig. 23).

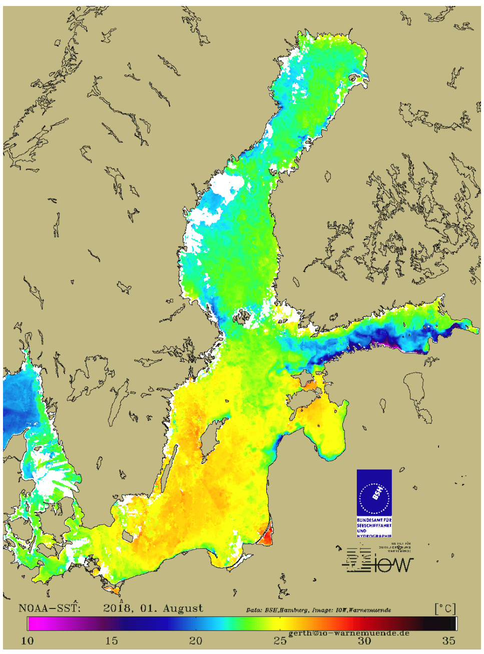


Fig. 23: SST distribution of the Baltic Sea on August 1, the warmest day of year 2018.

Only in the Gulf of Finland, the SST was reduced due to upwelling induced by easterly winds. This situation continued until August 4 before a stronger cooling took place particularly in the northern Baltic. On August 10, the SST was still around 23 °C in the Baltic Proper but already less than 20 °C in the northern parts, partly due to upwelling induced by westerly winds. The cooling continued until the end of the month, but the temperatures were still rather high with values of about 18-20 °C in the Baltic Proper and 15-17 °C in the central parts of the northern Baltic. These high temperatures in July and August led to the strong positive anomalies in the monthly averages (Fig. 18). The SST averages of the months June, July, and August 2018 determined the maxima in the variation range since 1990 as seen in the temperature distribution along the transect through the central basins in Fig. 22.

The situation continued until September 10, before the temperature dropped by 3 K in the Baltic Proper during a strong wind event. From about September 10 until the end of October, prevailing westerly winds induced upwelling along the entire Swedish coast. This is also visible in anomalies of September and October averages in Fig. 19. In September, a further cooling started after September 20, leading to temperatures of 5-8 °C in the upwelling areas and up to 15-17 °C in the eastern and southern Baltic by the end of the month.

In October, the influence of upwelling areas increased and strong wind mixing reduced the SST by the end of the month in the Gulf of Bothnia to 4-9 °C and 10-13 °C in the southern Baltic.

In November, the cooling continued particularly in the southern and eastern Baltic from 8-12 °C to 7-10 °C. In the Gulf of Bothnia, temperatures of 4-7 °C prevailed the entire month.

After the first decade in December, the SST decreased from 5-7 °C to 3-6 °C in the Baltic Proper and from 0-6 °C to 0-4 °C in the Gulf of Bothnia persistent until the end of the month. December 2018 was warmer than the long-term average.

Overall, 2018 was in terms of the SST as well as in the air temperatures of the Baltic Sea the warmest year of the last 29 years since 1990 (Fig. 24), followed by the years 2014, 2015, and 2016 reflecting the strong warming in the Baltic in the last decade. The annual temperature average throughout the Baltic Sea was 1.19 K higher than the long-term average, followed by 2014 with 1.14 K. The months May to August contributed mostly by their high positive anomalies.

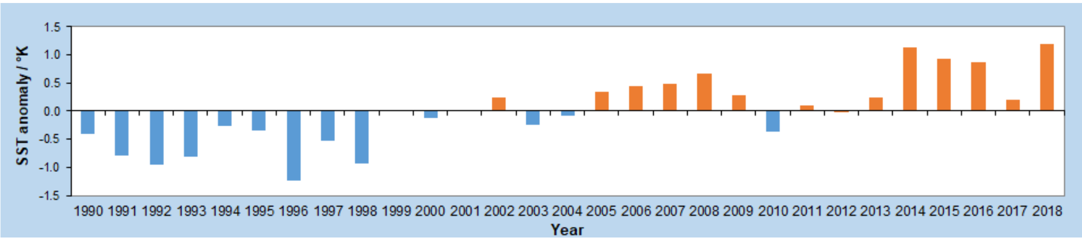


Fig. 24: Anomalies of the annual mean sea surface temperature of the entire Baltic Sea during the last 29 years (1990-2018)

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 2018, monitoring cruises were performed in February, March, May, July 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 sea 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 both the surface and the intermediate winter water layers and reflects the lateral heat flows due to salt-water inflows from the North Sea and diapycnal mixing. The intermediate winter water layer conserves the late winter surface temperature of the Baltic until 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 the atmospheric temperature (cf. chapter 2). The winter of 2017/2018 started very mild until the end of January 2018. During February and March two cold periods with a high number of frost days led to strong surface cooling. The sea surface temperatures were on the level of a normal winter. This is reflected also by the ice coverage of 182 005 km^2, which was close to the long-term average. The spring started with air temperatures well above the long-term mean. The air temperatures remained at a high level for the rest of the year. From April to December 2018, the air temperature anomaly ranged between 1.5 and 2.5 K (cf. chapter 2).

The deep water conditions in the central Baltic in 2018 were mainly controlled by subsequent minor inflow events of 2016 to 2018 that followed the extreme Christmas MBI of December 2014 (MOHRHOLZ et al., 2015). The most recent barotropic inflow events were observed in September and December 2018.

At the beginning of February 2018, the temperature distribution along the Baltic talweg revealed the typical winter cooling in the surface layer. As a result of the warmer than average January (compare chapter 2), surface temperatures were well above the long-term mean for February. In the shallow areas of the Mecklenburg Bight values of about 4.0 °C were observed, which was more than 2 K above the climatological mean of 1.8 °C. Surface temperatures in the western part of Arkona Sea were slightly higher. At the central station TF0113 the SST was about 4.5 °C (climatological mean 1.9 °C). In the entire Baltic Sea, the surface temperatures resulted in a high density, well above the maximum. Thus, further cooling forced temperature driven mixing. In the central Baltic, the deep convection associated with the 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 thus, reached as far down as the upper boundary of the permanent halocline. With 4.5 °C, the upper layer temperature at station TF271 exceeded the temperature of the density maximum by 1.7 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 Sea (between 4.2 and 4.5 °C) were about 2K above the long-term average, and comparable to the extreme warm temperatures in February 2016.

The temperature distribution below the halocline reflected the impact of the inflow events of saline water from the North Sea. A series of small inflows between October 2017 and January 2018 transported warm saline water into the western Baltic. It dominated the bottom temperature distribution in the Arkona and the Bornholm Basin. Waters of the inflows covered a 15m thick bottom layer in the centre of the Arkona Basin, with a bottom temperature of 9.3 °C. Baroclinic late summer inflows and the minor inflows in autumn 2017 have flushed the halocline of the Bornholm Basin with warm water. By February 2018, this water was partly 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 deep layer of the Slupsk Furrow. The maximum temperature in the halocline of the Bornholm Basin was about 9.5 °C. Due to mixing with ambient water, the temperature of this water body decreased eastward. In the Slupsk Furrow, bottom water temperatures of 8 °C were observed. The deep layers of the Bornholm Basin were covered by the cooler and highly saline waters from recent inflow events. Here, the bottom temperature was about 6.8 °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. They 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 6.9 °C, about 0.3 K below the value observed in February 2017. The bottom water temperature in the Farö Deep was slightly lower with 6.8 °C. It was 0.3 K higher than the temperature in the eastern Gotland Basin at 120m, which is the sill depth between both locations. Thus, recent overflows of the sill have not reached the bottom layers of the Farö Deep.

The cold air temperatures in February and March 2019 led to a strong cooling of the surface layer of the Baltic. In the western Baltic the surface temperatures observed during the monitoring cruise in March ranged between 1.3 °C and 1.6 °C. Compared to the positive temperature anomaly of 2K at the beginning of February, the SST was now about 0.5 K below the climatological mean. As a result of the strong cooling, the surface temperature of the western Baltic was well below the temperature of the density maximum. In the central Baltic Sea the SST dropped to values close to the climatological mean. In the Bornholm Basin and in the eastern Gotland Basin the SST was about 2.3 °C.

The temperature changes below the surface layer were weak. Only the ongoing eastward advection of the warm water body from the summer and autumn inflows caused some changes. The warm water layer at the bottom of the Arkona Basin vanished. The bottom water temperature in the Bornholm basin of 6.9 °C remained at the level observed in February. The warm halocline layer in the Bornholm basin was further eroded due to the deep vertical convection in the surface layer. A significant part of the warm halocline water left the basin via the Slupsk Sill and formed the new bottom water layer in the Slupsk Furrow. Here, the bottom water temperature increased to 8.3 °C. The former deep waters from the Slupsk Furrow had partly 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 isotherms in the halocline layer of the eastern Gotland Basin indicate the active inflow process. The bottom temperatures at station TF 0271 (Gotland Deep) and in the Farö Deep did not change significantly and were still at 6.9 °C and 6.8 °C respectively.

Between March and May, the surface water of the Baltic Sea warmed considerably due to strongly increasing air temperatures and above average solar radiation. Surface temperatures ranged between 10.9 °C in the Kiel Bight, 9.7 °C in the Arkona Basin, 8.6 °C in the Bornholm Basin, and 9.8 °C in the eastern Gotland Basin. Thus, the SST was about 1.0 to 4.0 K higher than the climatological mean values for May. The highest temperature anomaly was observed in the eastern Gotland Basin with 4.1 K.

The seasonal thermal stratification was well pronounced in the entire Baltic, which was quite unusual for the first half of May. The thermocline depth was extremely shallow ranging between 10 and 16m along the talweg transect. This was caused due to the anomalous weak wind conditions in spring 2018. The winter water layer was well pronounced and thicker than in previous years, due to the shallow thermocline. Usual winter water temperatures are about 2 °C, controlled by the temperature of the maximum density of surface water. In the eastern Gotland Sea, the minimum temperature of intermediate winter water was 2.3 °C in May 2018. It was significantly lower (-1.5 K) than in the previous year. In the Gotland Basin the upper part of the intermediate layer depicted a very patchy structure, most probably caused by lateral intrusions. The minimum temperature of 2.2 °C was observed in the intermediate layer north of the Farö Deep.

Below the intermediate layer the temperatures increased with depth. In the halocline of the Bornholm Basin, the warmer water body of the deep layer was mixed up with the cold water from the intermediate layer. Here, the maximum temperature decreased from 8,9 °C in March to about 8.2°C. The bottom water temperature of 6.9 °C in the Bornholm Basin remained at the level from March 2018. In the Slupsk Furrow the major part of the warm deep water has passed the eastern sill of the furrow towards the eastern Gotland Basin. Compared to March the bottom temperature was decreased by 1.1 K to 7.4 °C in the Slupsk Furrow. 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 90 and 120 m, where it contributes to ventilation of the halocline layer. The bottom layer temperatures in the eastern Gotland Basin were not changed and remained at 6.9°C.

By the end of July 2018, the SST had reached unusual high levels due to ongoing positive air temperature anomalies and a low cloud coverage. A strong summer thermal stratification had established throughout the Baltic Sea. The seasonal thermocline lay at depths between 15 m and 25 m, and separated the extreme warm layer of surface water from the cool winter intermediate water. The surface temperatures in spring were well above the long-term mean. This trend continued until July 2018. In the Arkona Basin the SST reached 23.2 °C in a very thin surface layer. However, also at 10m depth the temperature was still at 20°C. At station TF213 in the Bornholm Basin a SST of 22.4 °C was recorded on 27 July, and SST of extreme 23.4 °C was observed at station TF271 in the eastern Gotland Basin. There, the climatological mean value for July is 16.0 °C. Generally, the SST was 4.0 to 7.0 K above the long-term mean in July, and among the highest values ever observed in this month.

Below the surface layer, the minimum temperatures in the intermediate water were about 3.1 °C in the eastern Gotland Basin, and 2.9 °C in the northern Gotland Basin, which caused an extreme vertical temperature gradient. Also in the Bornholm Basin the winter water was still present. Here its core temperature was about 3.0 °C. Usually, wind mixing would cause a more efficient erosion of the winter water layer, but the high SSTs and low wind forcing decoupled the winter water layer from the mixed layer more efficiently than in "normal" years.

The calm weather conditions in early summer 2018 favoured baroclinic inflow conditions at the Darss Sill. Warm saline water from the Kattegat entered the Baltic via the Belt Sea and formed a 15 to 20 m thick warm bottom layer in the entire Arkona Basin, with temperatures up to 16.0 °C.

A part of this water body has just passed the Bornholmgat. The warm water was interleaved in the halocline of the western Bornholm Basin at depth of 50 to 70 m. The core temperature of this water body was about 13.2 °C.

The bottom layer of the Bornholm Basin was still covered with water from the autumn inflows of the previous year. At the central station TF0213 the bottom temperature was about 7.0 °C. In the Slupsk Furrow similar bottom temperatures of 7.1 °C were observed. The deep water conditions in the central Baltic remained unchanged in comparison to spring 2018. The bottom temperature in the eastern Gotland Basin was still at 6.9 °C.

The temperature distribution in mid-November 2018 revealed ongoing autumnal erosion of the thermocline in the surface layer. Since the high positive air temperature anomaly, first recorded in April, was continuously ongoing, the SST observed in November 2018 was higher than normal. The surface layer had deepened, extending to a depth of 45m depth in the eastern Gotland Basin. In the Arkona Basin surface temperatures between 9.8 °C and 10.2 °C were observed. Also in the Bornholm Basin the SST was still high, with 10.2 °C at station TF213. This is 2.5 K above the climatological mean for November. In the Slupsk Furrow, the maximum SST of 10.6 °C was detected, 3.0 K above the long-term average. Further to the eastern Gotland Basin and the Farö Deep, a slightly decreasing surface temperature was found. The station TF271 and the Farö Deep depicted surface temperatures of 9.05 °C and 8.7 °C respectively. The deepening of thermocline reduced the vertical extent of the intermediate winter water layer in the central Baltic to a layer of 30 m to 40 m thickness, with minimum temperatures of 3.6 °C (station TF271). Only small remains of intermediate winter water were present in the Bornholm Basin and the western part of Slupsk Furrow.

The baroclinic inflow events in the summer and autumn brought significant amounts of warm saline water into the western Baltic. This water spread along the bottom of the Arkona Basin and the halocline of the Bornholm Basin eastward. Maximum temperatures in this water body of 14.0 °C and 12.6 °C were observed in the Arkona Basin and Bornholm Basin, respectively. The major part of the water is sandwiched between the upper layer and the deep water in the Bornholm Basin. However, also the deep layer of the Slupsk Furrow was completely covered by the warm waters. At the time of the cruise, the tip of the warm water has already passed the eastern sill of the Slupsk Furrow, and spread eastward to the Gotland basin.

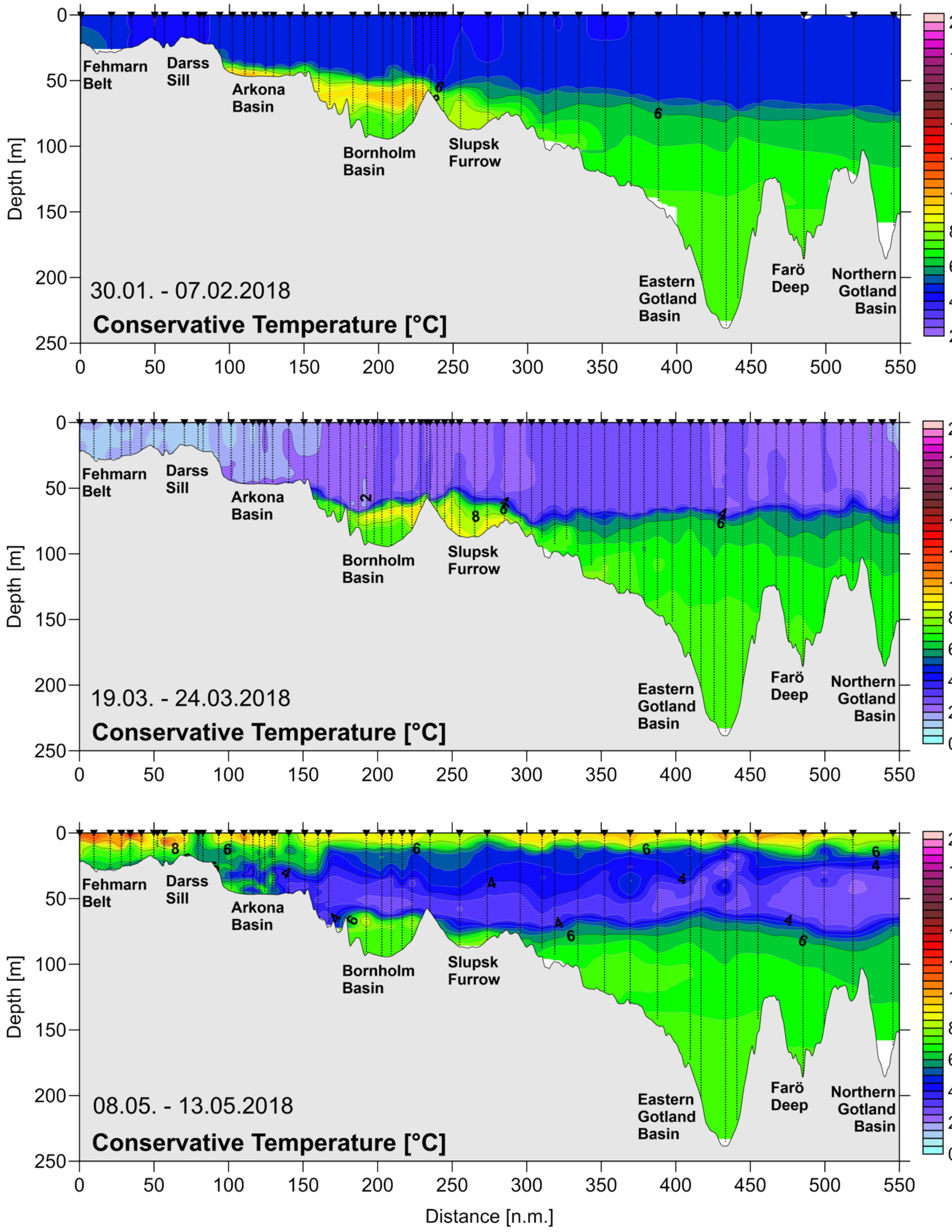


Fig. 25a: Temperature distribution (January, March, May cruises) along the talweg transect through the Baltic Sea between Darss Sill and northern Gotland Basin.

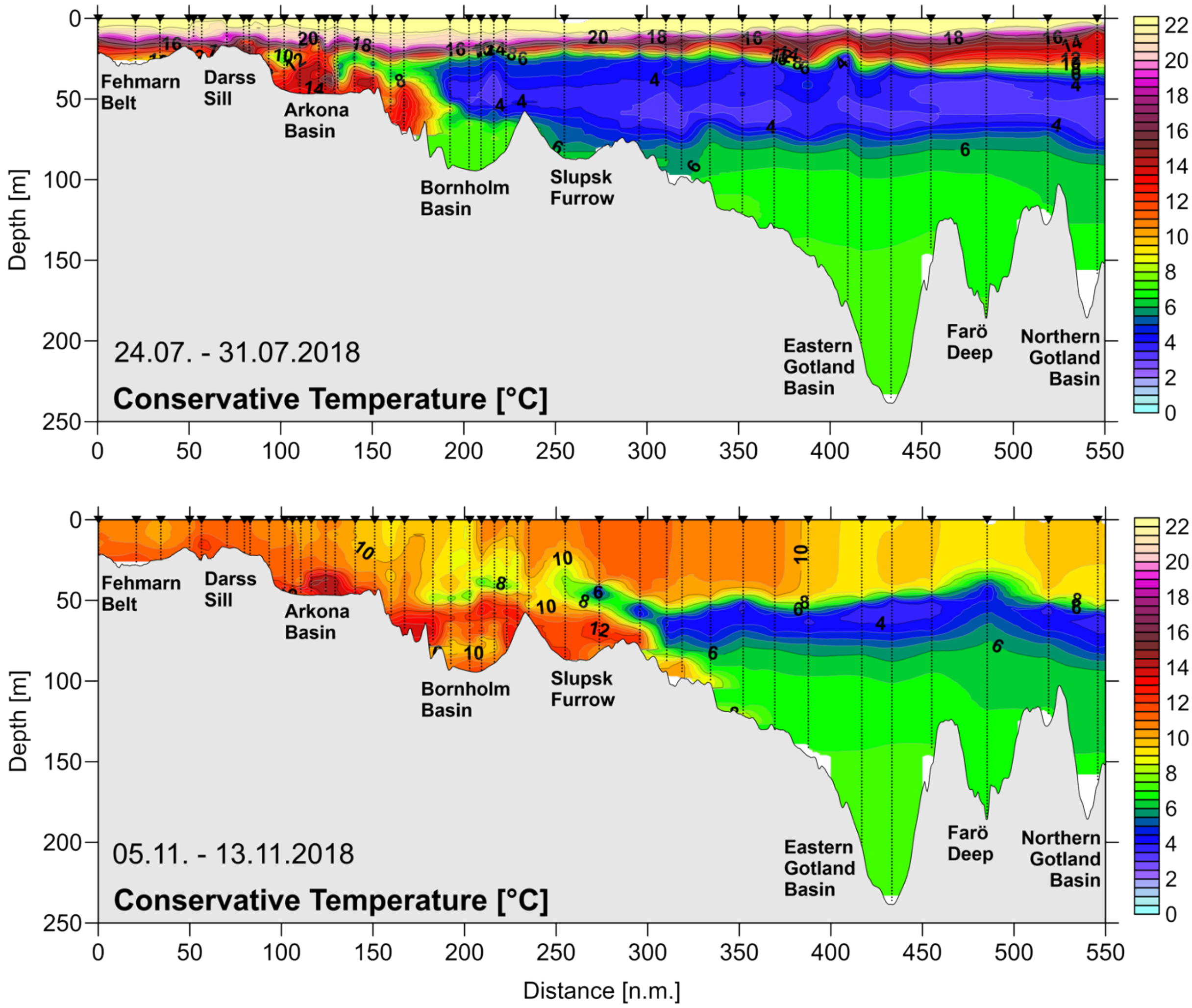


Fig. 25b: Temperature distribution (July and November cruises) along the talweg transect through the Baltic Sea between Darss Sill and northern Gotland Basin.

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[1] which is restricted to temperature measurements, 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 time series at five depths in the deep water of the eastern Gotland Basin between January and December 2018. The temperature stratification in the deep water is characterized by a downward increasing temperature. However, the temperature gradient was rather weak. The temperature difference between 140m depth and the bottom was about 0.1 to 0.2 K. Throughout nearly the entire year 2018, there were no significant changes in the deep water temperature of the eastern Gotland Basin. No lateral inflow of new water was detected. By mid-December 2018, an extreme temperature increase in the bottom layer was observed, first registered by the lowest sensors (see Fig 26). Maximum temperature of 8.6 °C was detected by the end of December. This is an extreme high temperature for the bottom layer in the

[1] operational since 1998. This mooring provides the data basis of the well-known 'Hagen Curve'.

central Baltic. It was caused by the arrival of the densest water from the warm baroclinic summer inflows. The temperature increase in the shallower layers was only moderate. It points to a small inflow volume of the warm water body.

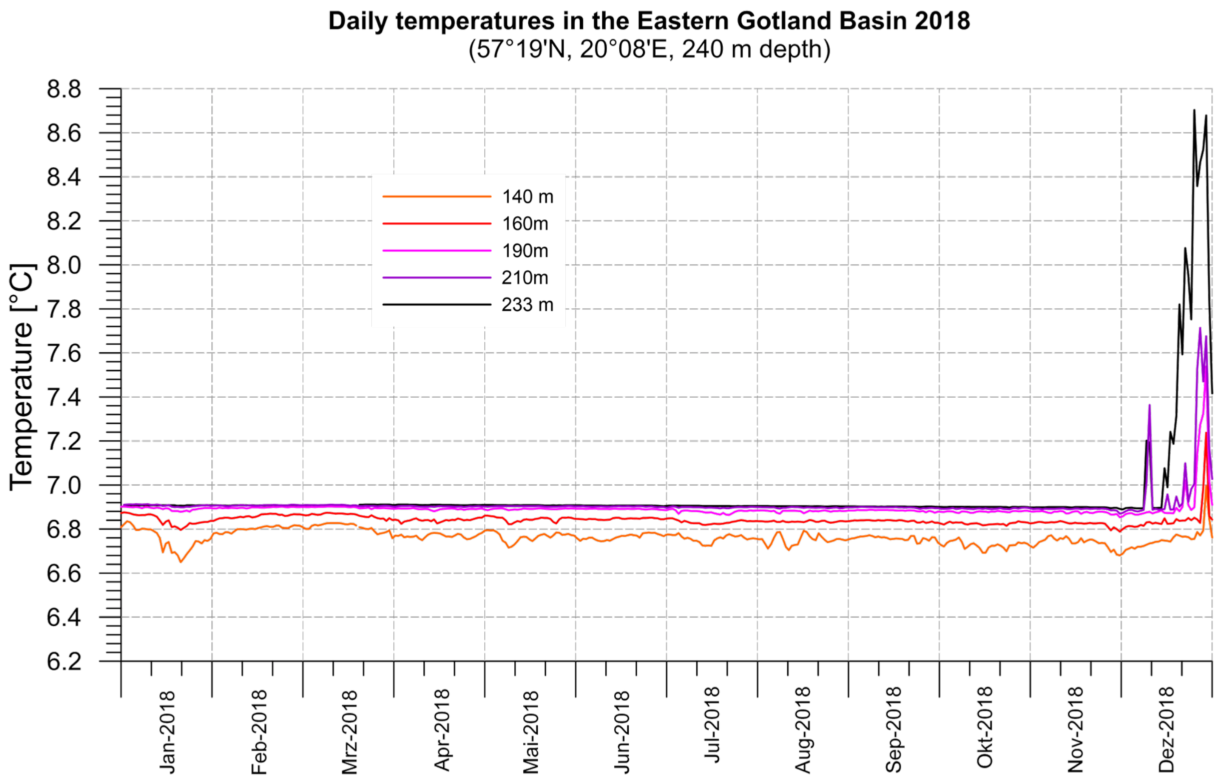


Fig. 26: Temporal development of deep water temperature in the Eastern Gotland Basin (station Tf271) from January to December 2018 (daily averages of original data with 10 min sampling interval).

Table 7 summarises the annual means and standard deviations of temperature in the deep water of the central Baltic Sea based on CTD measurements over the past five years. Compared to 2017 the deep water temperatures in the Bornholm Basin increased significantly, due to the warm baroclinic inflows in summer and autumn. In the central Baltic Sea, only minor changes in deep water temperature were recorded. Ongoing mixing processes caused a slight decrease in the eastern Gotland Basin and the Farö Deep. In the northern and western Gotland Basin the deep water temperatures increased by 0.1 to 0.13 K. This continued the increasing trend since the extreme Christmas MBI in 2014. Inflow waters of the recent barotropic inflows still shift former deep water from the eastern Gotland Basin towards north and further to the western Gotland Basin. In deep basins of the western Gotland Basin the bottom temperature was the highest observed during the last five years. The standard deviations of temperature fluctuations in 2018 were highest in the Bornholm Deep in the westernmost basin. The stronger fluctuations observed here are caused by the high baroclinic activity in summer and autumn, and are associated to the deep-water exchange.

Table 7: 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= 5-26)

Water temperature (° C; maximum in bold)

Station	Depth/m	2014	2015	2016	2017	2018
213 (Bornholm Deep)	80	6.99 ±1.29	7.01 ±0.08	7.06 ±0.63	7.06 ±0.28	**7.81 ±1.49**
271 (Gotland Deep)	200	6.11 ±0.19	6.79 ±0.19	**7.06 ±0.12**	7.05 ±0.15	6.89 ±0.01
286 (Fårö Deep)	150	5.69 ±0.04	6.33 ±0.25	6.56 ±0.06	**6.83 ±0.15**	6.70 ±0.04
284 (Landsort Deep)	400	5.27 ±0.06	5.46 ±0.30	5.92 ±0.10	6.14 ±0.19	**6.27 ±0.03**
245 (Karlsö Deep)	100	5.00 ±0.04	5.03 ±0.06	5.28 ±0.09	5.53 ±0.06	**5.67 ±0.12**

Salinity (maximum in bold)

Station	Depth/m	2014	2015	2016	2017	2018
213 (Bornholm Deep)	80	16.06 ±0.41	**18.86 ±0.25**	18.26 ±0.40	17.40 ±0.46	16.64 ±0.32
271 (Gotland Deep)	200	12.06±0.11	12.95 ±0.35	**13.35 ±0.09**	13.30 ±0.04	13.17 ±0.03
286 (Fårö Deep)	150	11.36 ±0.08	11.93 ±0.22	12.35 ±0.12	**12.58 ±0.07**	12.50 ±0.12
284 (Landsort Deep)	400	10.37 ±0.08	10.63 ±0.33	11.12 ±0.13	11.29 ±0.19	**11.41 ±0.05**
245 (Karlsö Deep)	100	9.58 ±0.11	9.64 ±0.17	10.00 ±0.16	10.28 ±0.11	**10.44 ±0.21**

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

Station	Depth/m	2014	2015	2016	2017	2018
213 (Bornholm Deep)	80	2.07 ±1.47	**3.60 ±1.75**	1.30 ±0.93	0.90 ±0.83	0.16 ±0.37
271 (Gotland Deep)	200	-2.94 ±2.38	**0.93 ±0.80**	0.55 ±0.26	0.13 ±0.11	-0.85 ±0.50
286 (Fårö Deep)	150	-2.35 ±0.53	-0.87 ±0.20	-0.05 ±0.23	**0.34 ±0.33**	-0.73 ±0.42
284 (Landsort Deep)	400	-1.02 ±0.68	-0.86 ±0.18	-0.98 ±0.23	**-0.41 ±0.31**	-0.57 ±0.40
245 (Karlsö Deep)	100	-0.85 ±0.52	-0.87 ±0.51	-0.93 ±0.47	**-0.75 ±0.66**	-1.89 ±0.72

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 bottom waters 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. Duration and influence of minor inflow events are 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 2018 the evolution of salinity distribution was mainly controlled by the small inflows events throughout the year. The baroclinic inflows in late summer and autumn 2018 caused the most significant changes in the western Baltic. However, none of the inflows could be completely covered by the IOW monitoring cruises. Except the March cruise, all data sets show an inflow situation in the western Baltic. However, the number of monitoring cruises per year does not provide the temporal resolution needed for detailed statistical analyses related to the occurrence of MBIs.

At the beginning of February, a saline water body was detected in the Fehmarn Belt. The maximum salinity was only 19 g/kg, pointing to a minor inflow. In the Arkona Basin, a very thin saline bottom layer of 5m thickness and 13 g/kg salinity was found, which proved the weak inflow activity during the recent month. The deep layers of Bornholm Basin were still filled with high saline water from the inflow series 2016/2017. Here, the bottom salinity was about 17.1 g/kg. The halocline of the Bornholm Basin was occupied by warm water patches from the baroclinic autumn inflows 2017 with salinity between 9 and 15 g/kg. After the inflow series of the recent years, the salinity in the deep water of the central Baltic Sea was still at a high level at the beginning of 2018. On the seafloor of the Gotland Deep, a salinity of 13.3 g/kg was measured in

February 2017. This was still close to the overall maximum of 13.6 g/kg observed after the extreme inflow event in 1951. The 12 g/kg isohaline lay at a depth of around 115m, after 103m in February 2017. The 13 g/kg isohaline was found at 161m depth, 7m deeper than one year before. The bottom salinity in the Landsort deep was 11.38 g/kg (11.18 g/kg in February 2017).

By the second half of March, the salinity distribution did not depict significant changes, due to the lack of substantial inflows. The small pool of saline water at the bottom of the Arkona Basin vanished almost completely. The bottom salinity in the Bornholm Basin decreased slightly to 17.0 g/kg in the central part of the basin. The halocline depth in the Bornholm Basin dropped from 50m in February to 59m in March. The halocline in the basin was well below the sill depth of the Slupsk Sill, thus, no further drainage of saline water into the Slupsk Furrow was expected. In the Slupsk Furrow, the bottom salinity was only 13.3 g/kg. In the eastern Gotland Basin the conditions remained unchanged. At the Gotland Deep the 12 g/kg and the 13 g/kg isohalines were found at 107m and 159m, respectively. The bottom salinity was still 13.3 g/kg. In the Farö Deep, the 12 g/kg isohaline was observed at 113m depth with a bottom salinity of 12.74 g/kg.

At the beginning of May, a bottom water body of highly saline water was observed in the Fehmarn Belt. The maximum salinity was 28.1 g/kg. The minor inflow from April 2018 had caused a saline water pool in the Arkona Basin. In the centre of the basin, the halocline was found at 35 to 40 m depth. The bottom salinity was about 17.7 g/kg. In the Bornholm Basin the halocline depth rose to 55 m, which is equal to the depth of the Slupsk Sill. The bottom salinity dropped slightly to 16.88 g/kg. The volume of saline deep water in the Slupsk Furrow was significantly reduced due to the fact that any saline water lying in depths above that of the eastern sill of the furrow were subject to eastward advection. However, the bottom salinity in the furrow remained at 13.4 g/kg. At station TF271 (Gotland Deep) the bottom salinity was unchanged at 13.29 g/kg. Here, the 13 g/kg isohaline dropped from 159 m in March to a depth of 167 m. The 12 g/kg isohaline changed from 107m to 118m. In the Farö Deep, the depth position of the 12 g/kg isohaline was nearly unchanged at 115m depth. The bottom salinity was slightly reduced to 12.69 g/kg.

In July, changes of salinity distribution in the western Baltic were caused by the baroclinic summer inflows, which enhanced the stratification in the Fehmarn Belt, where a bottom salinity of 25 g/kg was observed. The thin bottom layer in the Arkona Basin was filled with warm waters from the baroclinic inflows. The bottom salinity was about 16.7 g/kg. In the Bornholm Basin, mixing with overlaying water caused a slight dilution of deep water. The bottom salinity slightly sunk to 16.7 g/kg. The saline deep water layer in the Slupsk Furrow had not yet been exchanged by the end of July. Here, the bottom salinity was slightly reduced to 13.2 g/kg. Also in the central Baltic basins no significant changes were observed. The depth of the 13 g/kg isohaline in the Gotland Deep was at 166m, the same depth as in May. The bottom salinity in the Gotland Deep and the Farö Deep was 13.28 g/kg and 12.74 g/kg, respectively.

In November 2018, the baroclinic inflow process was almost finished. In the Arkona Basin, warm and highly saline water from the baroclinic summer/autumn inflows replaced the bottom water. The maximum bottom salinity amounted to 20.1 g/kg. The halocline depth was at 40m depth. The warm saline water had also reached the bottom layer of the Bornholm Basin, where It increased the bottom salinity by 1 g/kg to 17.75 g/kg. The halocline depth in the eastern Bornholm Basin rose to 45m, which is about 10m above the sill depth of the Slupsk Sill. This forced an ongoing overflow of the Sill and led flushing the Slupsk Furrow with saline inflow water. Here, the bottom salinity increased to 15.4 g/kg. Some parts of the saline waters left the Slupsk Furrow towards the eastern Gotland Basin, where the deep water salinity had not changed significantly since February 2018.

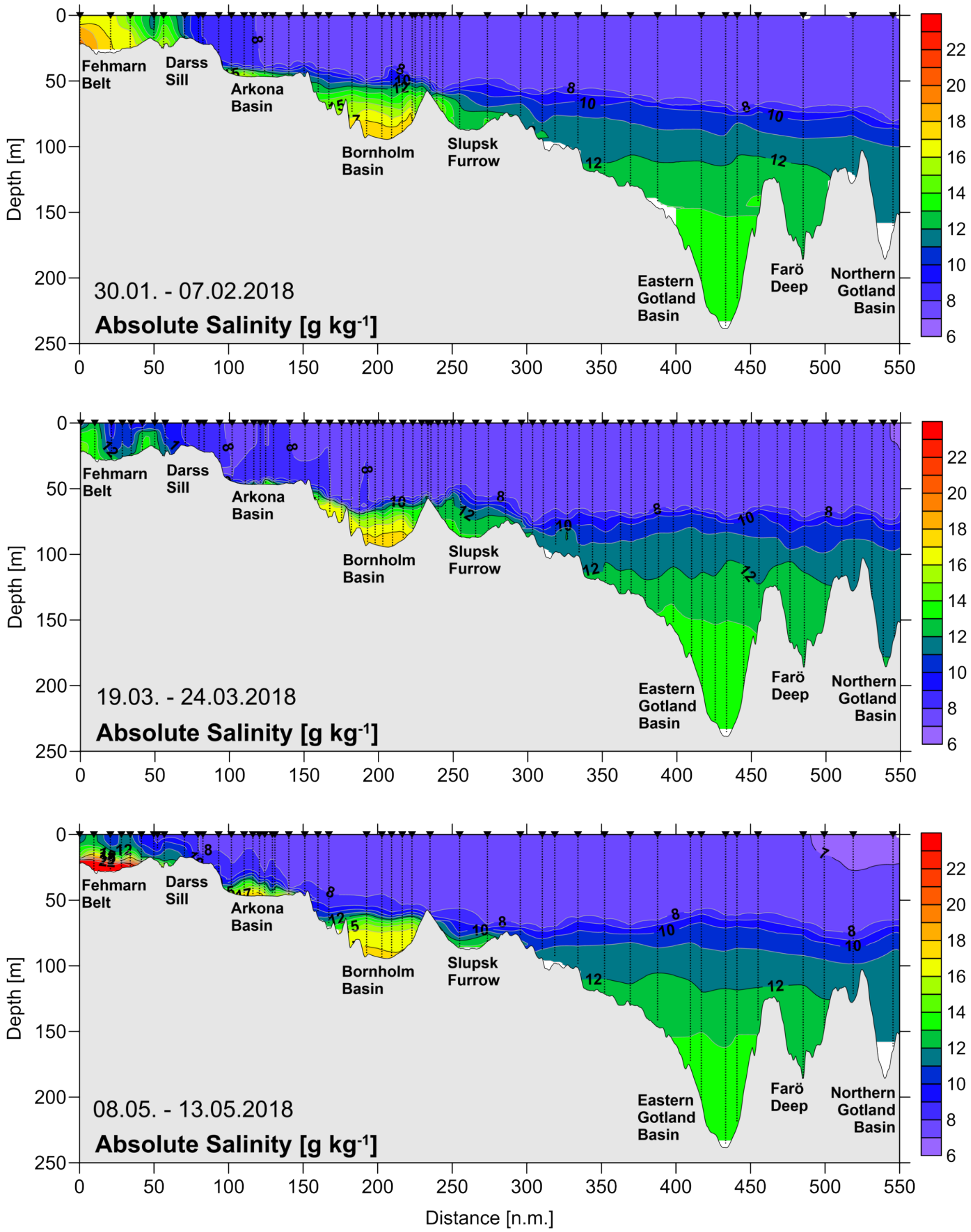


Fig. 27a: Salinity distribution along the talweg transect through the Baltic Sea between Darss Sill and northern Gotland Basin (January, March, May).

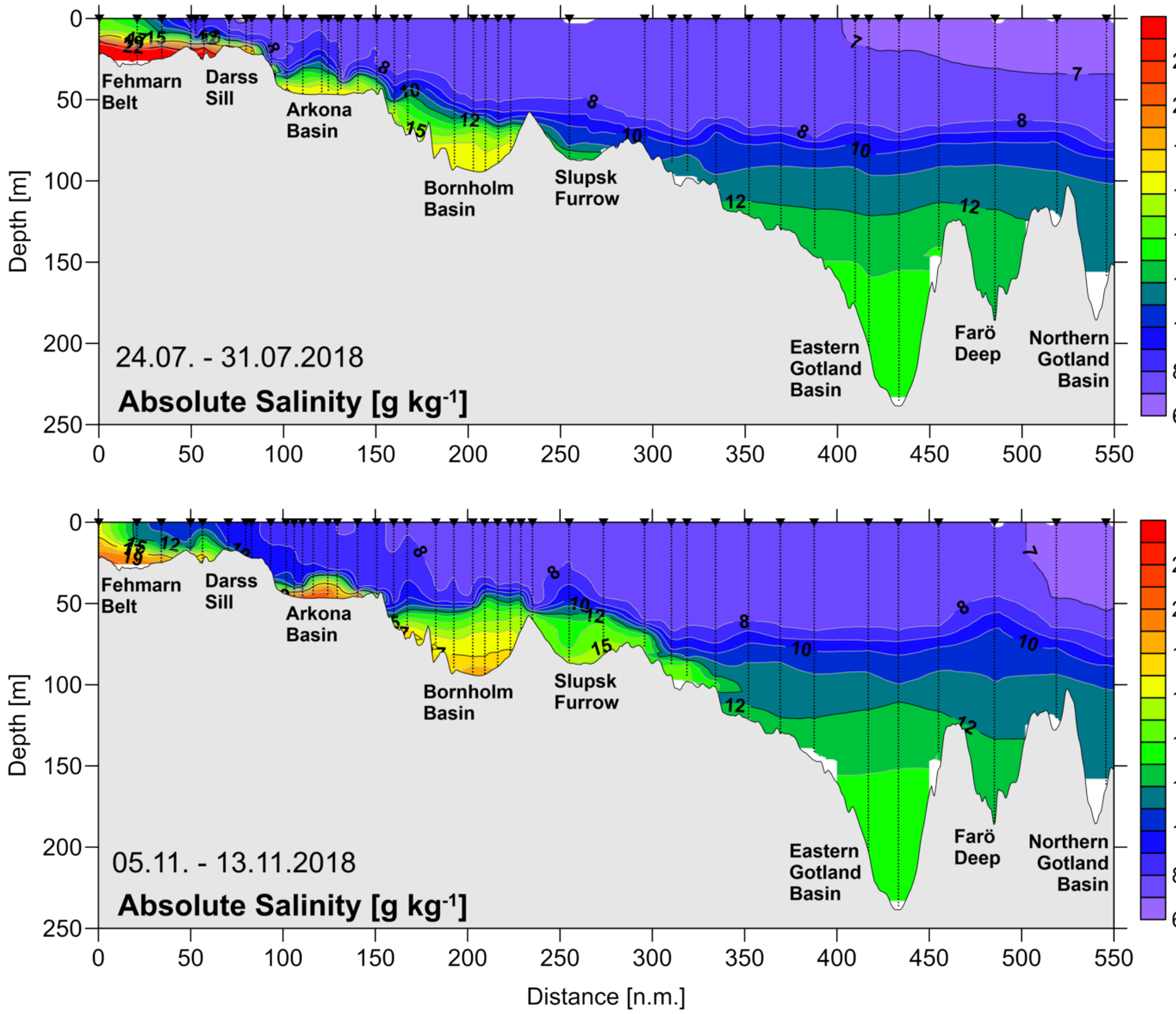


Fig. 27b: Salinity distribution along the talweg transect through the Baltic Sea between Darss Sill and northern Gotland Basin (July, November).

Table 7 shows the overall trend of salinity in the deep water of the Baltic in the past five years. After the series of inflow events from 2014 to 2016, the bottom salinity in the Gotland Deep and Farö Deep reached its maximum in 2017. In 2018, the deep water salinity in both basins dropped slightly due to mixing and lack of significant inflows. In the Karlsö Deep and Landsort Deep the deep water salinity reached its maximum values of the past five year period. In the Bornholm Basin, a decrease of bottom salinity was observed in 2018, although the salinity still remained high. The high standard deviation of salinity in the Bornholm basin and the Karlsö Deep points to rapid fluctuations, caused by 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 Sea. Table 8 summarises the variations in surface layer salinity. Compared to the values in 2017, surface layer salinity in the Bornholm Basin increased slightly in 2018. The surface salinity decreased in the eastern Gotland Basin and the Farö Deep, and increased in the western Gotland basin. Except for the Bornholm Basin, the standard deviations of surface salinity are close to the level of the long-term average. Generally, the surface salinity will increase with a delay of about ten years after large inflow events. Thus, a significant increase in surface salinity was not expected in 2018.

Station	1952-2005	2014	2015	2016	2017	2018
213 Bornholm Deep	7.60 ±0.29	7.65 ±0.18	7.76 ±0.20	7.75 ±0.26	**7.46 ±0.20**	7.53 ±0.08
271 Gotland Deep	7.26 ±0.32	**6.87 ±0.17**	7.06 ±0.15	6.89 ±0.34	7.33 ±0.22	7.09 ±0.27
286 Fårö Deep	6.92 ±0.34	6.73 ±0.21	6.74 ±0.25	**6.63 ±0.33**	7.13 ±0.43	6.92 ±0.34
284 Landsort Deep	6.75 ±0.35	6.60 ±0.24	**6.29 ±0.44**	6.57 ±0.16	6.54 ±0.34	6.59 ±0.32
245 Karlsö Deep	6.99 ±0.32	7.00 ±0.13	**6.91 ±0.25**	6.98 ±0.17	6.93 ±0.18	7.06 ±0.18

Table 8: Annual means of 2014 to 2018 and standard deviations of surface water salinity in the central Baltic Sea (minimum values in bold, n=5-26). Long-term averages of the years 1952-2005 taken from BALTIC climate atlas (FEISTEL et al., 2008a)

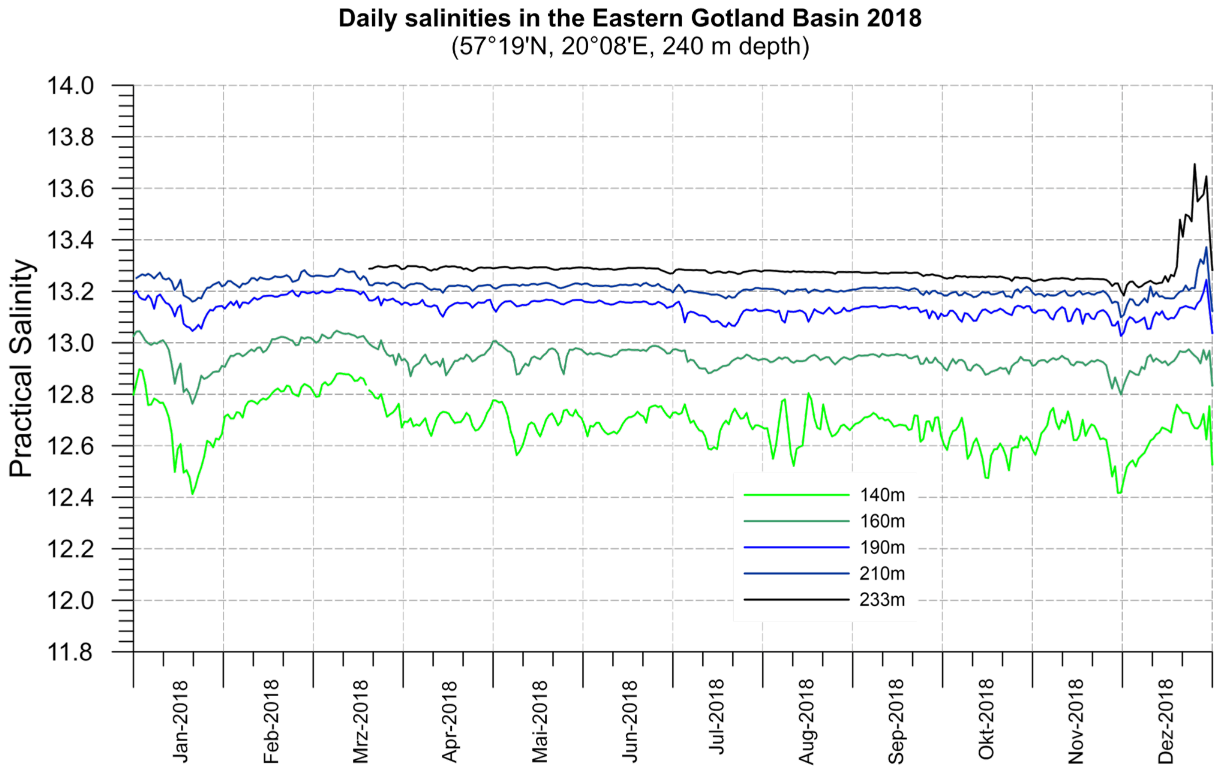


Fig. 28: Temporal development of deep water salinity in the Eastern Gotland Basin (station TF271) from January to December 2018 (Daily averages of original data with 10 min sampling interval).

Figure 28 shows the temporal development of salinity in the deep water of the eastern Gotland Basin between January and December 2018, based on data from the hydrographic moorings described above. As seen in the temperature data, there were no significant changes of the saline stratification until mid-December 2018.

The deep water salinity depicted a small decrease during the year 2018, due to vertical mixing. This process reduced the deep water salinity by about 0.1 g/kg from January to December 2018.

The arrival of the water from the baroclinic summer inflows increased the bottom salinity by 0.4 g/kg to 13.6 g/kg. The salinity time series reveals some short-term fluctuation whose amplitude decreases with depth. Mostly, these fluctuations can be attributed to internal motions, which deflected the isohalines temporarily.

6.3 Oxygen distribution

For higher marine organisms, a sufficient oxygen content of the water is an important prerequisite to survive. For Baltic Sea deep waters, it is known that oxygen reaches low levels and after a few years of stagnation the water below the permanent halocline turns into anoxic and then to euxinic conditions hostile to life. This reflects the consumption of other oxidants after oxygen depletion. Among them, sulfate as a major constituent of Baltic Sea seawater plays an important role. Its reduction subsequently leads to the accumulation of hydrogen sulfide. The lack of oxygen is evaluated by HELCOM by using the oxygen debt indicator for deep waters to figure out a potential deviation from a "good environmental status". However, it raised emerging concern that also in Baltic Sea areas with water depths shallower than the permanent halocline of 60 to 80 m depth, waters are subjected to temporally low oxygen values due to hypertrophication. To observe the bottom water oxygen concentration in shallow areas and finally get a handle on its evaluation, it is aimed to develop an indicator that appropriately describes the oxygen condition also for these areas apart from the central deep basins. In shallow areas, the gas exchange with the atmosphere provides an elevated oxygen content of the seawater. Thus, oxygen is usually close to saturation which is mainly controlled by temperature, but also influenced by salinity and air pressure. Assimilation and dissimilation are further processes controlling the oxygen content in seawater, with the importance of the assimilation increasing with water depth. In deeper water layers without contact to the atmosphere, oxygen concentration clearly declines by respiration (Fig. 29, lower panel). In especially unfavorable hydrographic conditions, a density stratification can build up (pycnocline) which prevents any further gas exchange between the lower water body and the atmosphere. Ongoing oxygen consumption during organic matter degradation can then lead to a total depletion of oxygen (lower panel). Denitrification and a subsequent reduction of sulfate which in turn is converted to toxic hydrogen sulfide (shown as negative oxygen) even worsens the conditions.

The deep water oxygen concentration showed a general decrease until 2018 that turned to an ongoing accumulation of hydrogen sulfide after the MBI of December 2014 in recent years. The maxima of 2015 in the Bornholm and the eastern Gotland Sea had propagated along the talweg to the Fårö Deep and the Landsort Deep in 2017. All investigated deeps (Table 7 – third part) showed a worsening of the oxygen situation in 2018. The annual mean maximum of 0.88 ml/l oxygen that was recorded in 2017 at the Bornholm Deep weakened to 0.01 ml/l in 2018. At Gotland Deep in the reference level of 200 m, oxygen was already depleted in 2017 with 0.07 ml/l and showed the oxygen equivalent of -1.07 ml/l in 2018. The best oxygen/hydrogen sulfide situation at Fårö Deep (0.33 ml/l) and the Landsort Deep stations (-0.46 ml/l) in recent years decreased to -0.76 and -0.88 ml/l in 2018. Karlsö Deep recovered slightly from 2016 (-1.15 ml/l) to 2017 (-0.96 ml/l), but clearly worsened to -1.83 ml/l in 2018 (Table 7). The positive effect of the MBI in terms of oxygen supply seemed to have faded out completely and the stagnation with oxygen consumption/hydrogen sulfide accumulation continued.

Table 7 – third part: Oxygen concentration (ml/l) in deep waters of the Baltic Sea deeps (Hydrogen sulfide is converted to negative oxygen equivalents; maxima are given in bold)

Station	Depth /m	2014	2015	2016	2017	2018
213 (Bornholm Deep)	80	2.07 ±1.47	**3.60 ±1.75**	1.19 ± 1.00	0.88 ±0.70	0.01 ±0.28
271 (Gotland Deep)	200	-2.94 ±2.38	**0.93 ±0.80**	0.62 ±0.24	0.07 ±0.20	-1.07 ±0.57
286 (Fårö Deep)	150	-2.35 ±0.53	-0.87 ±0.20	-0.05 ±0.22	**0.33 ±0.33**	-0.76 ±0.77
284 (Landsort Deep)	400	-1.02 ±0.68	-0.86 ±0.18	-0.92 ±0.33	**-0.46 ±0.26**	-0.88 ±0.52
245 (Karlsö Deep)	100	**-0.85 ±0.52**	-0.87 ±0.51	-1.15 ± 0.34	-0.96 ± 0.58	-1.83 ± 1.38

The seasonal cycle of primary production and the temperature dependency of the oxygen saturation determines the oxygen concentration in surface water. This development is shown in the upper panel of Figure 29. During spring time, the primary production caused the highest oxygen concentration in March in the Belt Sea, the Mecklenburg Bight, and the Arkona Sea (light green bars). An additional temperature effect cannot be excluded since water temperature were lowest in March. The Bornholm Sea and the different areas of the Gotland Sea showed the peak in May 2018. Lowest values were observed in surface waters in summer. They recovered after the degradation of the seasonal thermocline in November. 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 2018. This indicated an ongoing decoupling of the bottom waters from the surface water processes, i.e. primary production and air-sea gas exchange. Intensified remineralization in bottom waters and sediments after a sequence of sedimented surface water blooms caused oxygen consumption. The oxygen concentration in bottom waters scatters around zero in the Bornholm Sea and the areas of the Gotland Sea, and thus appears to be higher in the Gotland Sea bottom waters compared to the selected long-time reference depth of the deep basins shown in Table 7. This in turn could indicate that some oxygen containing waters may have reached the Gotland Sea in 2018.

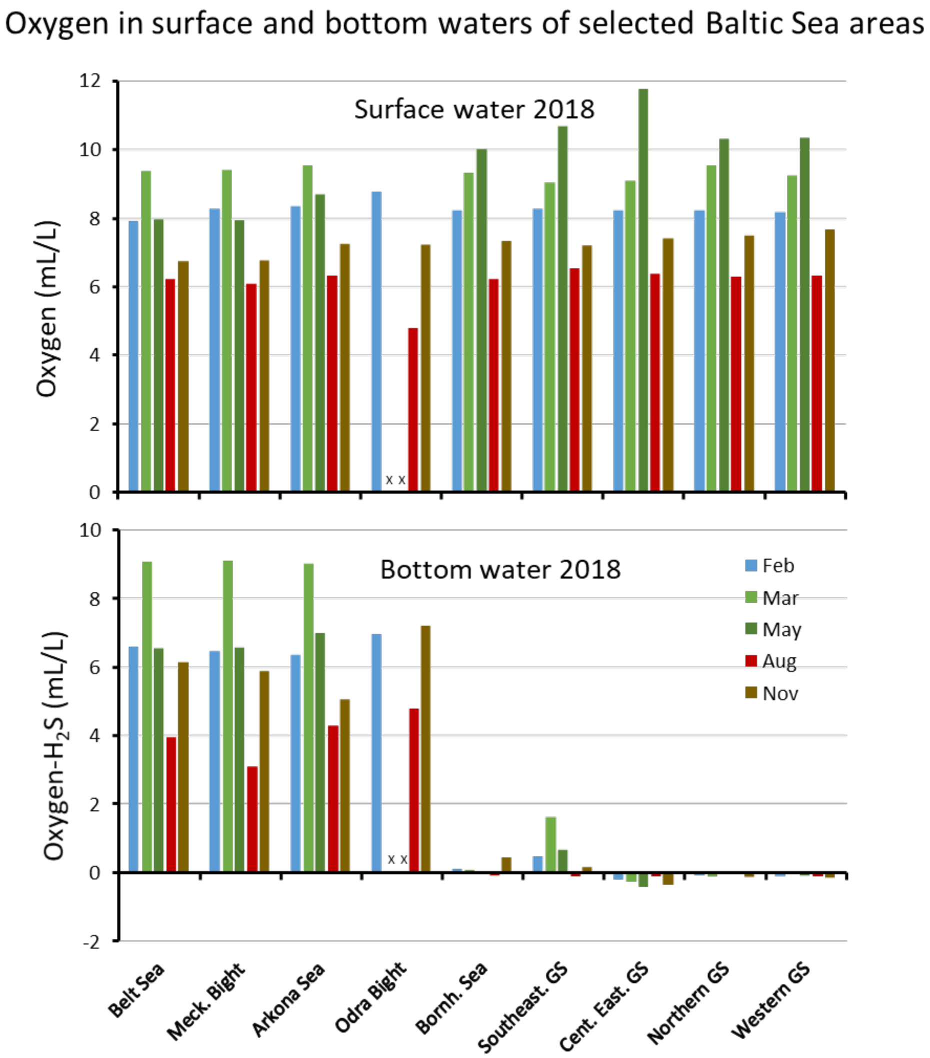


Fig. 29: Comparison of average oxygen concentrations in surface (upper panel) and average oxygen/hydrogen sulfide concentrations in bottom waters (lower panel) of the studied Baltic Sea areas: Belt Sea, Mecklenburg Bight, Arkona Sea, Bornholm Sea, central Eastern Gotland Sea, Northern Gotland Sea, and Western Gotland Sea (based on IOW data of 2018).

A period most critical for oxygen concentration in bottom waters of the shallow Baltic Sea areas is the time of the end of summer/early autumn, when usually the strongest oxygen depletion is observed. Since the IOW monitoring campaigns do not cover that time period, we use the findings of the State Agency for Agriculture, Environment and Rural Areas Schleswig-Holstein (LLUR) which routinely measures near-bottom oxygen concentrations at that time of the year. Investigations in 2018 were conducted from September 3 - 17. Near-bottom oxygen concentrations were measured on 38 stations (LLUR, 2018), 30 stations showed a water depth ›15 m (Figure 30).

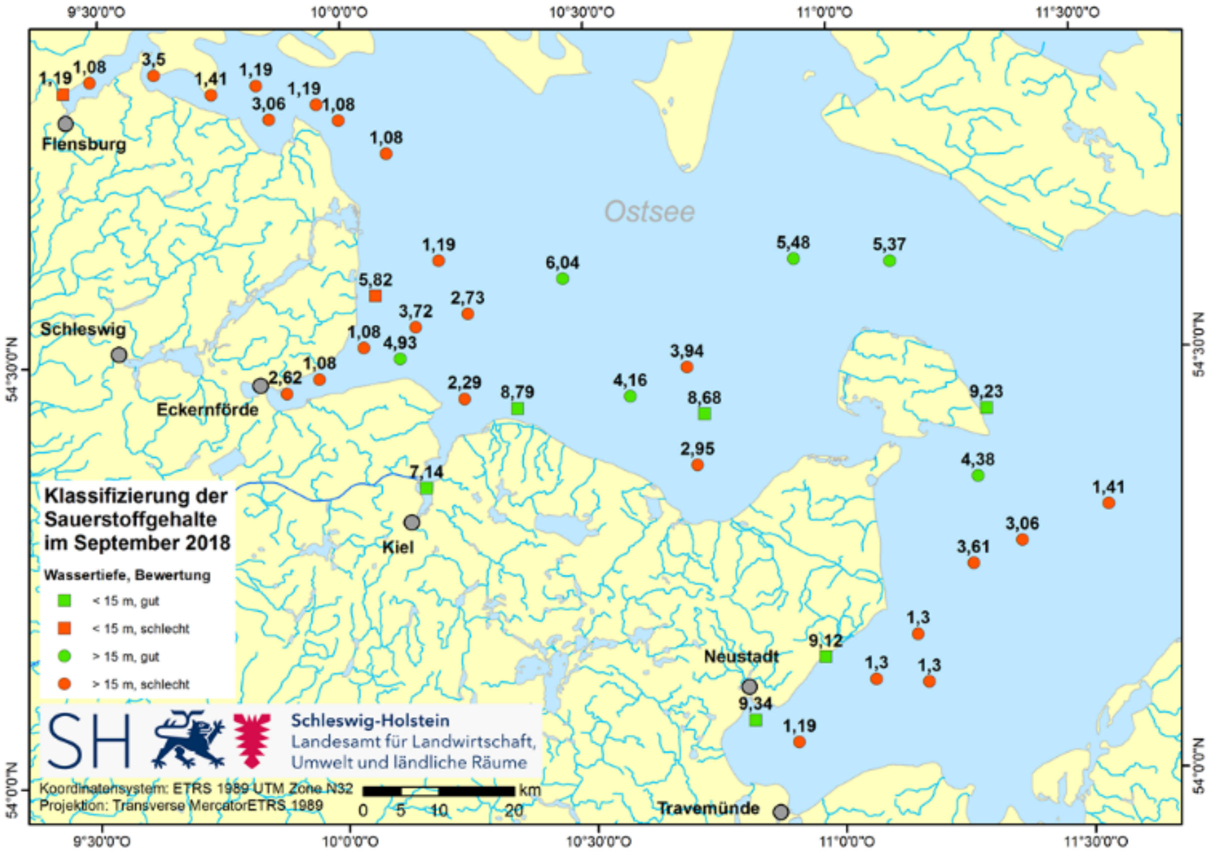


Fig. 30: Classified oxygen concentrations in the Belt Sea in September 2018 (LLUR, 2018) – O_2 [mg/l] x 0.7005 = O_2 [ml/l]

Measured bottom water oxygen concentrations (Figure 30) are indicated at the respective sampling sites. In September 2018, the values at 24 stations (80%) were below the threshold value of 4 mg/l for the deeper stations which was a slightly improved situation compared to 2017. Two of eight shallow stations (25%) showed oxygen concentrations below the threshold value of 6 mg/l. 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 contrast to the shallow areas, the deep-water conditions in the more easterly, deeper basins of the Baltic Sea 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 2018.

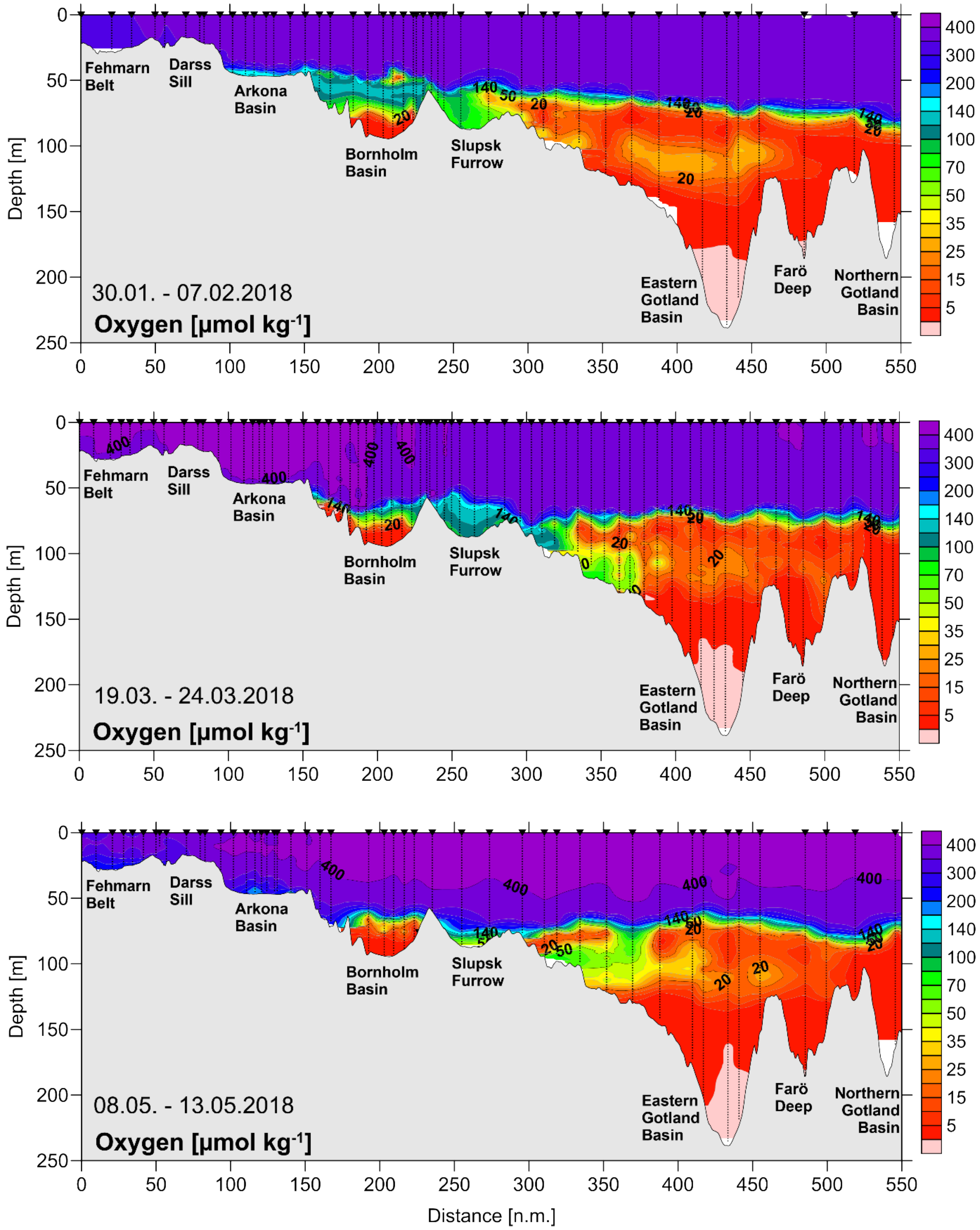


Fig. 31a: Vertical distribution of oxygen in 2018 (January, March, May) between the Darss Sill and the northern Gotland Basin (H_2S values are not considered). Values below ~15 µmol/kg could not be distinguished from 0 µmol/kg.

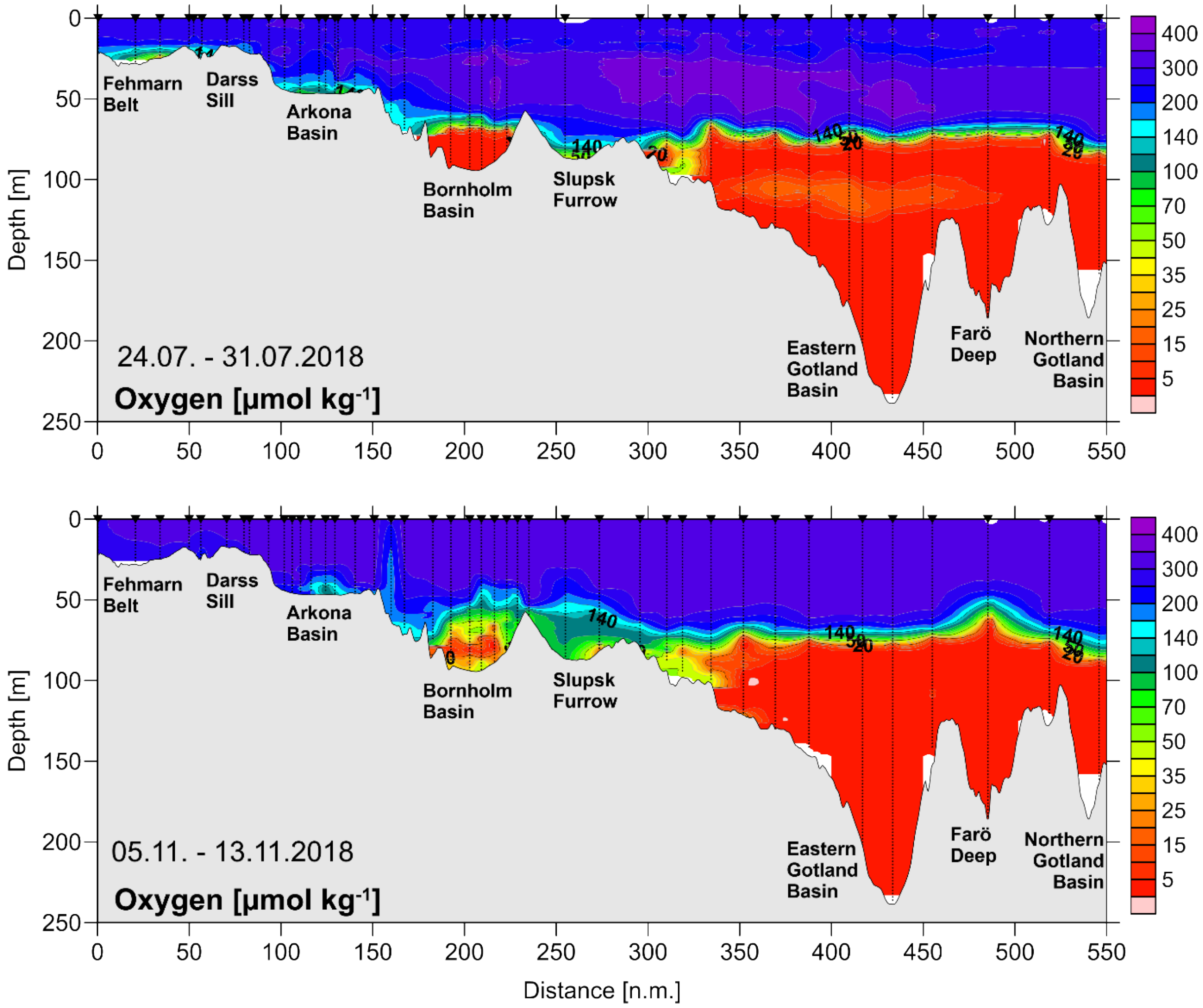


Fig. 31b: Vertical distribution of oxygen in 2018 (July, November) between the Darss Sill and the northern Gotland Basin (H_2S values are not considered). Values below ~15 µmol/kg could not be distinguished from 0 µmol/kg.

6.4 Inorganic nutrients

The eutrophication of the Baltic Sea is still of major concern despite many reduction measures that have been implemented in the last decades. According to the status assessment, 97 % of the region was termed eutrophied for the years 2011–2016 (HELCOM, 2018a). It was concluded that signs of improvement in some areas are overwhelmed by the effects of past and current nutrient inputs that still predominate the overall status. Thereby, a 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 one for 2014 (PLC-6) (HELCOM, 2018b) shows that total waterborne and airborne inputs of nitrogen to the Baltic Sea decreased from 977,000 Mg to 826,000 Mg. For phosphorus a decline from 35,500 Mg to 31,000 Mg was given for 2006 to 2014, 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, 2018b). 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, 2018a). 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.

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 of the eastern Gotland Sea and the Bornholm Sea surface waters on the respective deep stations in 2018. 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 2018, already at low surface water temperature of below 3 °C, the spring bloom started in the central Gotland Sea and in the Bornholm Sea by the end of March to early April. This led to a rapid decline of nitrate. The phosphate concentration decreased only slowly down to the limit of detection which was reached by mid-May at the Gotland Deep station as well as at the Bornholm Deep station. At nitrate depletion, the spring bloom in 2018 likely came to an end by mid-April almost parallel in the Bornholm Sea and the eastern Gotland Sea. On both stations slightly elevated nutrient concentrations were measured in early June in times of usually low nutrient availability. However, the surface water nutrient concentrations on the Bornholm Deep and Gotland Deep stations did not reach significant amounts before early November in 2018. At that time, cooling enabled wind-induced mixing and the supply of nutrients from deeper layers. Mineralization processes at depth had caused an increase in nutrient concentrations that subsequently replenished the surface water until the end of the year.

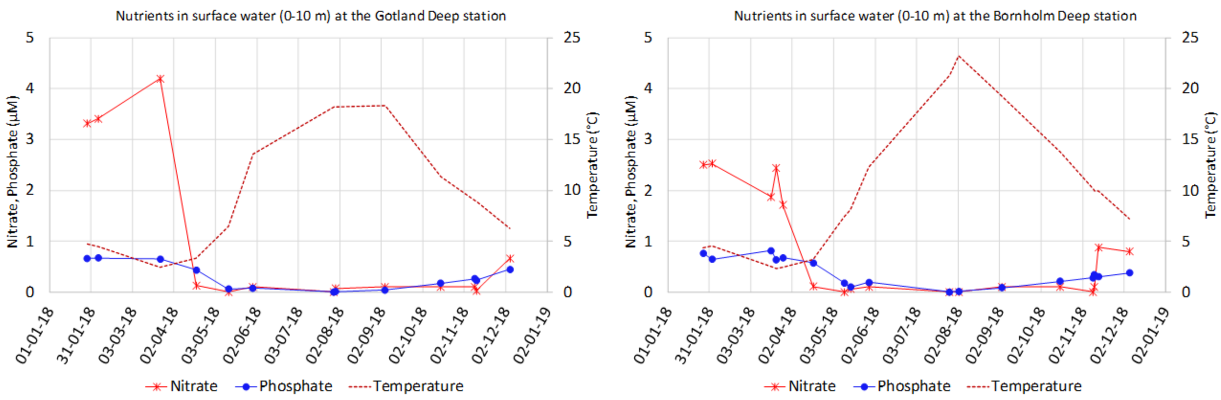


Fig. 32: Seasonal cycle of the average phosphate and nitrate concentrations in 2018 compared to temperature of the surface layer (0-10 m) at the Gotland Deep station (TF271 - left) and at the Bornholm Deep station (TF213 – right), respectively, by using IOW and SMHI data.

The prolonged uptake of phosphate is probably caused by the low dissolved inorganic nitrogen/phosphorus ratio present in the winter surface water of the Baltic Sea. This might have led to nitrate exhaustion before phosphate was completely consumed. The favorable uptake ratio is about 16 that had already been shown by an early study of Redfield (REDFIELD et al., 1963) and was proven to be a valuable approximation many times thereafter. The DIN/DIP ratio (mol/mol) was determined from the sum of ammonium, nitrate, and nitrite concentrations versus the phosphate concentration. In the investigated areas the values scatter around 8 mol/mol in the western part and around 5 mol/mol in the eastern part in recent years (Fig. 33). This already indicated that nitrogen was a limiting factor through the year 2018 giving diazotrophic cyanobacteria an advantage especially in the Gotland Sea, Bornholm Sea and also in the Arkona Sea in that year. In that sense, the Arkona Sea belonged to the western part in 2017 but showed values comparable to the eastern part of the study area in 2016 and 2018. The overall decreasing trend from the Bornholm Sea to the southern Gotland Sea, further to the eastern, the northern, and the western Gotland Sea in 2017 was almost reversed in 2018. The DIN/DIP ratio of the western Gotland Sea just remained below that of the Northern Gotland Sea. The exceptional high DIN/DIP ratio of about 22 mol/mol in the Odra Bank area, which was even above the "Redfield ratio" in 2017, was found again in 2018.

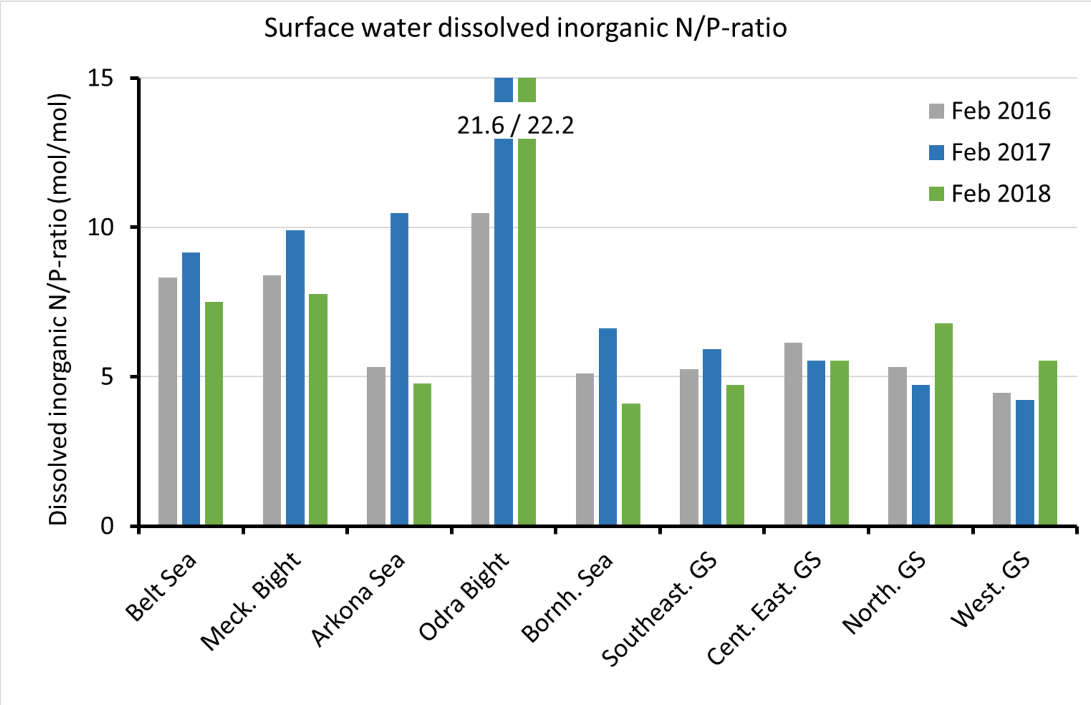


Fig. 33: Average dissolved inorganic nitrogen versus phosphate ratio in surface waters of selected Baltic Sea areas in February 2016, 2017 and 2018.

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

Station	Monat	2014	2015	2016	2017	2018
360 (Fehmarn Belt)	Feb.	0.57 ± 0.01	0.64 ± 0.01	0.66 ± 0.04	**0.54 ± 0.01**	0.66 ± 0.02
022 (Lübeck Bight)	Feb.	0.71 ± 0.04	0.63 ± 0.02	0.79 ± 0.15	**0.53 ± 0.09**	0.69 ± 0.00
012 (Meckl. Bight)	Feb.	**0.56 ± 0.00**	0.60 ± 0.01	0.68 ± 0.01	**0.56 ± 0.00**	0.70 ± 0.00
113 (Arkona Sea)	Feb.	**0.53 ± 0.00**	0.56 ± 0.00	0.64 ± 0.01	**0.53 ± 0.00**	0.67 ± 0.01
213 (Bornholm Deep)	Feb.	0.70 ± 0.01	**0.60 ± 0.00**	0.67 ± 0.06	0.61 ± 0.06	0.65 ± 0.01
271 (Gotland Deep)	Feb.	0.52 ± 0.01	**0.50 ± 0.02**	0.67 ± 0.04	0.70 ± 0.08	0.67 ± 0.01
286 (Fårö Deep)	Feb.	0.78 ± 0.01	**0.60 ± 0.00**	0.65 ± 0.08	0.69 ± 0.01	0.64 ± 0.01
284 (Landsort Deep)	Feb.	0.84 ± 0.01	-	0.75 ± 0.01	0.79 ± 0.03	**0.59 ± 0.01**
245 (Karls Deep)	Feb.	0.85 ± 0.00	0.80 ± 0.00	0.87 ± 0.09	0.91 ± 0.07	**0.70 ± 0.01**

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

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

Station	Monat	2014	2015	2016	2017	2018
360 (Fehmarn Belt)	Feb.	4.9 ± 0.2	7.5 ± 0.1	4.5 ± 0.5	**3.2 ± 0.1**	3.7 ± 0.0
022 (Lübeck Bight)	Feb.	6.6 ± 0.1	9.3 ± 0.2	6.3 ± 0.1	**4.5 ± 0.7**	6.1 ± 0.0
012 (Meckl. Bight) Bucht)	Feb.	4.5 ± 0.1	5.5 ± 0.0	4.8 ± 0.1	**4.4 ± 0.0**	4.7 ± 0.3
113 (Arkona Sea)	Feb.	5.2 ± 0.2	3.7 ± 0.0	3.2 ± 0.2	5.2 ± 0.0	**2.8 ± 0.0**
213 (Bornholm Deep)	Feb.	4.0 ± 0.1	3.3 ± 0.2	2.8 ± 0.2	3.8 ± 0.1	**2.5 ± 0.0**
271 (Gotland Deep)	Feb.	3.9 ± 0.0	**3.1 ± 0.0**	3.4 ± 0.4	3.9 ± 0.3	3.4 ± 0.0
286 (Fårö Deep)	Feb.	4.5 ± 0.1	3.4 ± 0.0	**3.3 ± 0.5**	3.9 ± 0.1	3.9 ± 0.0
284 (Landsort Deep)	Feb.	3.8 ± 0.3		3.9 ± 0.0	**3.4 ± 0.2**	3.9 ± 0.0
245 (Karls Deep)	Feb.	3.5 ± 0.2	**3.2 ± 0.0**	3.3 ± 0.3	3.3 ± 0.1	3.6 ± 0.0

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

Table 9 shows winter phosphate and nitrate concentrations of surface waters for the February months of recent years. The values obtained for February 2018 were in the range of previous years. Slightly lower values were determined for phosphate in the western Gotland Sea surface waters, i.e., for the stations Landsort Deep and Karlsö Deep, reflecting minimum values in 2018 of 0.59 and 0.70 µmol/l, respectively, compared to previous years. However, in the western Baltic Sea a reverse situation existed, with elevated phosphate values for the selected Belt Sea and Arkona Sea stations in 2018, compared to the 5-year minima in 2017. For nitrate, elevated values were determined in the Belt Sea, but clearly lower values were measured on the Arkona Sea and Bornholm Sea reference stations, 2.8 and 2.5 µmol/l, respectively. Only minor changes were observed in the Gotland Sea: Gotland Deep -0.5 µmol/l, Fårö Deep ±0.0 µmol/l, Landsort Deep +0.5 µmol/l, Karlsö Deep +0.3 µmol/l. The changes during the last five years indicate an interannual variability, but the reductions in nutrient concentrations, which show already some effects in coastal waters are still not reflected in the nutrients concentrations of the central Baltic Sea basins (NAUSCH et al., 2011; NAUSCH et al., 2014).

6.4.2 Deep water processes in 2018

In the deep waters of the central Baltic Sea, the nutrient distribution is primarily influenced by the occurrence or absence of strong barotropic and/or baroclinic inflows and, thus, by its oxygen/hydrogen sulfide concentrations in deep waters. The annual average phosphate concentration maxima of 2018 in the Gotland Sea almost reached that of the year 2014. Thus, the influence of the MBI on phosphate in deep waters has almost faded out. During oxic conditions, phosphate is bound to iron and transported to the sediment by particles. In 2018, this could no longer been observed in the investigated water layers (Table 10). The fading out of the MBI impact is also reflected in the depletion of nitrate in deep waters that leaves a residue of 1.6 µmol/l only in the Bornholm Deep in 2018. All other investigated stations at the selected reference depths show average annual nitrate concentrations below the detection limit (Table 10). It should be noted that anoxic conditions prevent mineralization of organic matter to nitrate. Instead ammonium is formed and represents the end product of the degradation of biogenic material. Consequently, accumulation of ammonium in deep waters was recorded in Baltic Sea deep waters, which still reached a relatively low value of 1.9 µmol/l in the Bornholm Deep, 6.0 µmol/l in the Gotland Deep, a bit lower values of 3.6 and 5.0 µmol/l in the Fårö and Landsort Deeps. The strongest enrichment of ammonium of 10.4 µmol/l was obtained as the annual average at the reference level of 100 m at Karlsö Deep station (Table 10). Figures 34 and 35 illustrate the nutrient concentration distribution in the water column on atransect between the Darss Sill and the northern Gotland Sea for the year 2018.

The stagnation period that has started already in 2015 in the Bornholm and Eastern Gotland Sea after the MBI of December 2014 (NAUMANN et al., 2018) continued in 2018. Oxygen is decreasing or after depletion, hydrogen sulfide is accumulating in deep waters (Table 7). This is accompanied by phosphate and ammonium increase and consumption of nitrate, or incomplete remineralization just to ammonium, and thus to nitrate values below the detection limit in the selected deep water layers (Table 10). However, bottom water concentration measurements reveal that a certain amount of oxygenated saline water might have penetrated close to the bottom in the Gotland Deep in 2018 and intermittently improved the oxygen/H_2S situation (Fig. 31). Beside the well-known seasonal cycle of temperature and nutrients in surface waters (Fig. 33, 34 and 35), also the distribution of nitrate concentration in deeper waters indicated some changes during 2018. The deep waters of the northern Gotland Sea, e.g., the Fårö Deep that showed some positive oxygen values in 2017 had elevated nitrate concentrations between the depth levels of 90-150m in March and May 2018. From the isoline plots it seemed to have propagated southward into the eastern Gotland Sea during winter (Figure 34a) and were subsequently consumed under developing anoxic conditions during the course of the year in 2018 (Figure 34b).

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

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

Station	Depth/m	2014	2015	2016	2017	2018
213 BornholmDeep	80	1.49 ± 0.31	1.57 ± 0.44	2.23 ± 0.29	2.51 ± 1.15	**4.73 ± 1.56**
271 Gotland Deep	200	**4.50 ± 1.54**	2.16 ± 0.29	2.56 ± 0.14	2.91 ± 0.92	4.08 ± 0.13
286 Fårö Deep	150	**4.60 ± 0.67**	3.26 ± 0.23	2.93 ± 0.22	2.49 ± 0.12	3.55 ± 0.68
284 Landsort Deep	400	**3.85 ± 0.35**	3.57 ± 0.26	3.25 ± 0.31	3.08 ± 0.22	3.12 ± 0.22
245 Karls Deep	100	3.99 ± 0.51	3.92 ± 0.19	**4.25 ± 0.34**	3.77 ± 0.24	3.63 ± 0.34
		2014	2015	2016	2017	

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

Station	Depth/m	2014	2015	2016	2017	2018
213 BornholmDeep	80	8.2 ± 1.8	11.1 ± 2.5	10.4 ± 1.9	7.5 ± 2.3	**1.6 ± 1.5**
271 Gotland Deep	200	**0.0 ± 00**	7.5 ± 3.3	9.3 ± 0.7	1.8 ± 2.2	**0.0 ± 0.0**
286 Fårö Deep	150	**0.0 ± 00**	**0.0 ± 00**	1.4 ± 1.7	5.5 ± 3.5	**0.0 ± 0.0**
284 Landsort Deep	400	**0.0 ± 00**	**0.0 ± 00**	**0.0 ± 0.0**	**0.0 ± 0.1**	**0.0 ± 0.0**
245 Karls Deep	100	**0.0 ± 00**	**0.0 ± 00**	0.1 ± 00	0.1 ± 0.0	**0.0 ± 0.0**

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

Station	Depth/m	2014	2015	2016	2017	2018
213 BornholmDeep	80	0.1 ± 0.2	0.2 ± 0.1	0.2 ± 0.1	0.2 ± 0.3	**1.9 ± 2.4**
271 Gotland Deep	200	**18.4 ± 10.9**	1.6 ± 3.7	0.2 ± 0.0	0.8 ± 0.9	6.0 ± 2.3
286 Fårö Deep	150	**12.8 + 3.6**	7.2 ± 2.1	2.0 ± 2.0	0.1 ± 0.0	3.6 ± 1.7
284 Landsort Deep	400	**7.9 ± 1.7**	6.5 ± 1.1	7.8 ± 3.3	3.8 ± 1.9	5.0 ± 2.2
245 Karls Deep	100	7.7 ± 2.1	7.7 ± 1.2	9.7 ± 1.7	8.4 ± 1.5	**10.4 ± 2.9**

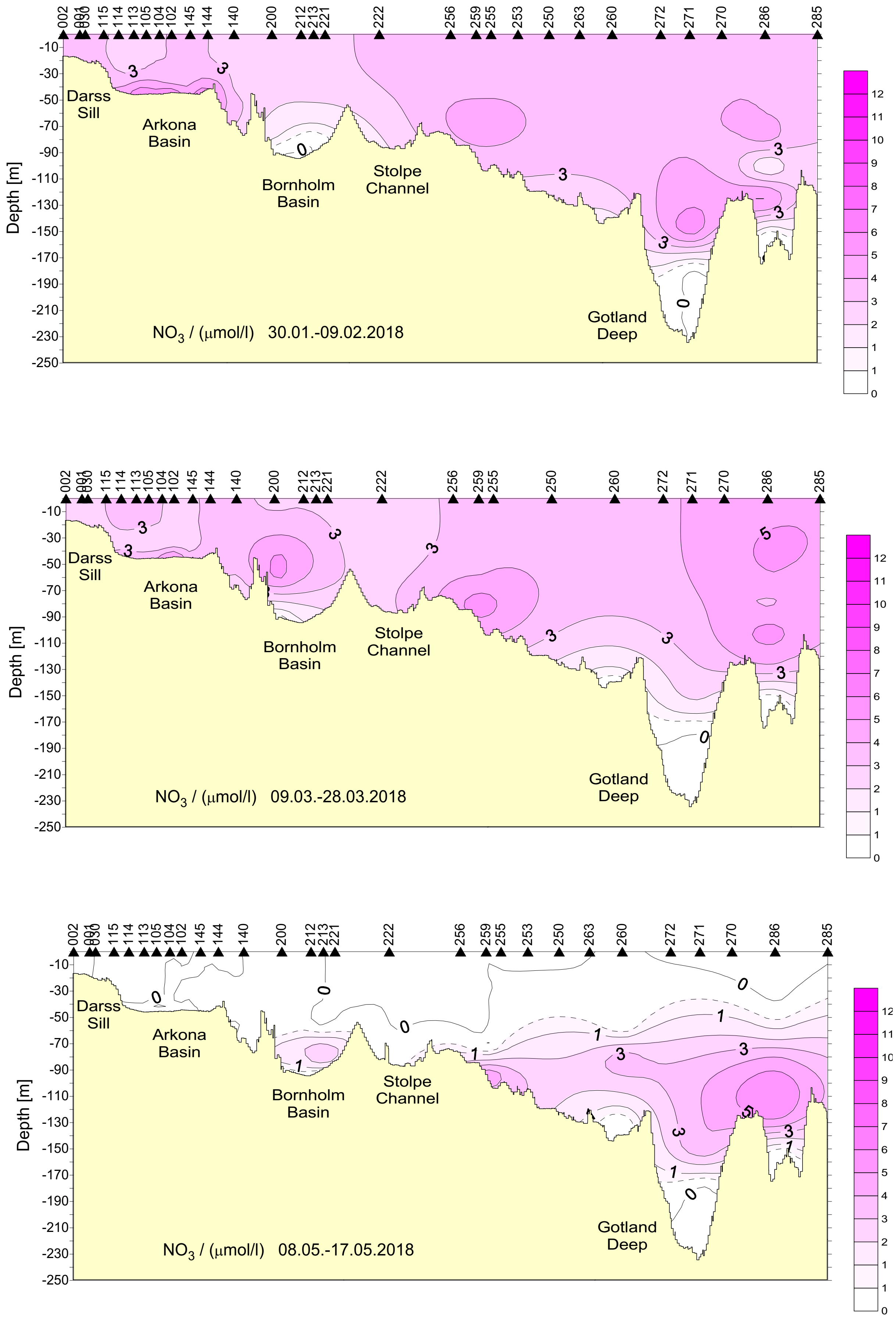
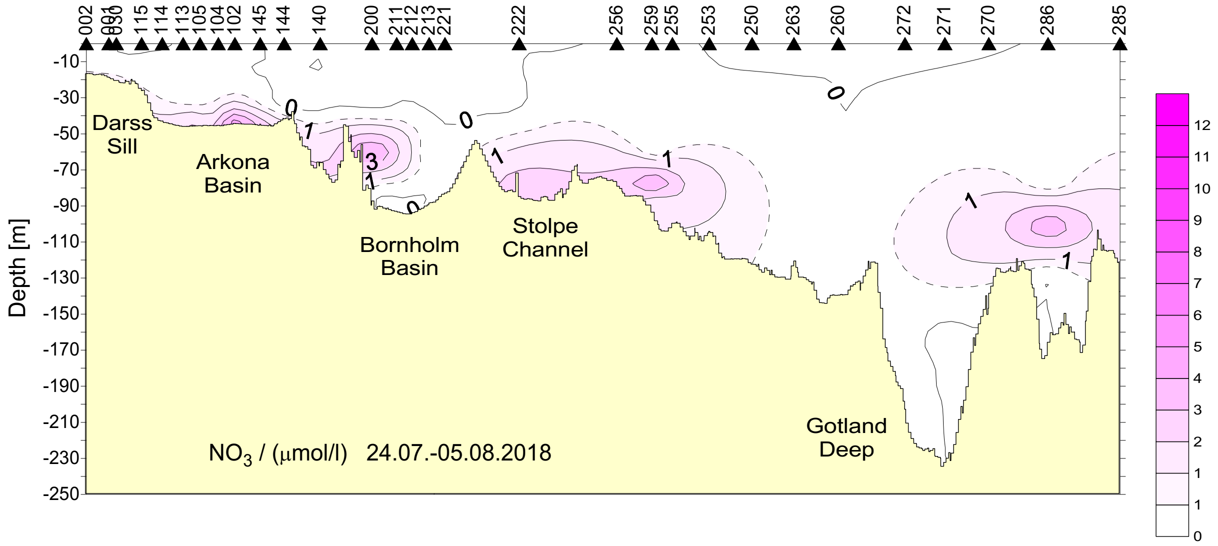


Fig. 34a: Vertical distribution of nitrate in 2018 between the Darss Sill and the northern Gotland Basin



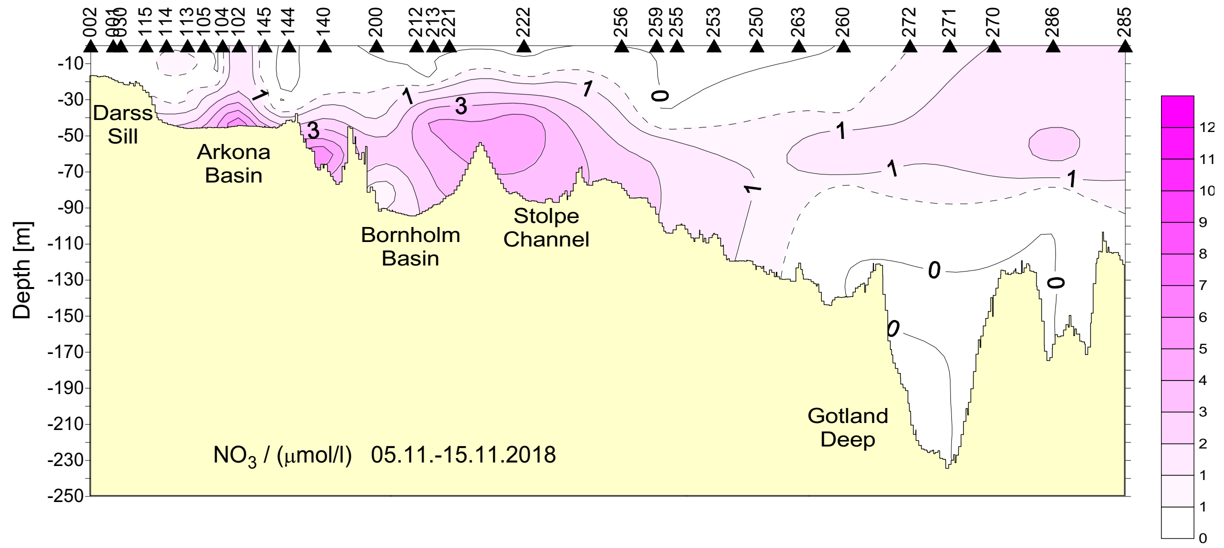


Fig. 34b: Vertical distribution of nitrate in 2018 between the Darss Sill and the northern Gotland Basin

Figure 34b clearly shows the depletion of nitrate throughout the water column during the summer of 2018. In deep waters, this was probably coupled to the oxygen depletion and the mostly euxinic conditions which in turn caused the remineralization stopped at the oxidation state of ammonium. Nitrate, if at all available, was consumed during remineralization under oxygen depletion. Subsequently, in autumn nitrate values increased in the southwestern Baltic Proper again.

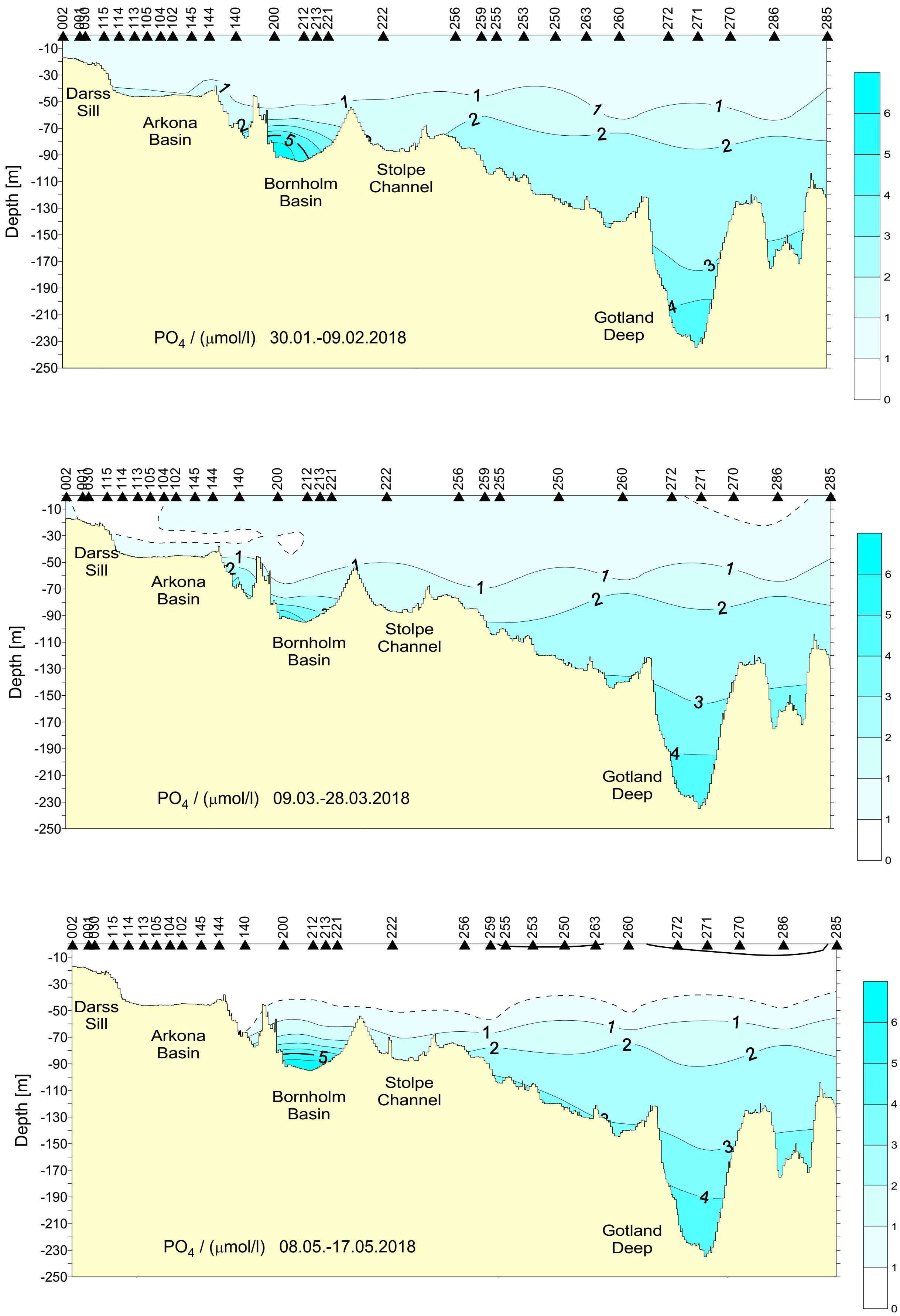


Fig. 35 a: Vertical distribution of phosphate in 2018 between the Darss Sill and the northern Gotland Basin

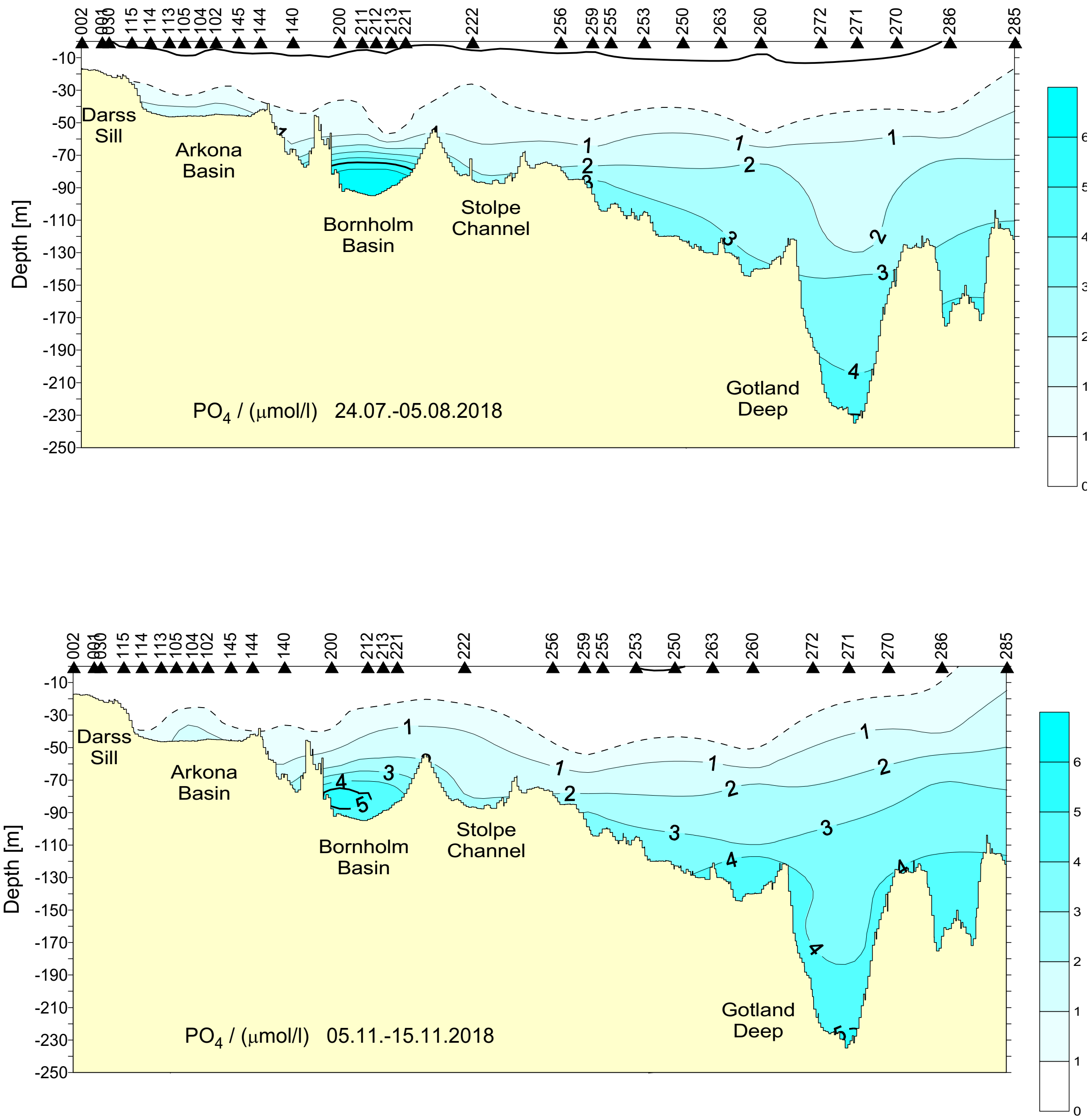


Fig. 35 b: Vertical distribution of phosphate in 2018 between the Darss Sill and the northern Gotland Basin

Figure 35 illustrates the horizontal and vertical distribution of phosphate along the transects from the Darss Sill to the northern Gotland Basin for the five monitoring cruises performed in 2018. It basically confirmed an advanced accumulation of phosphate in bottom waters of the Bornholm Sea and the eastern Gotland Sea during the year 2018 caused by ongoing stagnation. Phosphate is one component released 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°C in a spiral-shaped cooling tubing moisture was extracted in the dehumidifier. Before reaching the non-dispersive infrared detector, halogens were eliminated in the halogen scrubber 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 procedure, a reference material, the so called Consensus Reference Water (www.rsmas.edu/groups/biogeochem/CRM.html) is used.

The limit of quantification for DOC is set to DOC ‹ 25µmol/L and the standard deviation of the procedure to DOC ‹ 3µmol/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 4.4µmol/L C as stated in the IOW accreditation reports. Regular quality control of the measurements (at least twice a year) 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 26th, 2000 based on the ISO 17043 requirements (registration number R002).

The dissolved organic matter (DOM) is an important participant within the carbon and nutrient cycles in the Baltic Sea. 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 highly saline waters with less DOM originate from the North Sea. As a consequence, the DOC in surface water of the Baltic Sea has higher concentrations (200 – 500 moles C/dm^3) than the deep water (150 – 420 moles C/dm^3) at all stations. The concentration of dissolved organic nitrogen (DON) varies due to biogeochemical processes in the water column (Fig. 37 a,b). The relation of DOC/DON (C/N ratio) has in general mean values (16-20) near the Redfield ratio in surface water. The DOC/DON ratios in 2018 do not show any divergences from the long trend. A summary of all IOW long-term data from 1995 – 2018 is shown in figures (36 a,b).

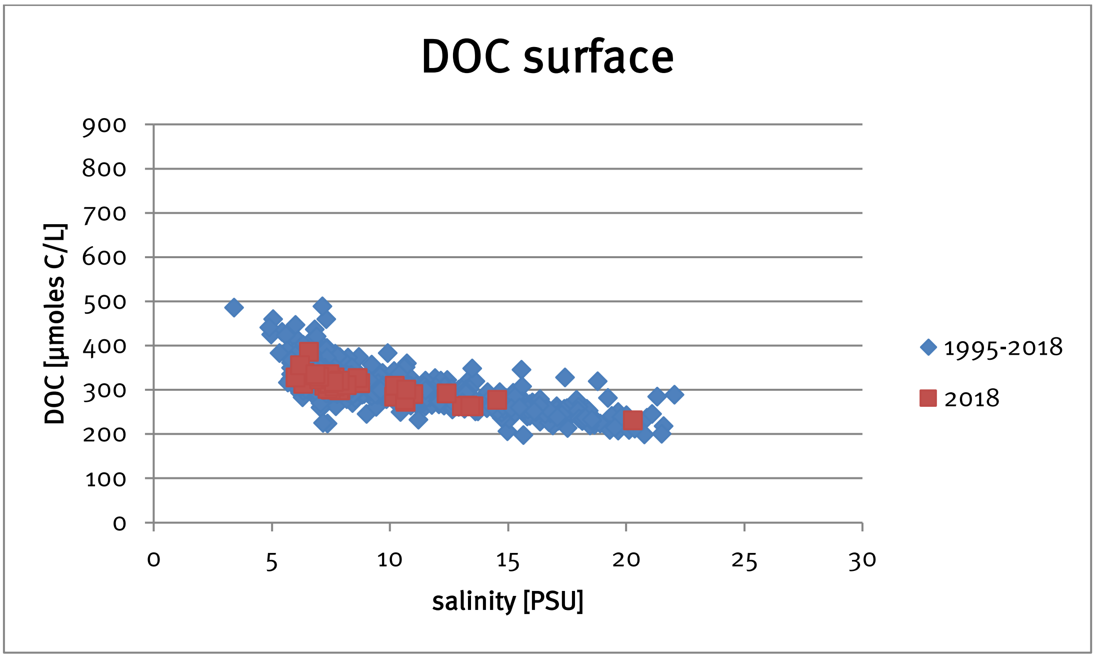


Fig. 36a: Dissolved organic carbon in the surface water from 1995-2018.

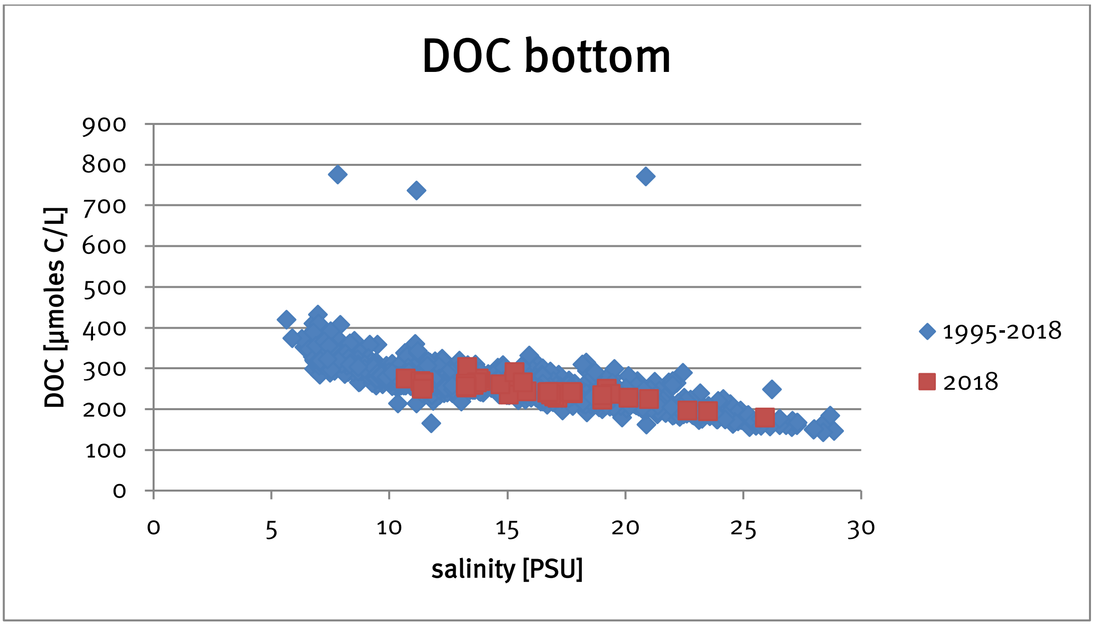


Fig. 36b: Dissolved organic carbon in the bottom water from 1995-2018.

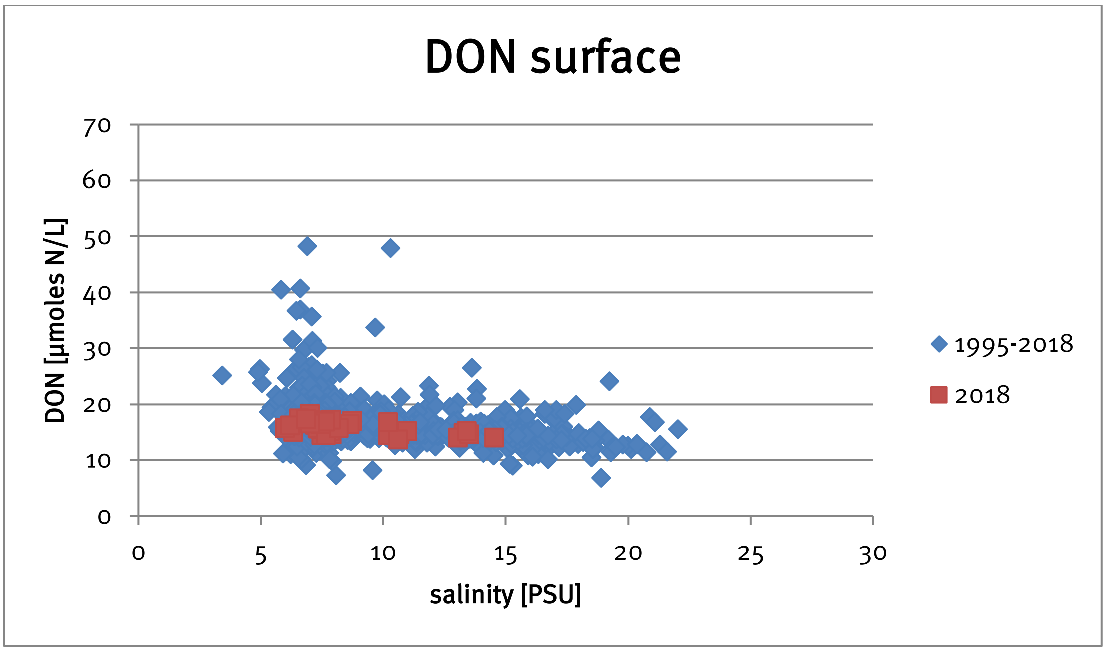


Fig. 37a: Dissolved organic nitrogen in the surface water from 1995-2018.

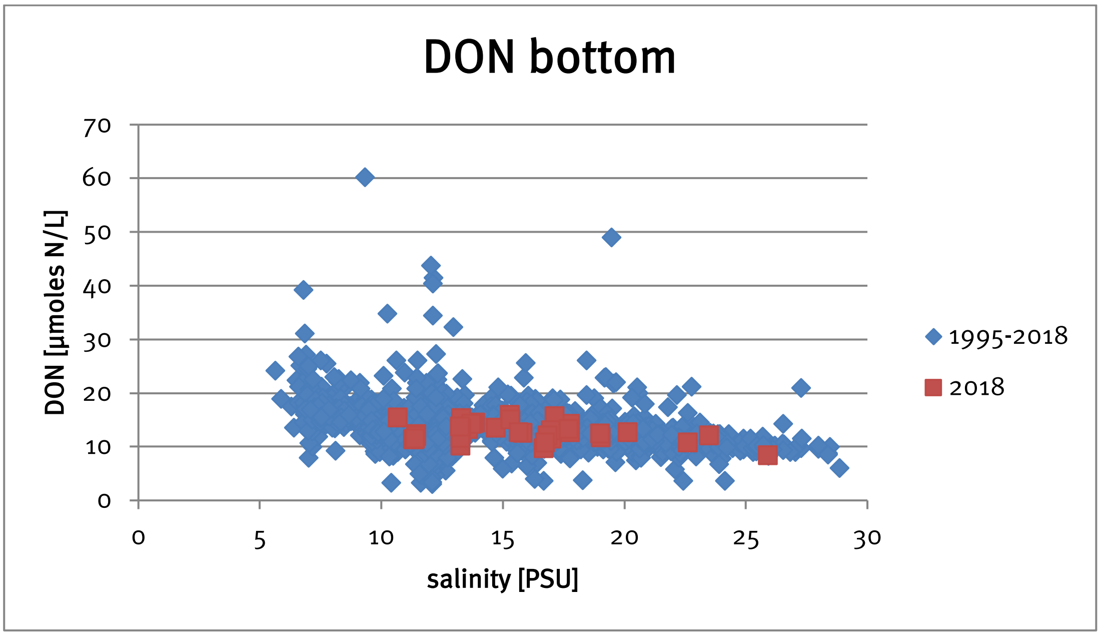


Fig. 37b: Dissolved organic nitrogen in the bottom water from 1995-2018.

The particulate carbon and nitrogen has 5-10 times lower levels than the dissolved forms (Fig. 38 a,b; 39 a,b). Higher variability reflects the seasonality of the biological production and remineralisation processes. The results from the year 2018 are in any parameter within the expected range.

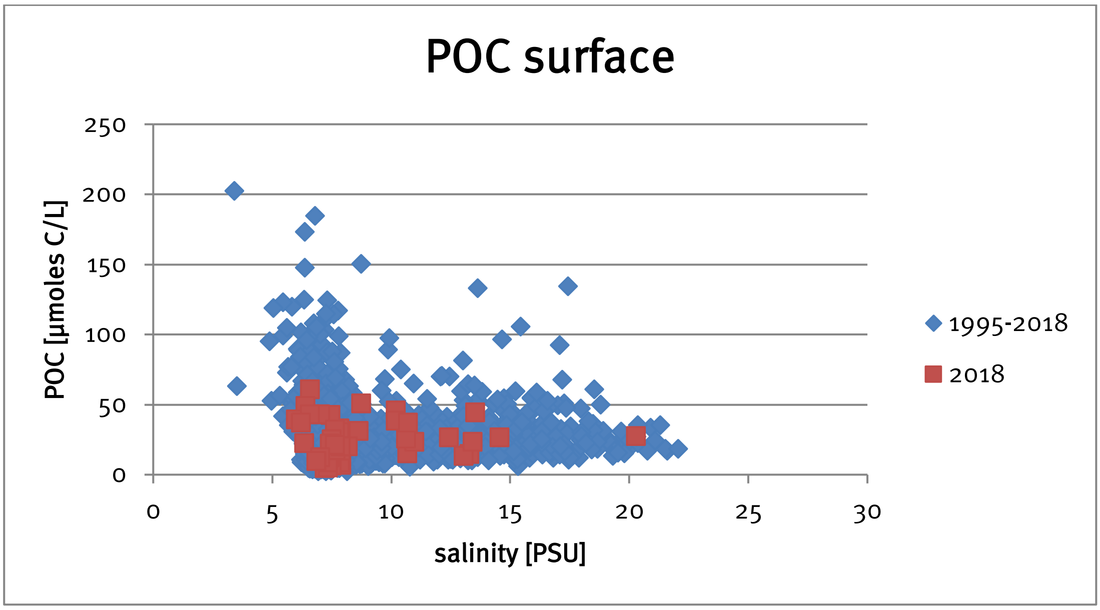


Fig. 38a: Particulate organic carbon in the surface water from 1995-2018.

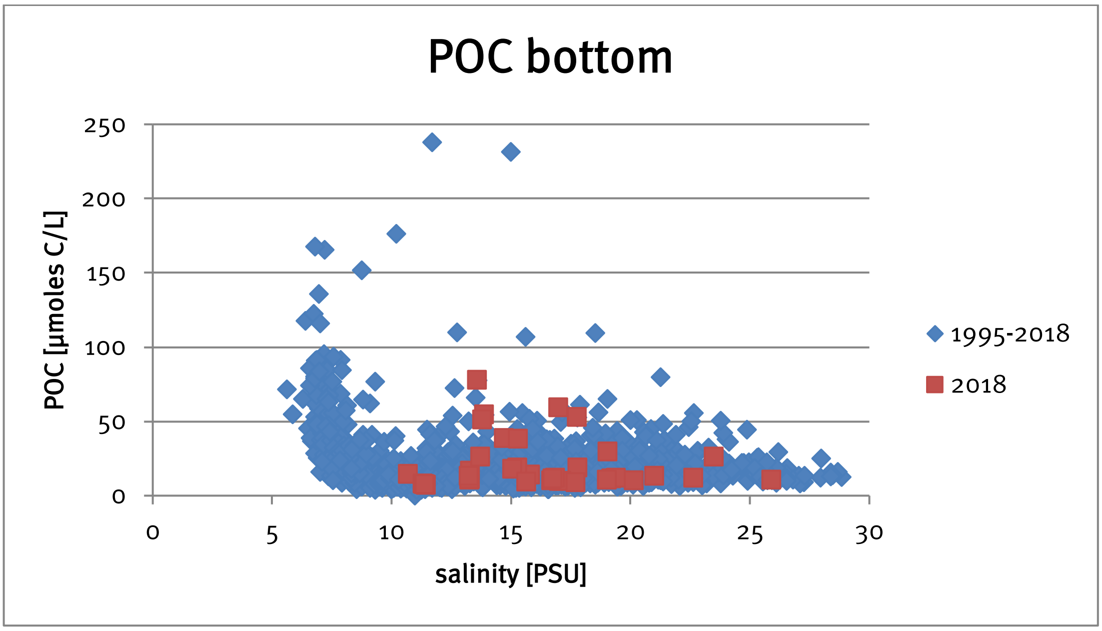


Fig. 38b: Particulate organic carbon in the bottom water from 1995-2018.

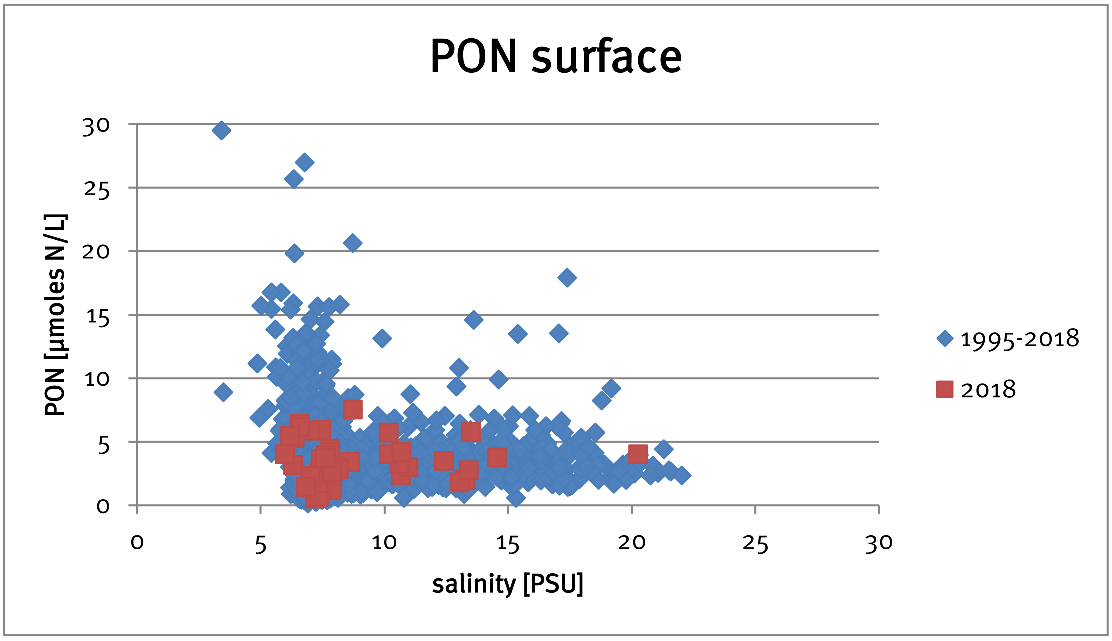


Fig. 39a: Particulate organic nitrogen in the surface water from 1995-2018.

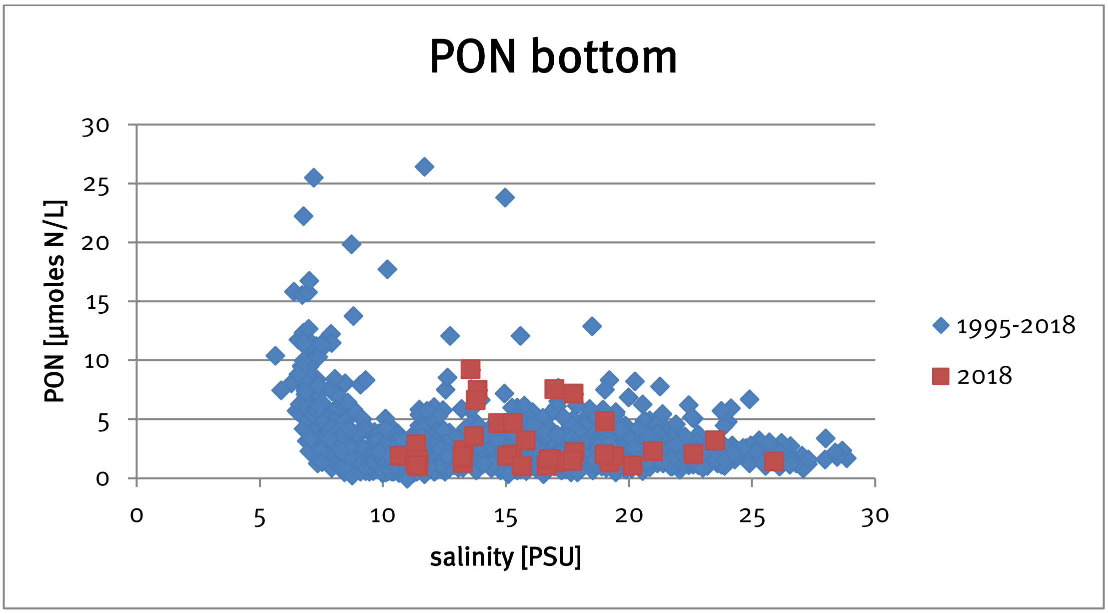


Fig. 39b: Particulate organic nitrogen in the bottom water from 1995-2018.

Stations

The seasonal DOC, DON and POC, PON changes at station MB, AB, BB and GB between February and November 2018 are shown in Figure 40, 41. Only the POC and PON data indicate the seasonality related to primary production during the year. The low increase in DOC during the year is due to the biological production during spring and summer time in the surface layer.

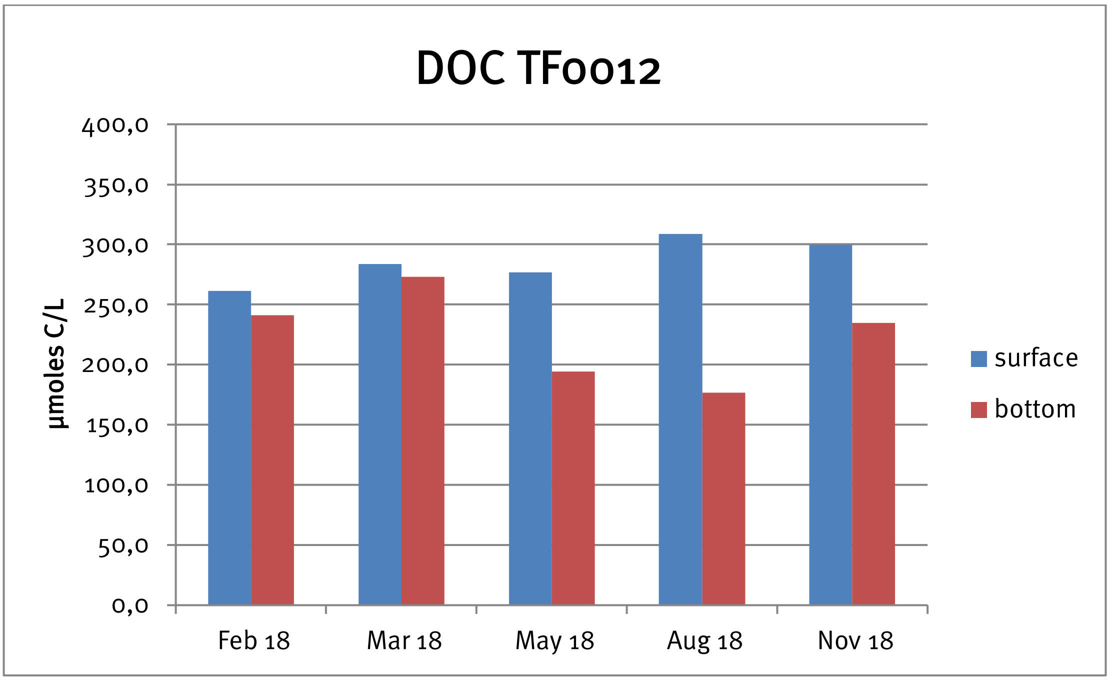


Fig. 40a: Surface (2m) and bottom (24m) dissolved organic carbon (µmol/l) at Station TF0012 in the Mecklenburg Bight

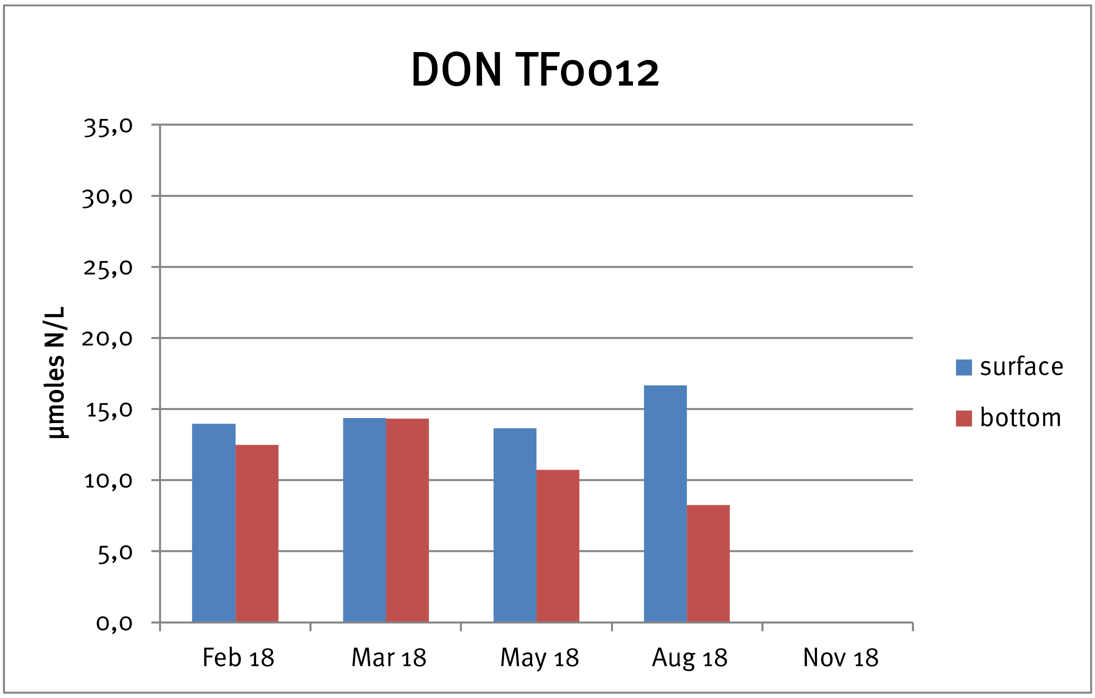


Fig. 40b: Surface (2m) and bottom (24m) dissolved organic nitrogen (µmol/l) at Station TF0012 in the Mecklenburg Bight

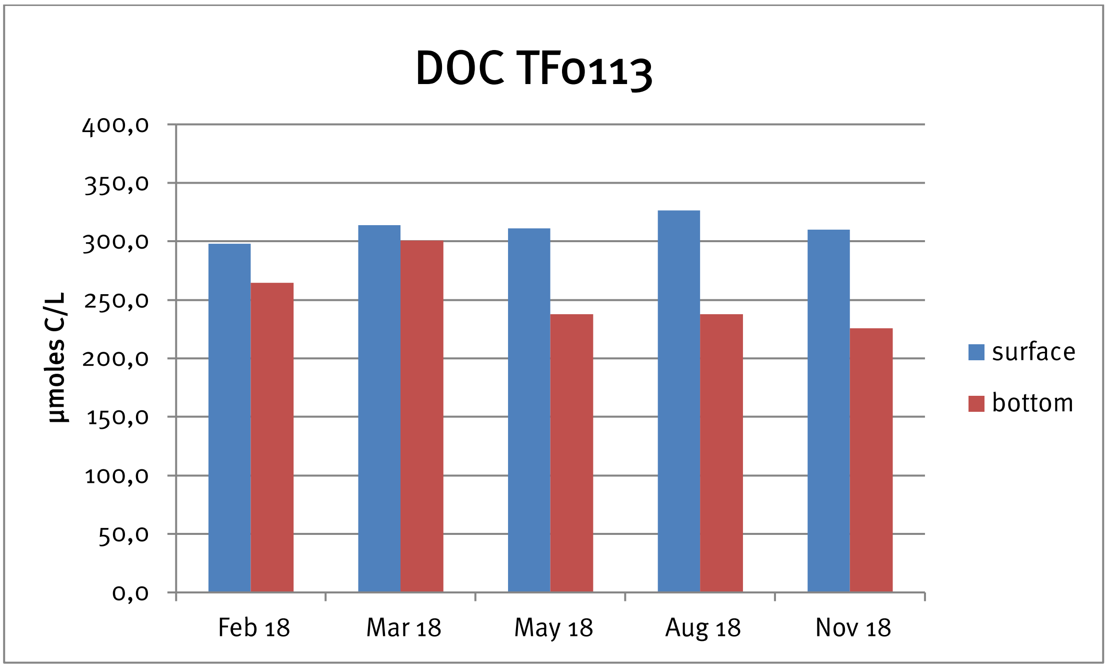


Fig. 41a: Surface (2m) and bottom (46 m) dissolved organic carbon (µmol/l) at Station TF0113 in the Arkona Basin.

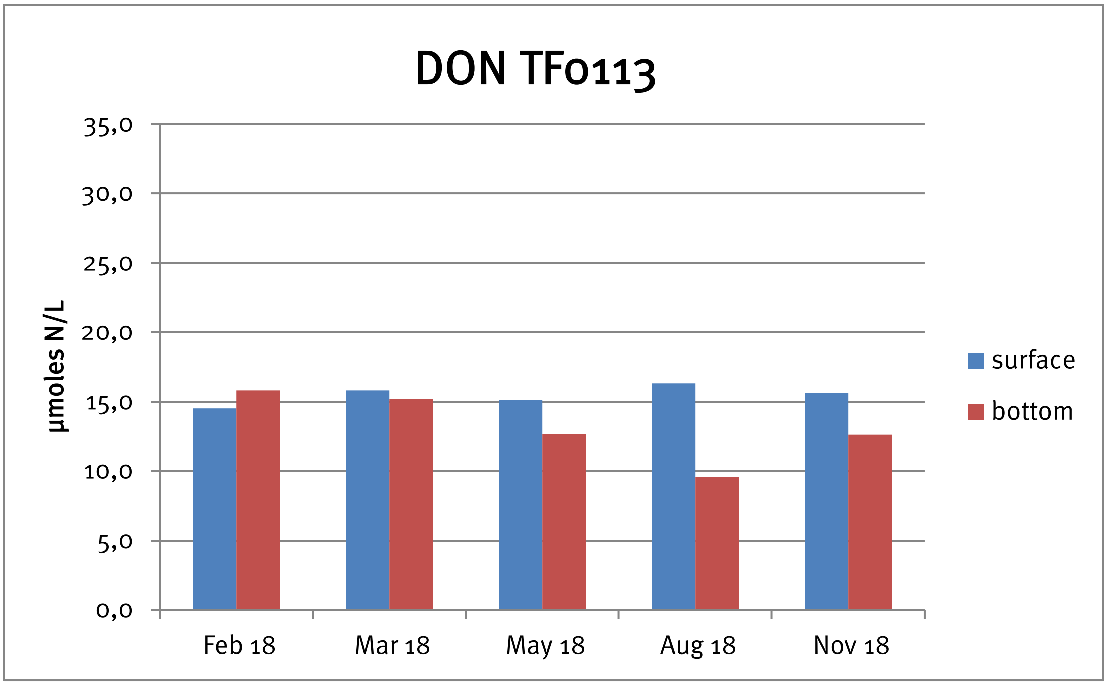


Fig. 41b: Surface (2m) and bottom (46 m) dissolved organic nitrogen (µmol/l) at Station TF0113 in the Arkona Basin.

The Bornholm Basin with its halocline at about 60 m has two separated water bodies. The surface water with lower salinities has relative stable DOC and DON concentration all over the entire year 2018, little variations are related to biological processes. The deep DOC concentration decreased from February to May and stayed stable for the rest of 2018. No more water exchange occurred, and the DON values have not changed significantly either.

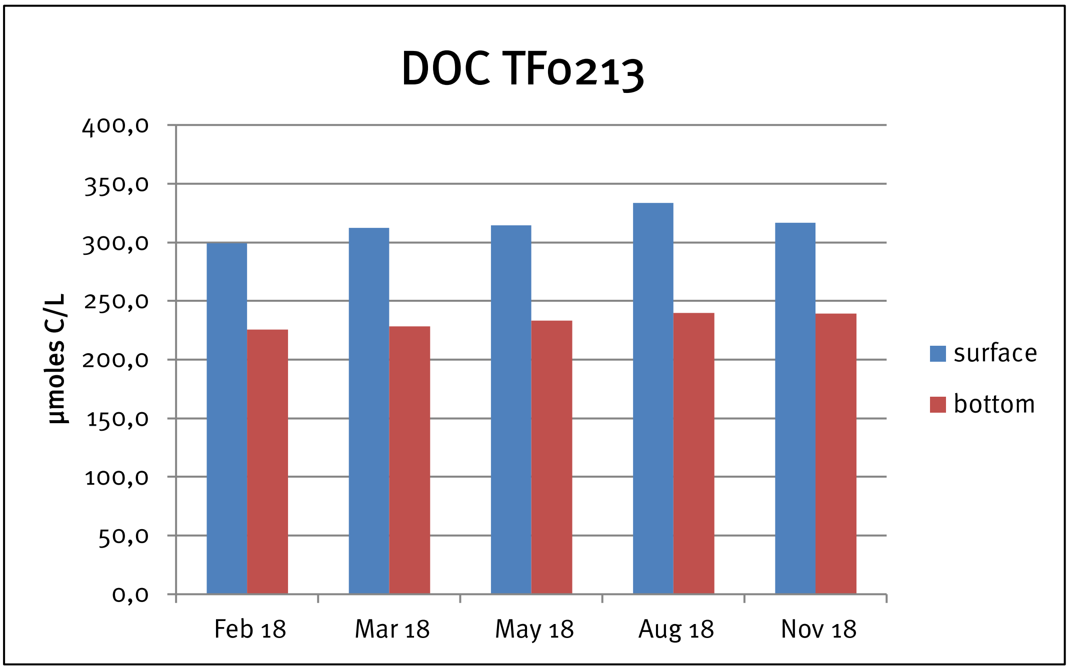


Fig. 42a: Surface (2m) and bottom (88 m) dissolved organic carbon (µmol/l) at Station TF0213 in the Bornholm Basin.

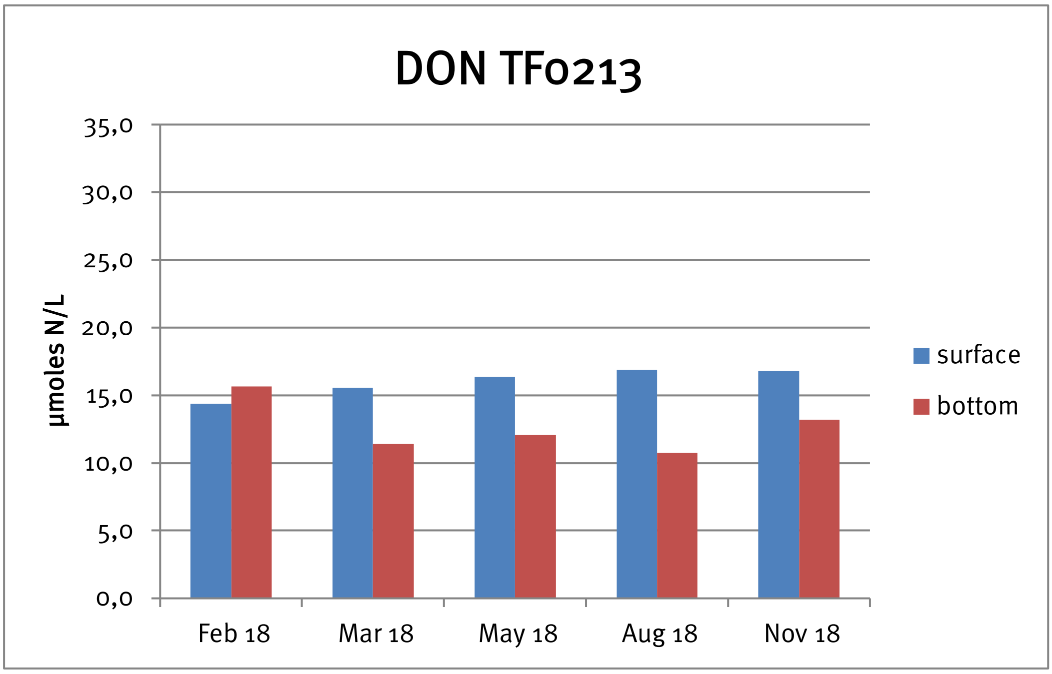


Fig. 42b: Surface (2m) and bottom (88 m) dissolved organic nitrogen (µmol/l) at Station TF0213 in the Bornholm Basin.

In 2018 the DOC and DON concentration did not change significantly, values nearly match those of the long-term measurements.

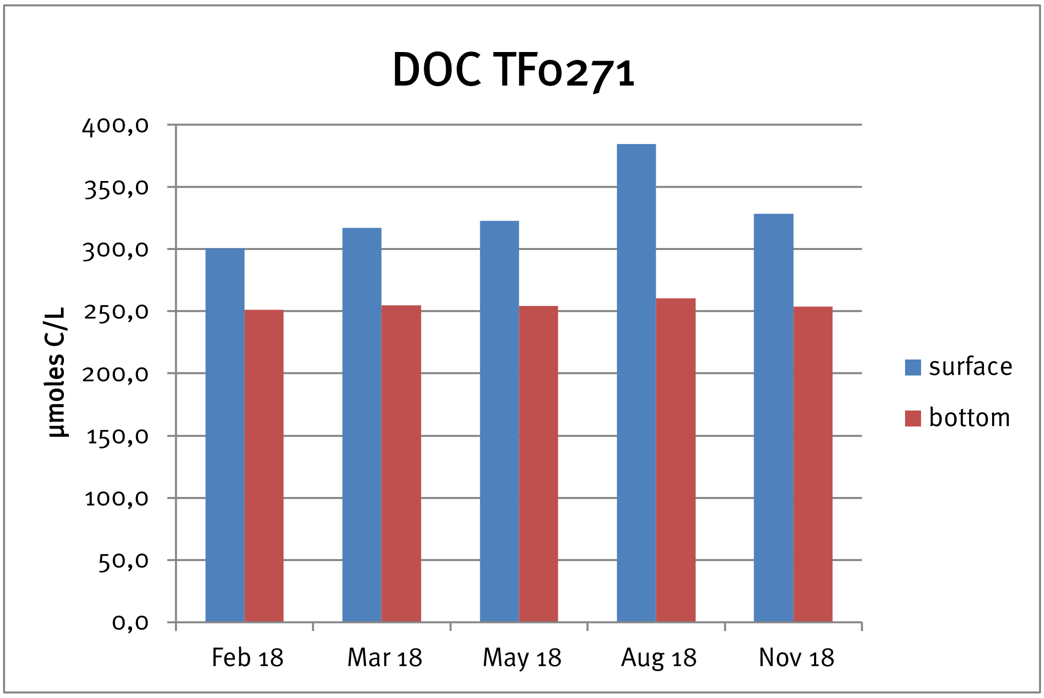


Fig. 43a: Surface (2m) and bottom (236 m) dissolved organic carbon (µmol/l) at Station TF0271 in the eastern Gotland Basin.

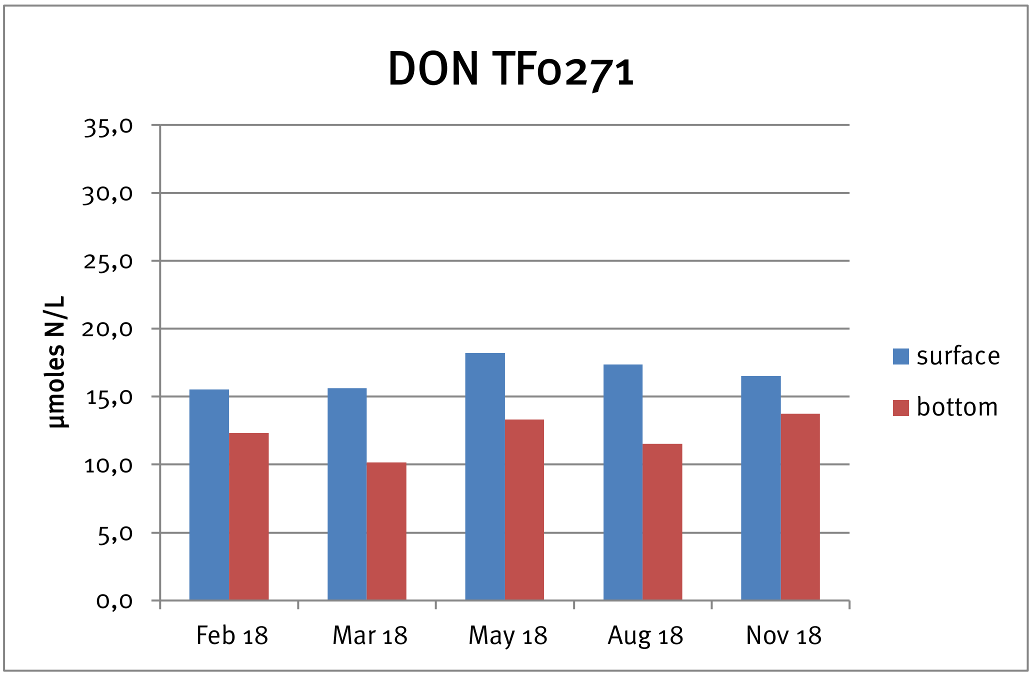


Fig. 43b: Surface (2m) and bottom (236 m) particulate organic nitrogen (µmol/l) at Station TF0271 in the eastern Gotland Basin.

Summary

For the southern Baltic Sea area, the cold sum of 67.7 Kd at Warnemünde station categorized the winter 2017/2018 as a mild one again. This value lies below the long-term average of 100.8 Kd in comparative data from 1948 onwards and ranks in the midrange as 34th warmest winter in this time series. Three longer cold periods of permanent frost occurred during February and March. All other winter months were mild showing cold sums far below the average.

With a warm sum of 395.5 Kd, measured at Warnemünde, the summer 2018 set a new record over the past 71 years. The value was twice as high as the long-term average of 153.4 Kd. In addition, the year 2018 was a very dry one, registering only 75 % of precipitation compared to the long-term mean. A period of 10 dry months occurred from February to November.

With respect to sea surface temperature, the year 2018 was as well the warmest year since 1990 and with 1.19 K far above the long-term SST average. March to August contributed to the average by extreme positive anomalies of up to 5 K. March and April showed negative anomalies due to the long lasting cold spell from February to March. The early winter months of the season 2017/2018 were 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 barotropic inflow events of weak intensity with estimated volumes between 215 km^3 and 233 km^3 occurred in the Baltic Sea in 2018. Near the bottom the salinity of the inflowing water only slightly exceeded 17 g/kg and was in mean around 15 g/kg. From September 12 to October 2, the sea level raised rapidly from -23.6 cm MSL to 44.8 cm MSL at station Landsort Norra, the annual top level. The inflow water comprised a total volume of 233 km^3. A second event of 215 km^3 occurred at the beginning of December, showing a sea level increase from -44.4 cm MSL to 16.3 cm MSL. In general, an annual mean wind speed of 6.5 m/s was registered, which is the lowest intensity since 1980. Long lasting calm periods of low easterly winds occurred during summertime inducing phases of baroclinic inflow events. Very warm surface water of the Kattegat area was imported to the Baltic deep water layer and a temperature increase of 3-5 K was registered in the deep basins.

The intermittent positive influence of the Major Baltic Inflow of December 2014 on the oxygen situation in the deep basins of the eastern Gotland and, less pronounced, to the western Gotland Sea basins was fading away. Meanwhile, mainly anoxic and euxinic conditions reappeared and have been intensified in 2018. This determined also the nutrient situation in the deep water of the northern and western Gotland Basin. In the eastern Gotland Sea the stagnation period has started 2016 and oxygen disappeared in 2017. Correspondingly, phosphate and ammonium concentrations were increasing since 2017 in the Eastern Gotland Sea basin. The annual average nitrate concentration indicates that oxygen is zero in all deep water areas by the end of 2018, with the Bornholm Sea showing a nitrate concentration of still 1.6 µmol/l in 2018 and a relatively low ammonium concentration of 1.9 µmol/l. Interestingly, the deep waters of the northern Gotland Sea that showed some positive oxygen values in 2017 seemed to be an intermediate source of nitrate to the deep waters of the eastern Gotland Sea early in 2018. The slow propagation of the MBI waters into northern, western and apparently also back into the eastern

Gotland Sea areas ceased in 2018. It still remains unexplained, why the oxygen supply of the strong MBI of 2014 declined so quickly.

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