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Hydrographic-hydrochemical assessment of the Baltic Sea 2015

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Content

Kurzfassung

Die Arbeit beschreibt die hydrographisch-hydrochemischen Bedingungen in der westlichen und zentralen Ostsee für das Jahr 2015. 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 19,8 Kd. Damit war der Winter 2014/15 sehr warm und belegt den 7. Platz der wärmsten Winter seit Beginn der Aufzeichnungen im Jahr 1948. Mit einer Wärmesumme von 182,3 Kd rangiert der Sommer im oberen Bereich der 68jährigen Datenreihe und reiht sich auf Platz 21 der wärmsten Sommer ein.

Die Situation in den Tiefenbecken der Ostsee war im Wesentlichen geprägt durch den großen Salzwassereinbruch vom Dezember 2014, der der drittgrößte jemals beobachtete war. Im Mai 2015 war die gesamte Wasserschicht im östlichen Gotlandbecken zwischen 140 m und dem Boden belüftet. Im Jahr 2015 wurden fünf weitere Einströme mit Volumina zwischen 141 und 270 km³ registriert. Zusammenfassend kann gesagt werden, dass in den letzten beiden Jahren verstärkt Wasseraustauschprozesse beobachtet wurden. Einige dieser Einströme erreichten die zentrale Ostsee und unterstützten die Effekte des großen Salzwassereinbruchs vom Dezember 2104 mit entsprechenden Konsequenzen für die biogeochemischen Kreisläufe.

Abstract

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

For the southern Baltic Sea area, the “cold sum” of the air temperature of 19.8 Kd in Warnemünde amounted to a very warm winter in 2014/15 and ranks as 7th warmest winter since the beginning of the record in 1948. The summer “heat sum” of 182.3 Kd is in the upper midrange over the past 68 years and ranks on place 21 of the warmest summers.

The situation in the deep basins of the Baltic Sea was mainly coined by the Major Baltic Inflow of December 2014 which was the third largest ever observed. In May 2015, the layer between 140 m and the bottom in the eastern Gotland Basin was completely ventilated. In 2015, inflow events with estimated volumes between 141 and 270 km³ occurred on five occasions. In conclusion, intensified water exchange processes were recorded in the last two years and some inflow pulses were able to reach the bottom water of the central Baltic Sea fostering the large Major Baltic Inflow of December 2014 with subsequent consequences for the biogeochemical cycles.

1. Introduction

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

Five routine monitoring cruises were undertaken in 2015 in all four seasons; additional observations were made in March and April. The data obtained during these cruises, as well as results from other research activities by IOW, form the basis of this assessment. Selected data from research institutions elsewhere in the region, especially the Swedish Meteorological and Hydrological Institute (SMHI) and the Maritime Office of the Polish Institute of Meteorology and Water Management (IMGW), are also included in the assessment. Fig. 1 gives the locations of the main monitoring stations evaluated; see NAUSCH et al. (2003) for a key to station nationality.

HELCOM guidelines for monitoring in the Baltic Sea form the basis of the routine hydrographical and hydrochemical monitoring programme within its COMBINE Programme (HELCOM, 2000). The monitoring cruises in February, March, May and November were performed RV *Elisabeth Mann Borgese*. The summer cruise in July/August took place on RV *Meteor* and was combined with several research projects. Details about water sampling, investigated parameters, sampling techniques and their accuracy are given in NEHRING et al. (1993, 1995).

Ship-based investigations were supplemented by measurements at three autonomous stations within the German MARNET environmental monitoring network. Following a general maintenance, the ARKONA BASIN (AB) station has been in operation again since June 2012. DARSS SILL (DS) station was also overhauled, and went back into operation in August 2013. The ODER BANK (OB) station was in operation from mid-March to mid-December 2015; it was taken out of service for a break over the winter of 2015/2016. See chapters 3-5 for details.

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

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

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

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

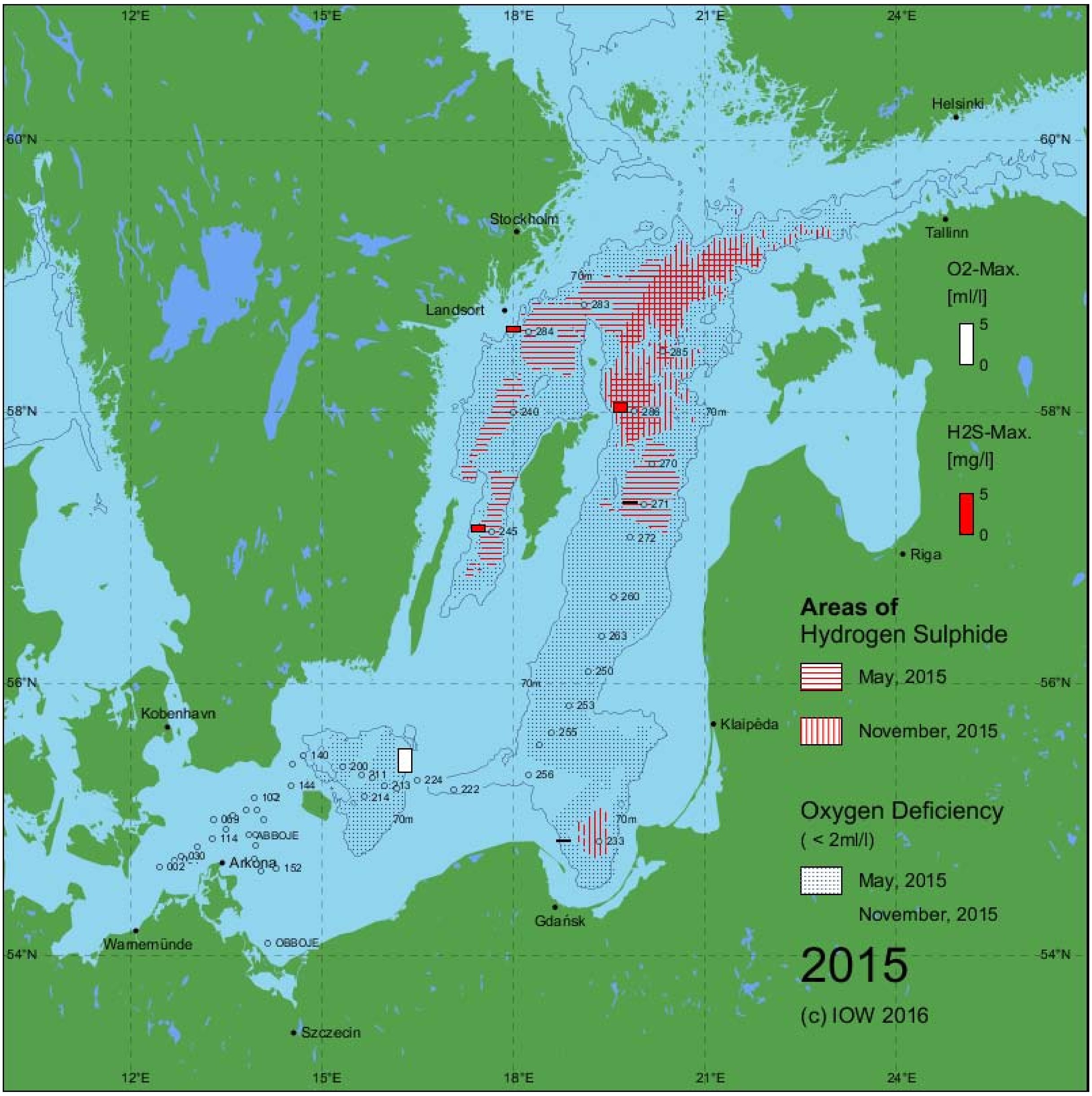


Fig. 1: Location of stations (■ MARNET- stations) and areas of oxygen deficiency and hydrogen sulphide in the near bottom layer of the Baltic Sea. Bars show the maximum oxygen and hydrogen sulphide concentrations of this layer in 2015; the figure additionally contains the 70 m -depth line

2. Meteorological Conditions

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

According to the analysis of DWD (DWD, 2015), 2015 was worldwide the warmest year since the beginning of extensive weather records in 1881, and for the German territory the second warmest together with the years 2000 and 2007. The mean annual temperature of 9.9°C was about 1 K higher than the average for 1981-2010 and 0.4 K lower than the previous year 2014. The year began with much too mild winter temperatures: along Germany's Baltic coast, January, February, March and April each exceeded the thirty-year mean by 1-1.7 K. These warm temperatures interrupted from May to July with balanced to slightly colder values than the thirty-year mean and August to December continued with warm temperatures well above the mean at the coast.

Across Germany, the amount of precipitation was 699 mm, 13 % below the average of 808 mm, and below 721 mm in 2014. In a regional comparison Schleswig-Holstein (883 mm) and Mecklenburg-Vorpommern (602 mm) showed values of 108 % and 98 % of their long term average for 1981-2010. The driest months were February and April.

The average annual sum of 1,743 hours of sunshine exceeded by 9 % the long-term average of 1,588 hours. The national ranking is led by Zugspitze station located in the Alps Mountains in southern Germany and followed by Arkona station (2,039 hours), the leader of the two previous years. January was the least sunny month: with an average of 35 hours, it was 31 % below the long-term average. Surprisingly in December, the sun shone 64 % longer than usual. The peak values belonged to the months of July and August: 254 and 246 hours respectively.

2.1 Ice Winter 2014/15

For the southern Baltic Sea area, the cold sum of 19.8 Kd at Warnemünde station amounted to a very warm winter in 2014/15 (Table 2). This value plots far below the long-term average of 103.6 Kd in comparative data from 1948 onwards and ranks as 7^{th} warmest winter in this time series. In comparison, Arkona station at 8.1 Kd (Table 3) is markedly lower, and even represents less than a quarter of the already warm winter 2013/14 (42.1 Kd). Given the exposed location of the north of the island of Rügen (it is surrounded by large masses of water), local air temperature developments are influenced even more strongly by the water temperature of the Baltic Sea (a maritime influence). In winter, milder values often occurred, depending on the temperature of the Arkona Sea, while in summer, the air temperature was more strongly suppressed compared with more southerly coastal stations on the mainland. Except for two shorter cold spells from 29th November to 3rd December 2014 and 1st to 6th February 2015 a very warm wintertime was recorded (Table 1). Overall, 34 days of slightly frost and only 2 days of ice were recorded at Arkona compared to 8 days and 20 days in the mild winter of 2013/14 (NAUSCH et al., 2015). The winter's warm temperature profile was also reflected in icing rates.

According to SCHMELZER (2015), this ice season in the Baltic Sea is classified as extremely weak. Given warm weather conditions, the maximum extent of ice was reached at 24th January 2015 with an area of 51 000 km². The Baltic Sea showed the second lowest ice coverage since the year 1720. The maximum extent of ice corresponded to some 12 % of the Baltic Sea's area (415 266 km²), and was largely centred on the northern half of the Gulf of Bothnia, marginal areas of the eastern Gulf of Finland (Newa Bight) as well as the Estonian coast between the mainland and the isles of Hiiumaa and Saaremaa. The south coast of the Baltic Sea remained free of ice. The value of 51 000 km² is far below values in recent years: 179 000 km² in 2011/12, 187 000 km² in 2012/13 and 95 000 km² in 2013/14. By some 24 %, it fell short of the average of 213 000 km² in the time series from 1720 onwards (Figure 2). By way of comparison, it also fell well short of the very low 30-year average of 156 000 km².

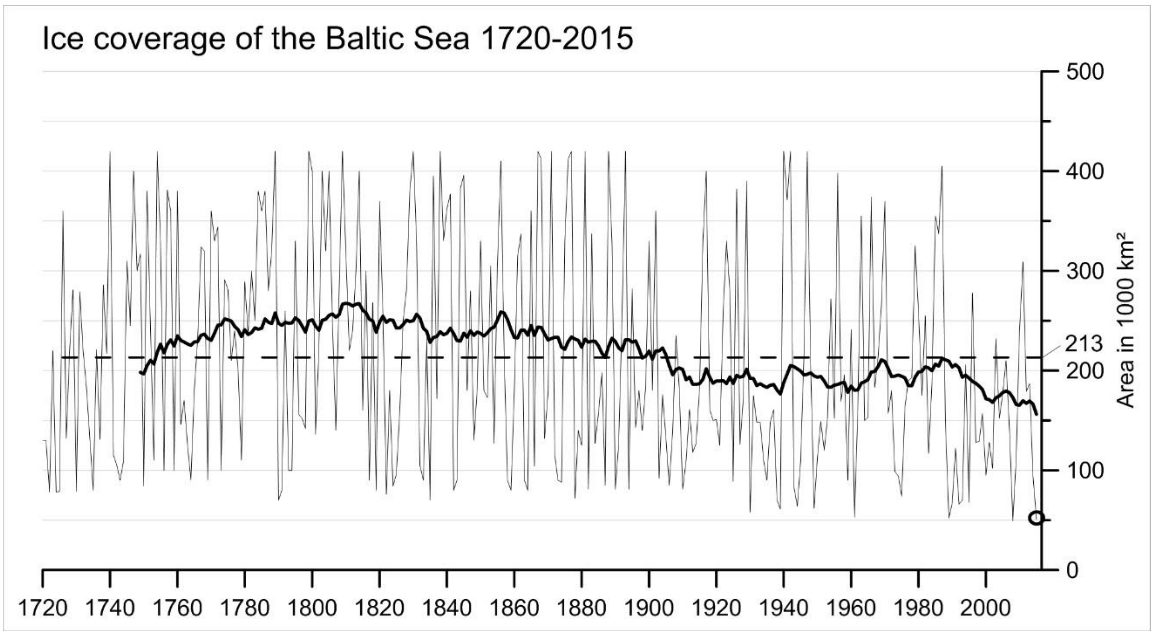


Fig. 2: Maximum ice covered area in 1000 km² of the Baltic Sea in the years 1720 to 2015 (from data of SCHMELZER et al., 2008, SCHMELZER, 2015). The long-term average of 213 000 km² is shown as dashed line. The bold line is a running mean value over the past 30 years. The ice coverage in the winter 2014/2015 with 51 000 km² is encircled.

Along Germany's Baltic Sea coast, local conditions were assessed as a very weak ice winter on the basis of an accumulated areal ice volume of 0.006 m (SCHMELZER, 2015). Besides various other indices, this index is used to describe the extent of icing, and was introduced in 1989 to allow assessment of ice conditions in German coastal waters (KOSLOWSKI, 1989, BSH, 2009). Besides the duration of icing, the extent of ice cover, and ice thickness are considered, so as to take better account of the frequent interruptions to icing during individual winters. The daily values from the 13 ice climatological stations along Germany's Baltic Sea coast are summed. The highest values yet recorded are as follows: 26.83 m in 1942; 26.71 m in 1940; 25.26 m in 1947; and 23.07 m in 1963. In all other winters, values were well below 20 m (KOSLOWSKI, 1989). At 0.006 m, the accumulated areal ice volume for winter 2014/15 is markedly lower than in previous years: 0.37 m in 2013/14, 0.38 m in 2012/13, 1.12 m in 2011/12 and 2.45 m in 2010/11. In the last hundred years only eleven winters showed similar icing in the western Baltic Sea. Only the inner river mouth of the Schlei and some sheltered areas along the Western Pomeranian lagoon chain recorded for some days icing. In the winter of 2014/15, an accumulated areal ice volume for the coast of Mecklenburg-Vorpommern and Schleswig-Holstein cannot be calculated. The number of recorded ice days was thus as follows: 1 at Rostock harbour; 17 ice days at the mouth of the river Schlei and 3 days at the Flensburg Fjord. More open German sea areas all remained ice-free, according to the BSH maritime data portal and SCHMELZER (2015).

2.2 Weather Developments in 2015

Over the course of 2015, pressure systems and air currents were prevailing from westerly to south-westerly directions (cf. Figures 4a, 5b, 6). At around 46 % of the annual sum, easterly winds greatly increased their share compared to the normal situation (cf. 4a, b). The Institute of Meteorology at FU Berlin has given names to areas of high pressure and low pressure since 1954; a sponsorship deal ('Wetterpatenschaften') has also been in place since 2002 (FU-Berlin, 2015).

January was dominated by a succession of Atlantic troughs that produced mild and stormy weather. Lows ('Bob', 'Klaudia', 'Daniel', gale 'Elon', gale 'Felix', 'Hermann', 'Jan', 'Kurt', 'Leonhard' and 'Mischka') moved across northern Europe. This phase of intensified westerly winds, especially the gales 'Elon' and 'Felix' (7^{th}-12^{th} January) with daily means of between 10-17.9 m/s and hourly maxima of 21.9 m/s caused a sea level rise at Landsort Norra to 64.5 cm MSL (mean sea level). At the second half of the month the wind situation calms down a bit and outflow occurred to 19.3 cm MSL before at the end of the month low pressure 'Mischka' raised the sea level again (Fig. 7a). The temperature profile for January revealed a high deviation of 1.7 K above the long-term average along Germany's Baltic Sea coast and showed a mean of 2.9°C. Sunshine duration in most areas of Germany was below average. At Arkona station, for instance, 89 % of the average duration was recorded (Table 1). The coast of Mecklenburg-Vorpommern recorded large amounts of precipitation (Arkona 164 %); in Schleswig-Holstein, values increased even more by around 98 %.

February began with the influence of low pressure "Mischka" over Scandinavia and westerly wind conditions. From 5^{th} to 20^{th} February the situation was changed by the high pressure cells

'Gabriela' over the British Isles moving to central Europe and later on 'Hanne' over Scandinavia. The wind situation calmed down and was turning between easterly, southerly and south-westerly directions. The sea level at Landsort Norra was falling from 43 cm MSL to -18.3 cm MSL (17th February). To the end of the month a through over central Europe was build and the low pressures 'Steffen', 'Thomas', 'Uli' and 'Winfried' circled around in the north. The mostly mild conditions continued during this month, with positive temperature anomalies of around 0.4 K along Germany's Baltic Sea coast, reduced precipitation at 35-77 % (Arkona station: 41 %), and again a record-high sunshine duration of more than half the usual value. At Arkona station, the same sunshine duration of 155 % was measured like in the February 2014.

In **March**, too, mild weather continued. The month started windy with daily means between 10-11.5 m/s where low pressures moved from the north Atlantic across Scandinavia ('Zacharias', 'Bardo', 'Carlo'). Afterwards high pressure was dominating over central and north-eastern Europe between 6th-23rd March ('Karin', 'Luisa', 'Maria' and 'Natascha') inducing easterly to south-easterly winds (Figure 5a, b). After a slightly inflow of water in the time span end of February to beginning March the sea level sunk rapidly from 19.8 cm MSL (11th March) to a lowstand -30.9 cm MSL (22nd March). Then this long lasting high pressure period shifted to a through over central Europe and cyclones moving across Scandinavia ('Isegrim', 'Jörg', 'Klaus', 'Lucien', 'Mike' and 'Niklas') which produced a smaller inflow pulse (Figure 7a). Along Germany's Baltic Sea coast, monthly averages deviated by 1.5 K. At the station Arkona a monthly mean of 4.4°C (1.6 K deviation) was measured. Across northern Germany it was too rainy, with amounts of precipitation between 113-127 % of the long-term average along the Baltic Sea coast. The average sunshine duration was 139 hours, 22 % higher than the long-term average of 114 hours (Arkona 118 %).

April started cool, stormy and rainy with ongoing influence of cyclones of the low pressures 'Niklas' and 'Peter'. Since 6th April high pressures 'Ostra' and 'Padma' moved from the British Isles across central Europe and the weather situation got calm and sunny. In the end of April low pressure 'Waldemar" and 'Vasco' were dominating, but the wind strength stayed below 5 Bft (daily means up to 8 m/s). The sea level rise starting in the end of March was going on with another small inflow pulse to a maximum level of 21.4 cm MSL. Together both smaller pulses showed a total volume of 161 km^3. Temperatures along Germany's Baltic Sea coast were some 0.4 K above the long-term average (Arkona 1.2 K). Amounts of precipitation varied greatly from area to area: in Schleswig-Holstein, it was more than 40 % too dry; in Rostock, it was 20 % too dry; at Arkona station, it was 42 % too dry; and in Ueckermünde on the Polish border, it was about 13 % too wet. An average of 225 hours of sunshine across Germany was 34 % above the long-term average. At Arkona station, it was about 18 % too sunny.

In **May**, the weather was mainly influenced by low pressure cells moving eastwards from the North Atlantic across northern Europe, bringing cool and moist air masses. High pressure 'Ulrike' located over northern Scandinavia interrupted this succession from 13th-15th May. Southern and central Europe was controlled by stable high pressure, causing mainly dry weather conditions in southern Germany. A disastrous event happened at the evening of May 5th where a tornado destroyed settlements on a 13 km long track in the south of Rostock. The city Bützow was hard affected, 30 people were injured and a material damage in an amount of two-digit million Euros was caused. During this month mainly moderate wind strengths were registered in the western Baltic Sea. At the station Arkona the daily means exceeded 10 m/s only at the 13th and 17th (Figure 5a). The sea level fluctuated only slightly between -4 cm MSL and 24 cm MSL (Figure 7a). Along the German Baltic Sea coast the air temperatures showed cold values of -0.6 K to -1.2 K below the long-term average. Only Arkona, influenced by the surrounding water masses, showed balanced temperatures (Table 1). Amounts of precipitation varied locally, for example Schleswig 53 % too rainy, Rostock -31 % to dry, Arkona 19 % to rainy, Ückermünde -8 % dry compared to the long-term average. Nationwide the sun shone 187 hours in mean, 9 % below the long-term mean of 205 hours. Arkona registered 267 hours (97 %).

The dominance of low pressure cells coming from the North Atlantic continued in **June.** The weather conditions turned out to be very changeable with short heatwaves accompanied with thunderstorms, hail, downpours and remarkable drops of temperature. The general wind situation was moderate below 8 m/s (4 Bft) and of westerly directions (Figure 5a, 5b), only at the third June a daily mean of 11.8 m/s was reached (low pressure ‘Kamil’). The sea level at station Landsort Norra varied again slightly between 0-20 cm MSL. The temperature at Arkona of 13.7°C was about -0.5 K lower than the long-term average for 1981-2010 and all other stations along the Baltic Sea coast showed similar values of about -0.5 K to -0.8 K below the average. Overall, June was too dry with 57 mm of precipitation (nationwide mean) compared to the long-term average of 77 mm (-26 %). Along the Baltic Sea coast the same situation is mirrored: -45 % in Schleswig, -32 % in Rostock, -33 % in Arkona and -38 % in Ückermünde. With 205 hours, sunshine duration was about 2 % slightly higher than the average of 202 hours. Arkona registered the national top value of 265 hours (105 %).

In the beginning of **July** the influence of high pressure continued (high ‘Annelie’) with hot temperatures above 30°C (Warnemünde: daily maximum of 34.9°C on 4th July). On 5th July the situation switched back to the dominance of low pressure cells coming from the North Atlantic and this lasted up to the end of the month. The ongoing moderate wind situation of the summertime was interrupted twice. Low pressure ‘Thompsen’ crossed the Baltic area from 8th to 10th July with a daily mean of 13.5 m/s and maximum gusts of 22.5 m/s (9 Bft). Temperatures cooled down drastically to maximum temperatures of 16°C and the sea level at Landsort Norra rose 22 cm by this storm event. From 26th to 27th July low pressure ‘Zeljko’ crossed the Baltic Sea bringing again western winds with daily means of 11 m/s and gusts up to 22.2 m/s. The sea level rose another 10 cm to a summer maximum level of 28.7 cm MSL (Figure 7a). Monthly temperatures varied across Germany with a warm south of 2-3 K above the long-term average of the years 1981-2010 and a cold northern part. Along the Baltic Sea coast the temperatures were on average slightly to cold. For example the station Arkona showed a value of 16.5°C (-0.6 K). The precipitation varied as well from a dry southern area to a wet north. The mean value of 73 mm rainfall was 12 % below the average of 83 mm. At the Baltic Sea the station Schleswig showed a too wet value of 31 % in contrast to Rostock with 2 % and 6 % were which recorded at Arkona. With 254 hours, sunshine duration was 12 % above the long-term average, while Arkona recorded 280 hours (101 %). The maximum of 306 hours was recorded in the south at station Straubing (Bavaria).

In **August** the classic summer weather returned. Extensive high pressure cells dominated the situation in central Europe and the Baltic area (highs 'Finchen', 'Gwendolin', 'Hildegard', 'Isabel' and 'Jessica'). For a period of three weeks the wind direction turned to the east and blew with moderate intensity up to 8 m/s (Figure 5a, 5b). In the time from 17th to 18th August the wind increased to daily means of 14.2 m/s and 12.5 m/s (maximum gusts up to 25.2 m/s, 10 Bft). This wind forcing caused an intensive outflow period to a sea level of -26.39 cm MSL at Landsort Norra, reached at 28th (Figure 7a). From the 25th August onwards the wind shifted back to south-western and western directions. Summery temperatures prevailed during the whole month, the mean value of 19.9°C was 2.4 K above the long-term average. At the German Baltic Sea coast values of 1.2 K at Schleswig, 1.3 K at Rostock, 0.7 K at Arkona and 2.2 K at the station Ückermünde above the average were reached. The amount of precipitation with 76 mm was only 1 % below the average of 77 mm. Areas in the north and the south were much more dry than central Germany. Along the Baltic Sea coast values varied from west to east (-11 % in Schleswig, -18 % in Rostock, -33 % in Arkona to -57 % in Ückermünde). Across Germany as a whole, sunshine duration was about 19 % (246 hours) above average at 206 hours. 296 hours were registered at Arkona (122 %), but the maximum of 301 hours (136 %) showed the station Fürstenzell (Bavaria).

September was characterised in the first days by low pressures over Central Europe changing to the influence of a stable high over Scandinavia ('Lajana', 9th – 11th). In the middle of the month troughs over western and central Europe occured. To the end the extensive highs 'Maybrit' and 'Netti' dominated the weather situation of the Baltic Sea. The daily means of wind strength increased to values between 5-9 m/s. From 5th to 6th September low pressure 'Jonas' crossed the area with daily means of 12.1 m/s and 11.6 m/s, gusts up to 24.4 m/s (upper 9 Bft) were registered at Arkona. After the lowstand of the Baltic Sea level to the end of August a smaller inflow pulse (sea level rise of 40.89 cm, volume of 141 km^3) was caused by these winds at the begin of the month (Figure 7a). Later on the sea level decreased a bit during the high pressure influence and fluctuated around -10 cm to 0 cm MSL. The monthly temperature of 13°C was a bit too cold by -0.5 K; 56 mm of rainfall was about 16 % below the average of 67 mm; at 140 hours of sunshine duration was also 6 % below the long-term average 1981-2010. In the south-west of the Baltic Sea area, temperatures were around the average of about -0.3 K to 0.3 K; in its western section, it was about 1 % too dry and in the east up to 31 %. Arkona registered rainfall of 51 mm meant it was about 9 % too dry there. In terms of sunshine duration, 211 hours (123 %) was recorded at Arkona, showing the nationwide maximum.

In **October**, a succession of extensive high pressure cells over Scandinavia and the British Isles (highs 'Netti', 'Oldenburgia', 'Quinta') controlled the weather situation with mild temperatures and moderate easterly winds (Figure 3b, 5b). The third long lasting outflow period in the course of the year occurred and lowered the sea level to a lowstand of -37.6 cm MSL (Figure 7a). On the 23rd October the situation changed and low pressure 'Uli' coming from the North Atlantic crossed the Baltic area. Westerly winds of strong intensity (daily mean: 11.1 m/s; gusts: 21.9 m/s) let the sea level rose by 27 cm to -10 cm MSL at Landsort Norra (Figure 7a). This first smaller inflow pulse showed a warm mean temperature of 12°C crossing the sills in the western Baltic Sea. A short phase of easterly winds at the end of the month lowered the sea level slightly to -24.9 cm MSL (Figure 3b, 7a). Stations along the Baltic Sea coast recorded monthly temperatures that on average were in a range between 0.5 K too warm and -0.7 K too cold. The nationwide average was 0.8 K too cold compared to the long-term mean of 1981-2010. At 46 mm, precipitation was 26 % below the average value of 63 mm; at 99 hours, sunshine duration was 8 % below average of 108 hours. Along the Baltic Sea coast precipitation varied between -37 % in Schleswig, -4 % in Rostock, -26 % Arkona, but Ückermünde was 15 % to wet. The sun shone at Arkona station 104 hours (89 %).

At the beginning of **November** a succession of 15 low pressure cells started, which were coming from the North Atlantic and crossed the Baltic area in a row (1.11. ‘Yorsch‘; 4.11. ‘Albert‘; 7.11. ‘BinRasheed‘; 9.11. ‘Carsten‘; 11.11. ‘Dieter‘; 12.11. ‘Eugen‘; 13.11. ‘Frank‘; 14.11. ‘Gunwald‘; 18.11. ‘Heini‘; 19.11. ’Iwan’; 20.11. ’Jürgen’, 21.11. ’Kunibert’; 25.11. ‘Lauritz’; 27.11. ‘Michel’; 30.11. ‘Nils’). Figure 3 shows the falling air pressure in the course of the month, the westerly wind direction and increasing wind strengths. At Arkona station 12 days showed daily means above 10 m/s and maximum gusts of 28.6 m/s (11 Bft) occurred at the 19th November. A rapid sea level rise of 77.5 cm was triggered (Figure 7a) and a next Major Baltic Inflow occurred after the large one of December 2014. The mean temperature of this inflowing water was around 10°C in the western Baltic and a bit cooler than the earlier small inflow pulse in October. Mild and moist air masses dominated the weather pattern and the nationwide mean temperature was with 7.5°C (3.1 K above the long-term average) the warmest value since the beginning of measurements. With 101 mm of rainfall, conditions were clearly much too wet, and were 52 % above the thirty-year mean of 66 mm. The average sunshine duration of 68 hours was 26 % higher than the average of 54 hours. Along the coast, too, the positive temperature anomaly of in mean 2.6 K matched the Germanys nationwide assessment. Arkona recorded only 120 mm of rainfall, 250 % of what is usual in November. The sunshine duration there was 38 hours, 30 % below average for 1981-2010.

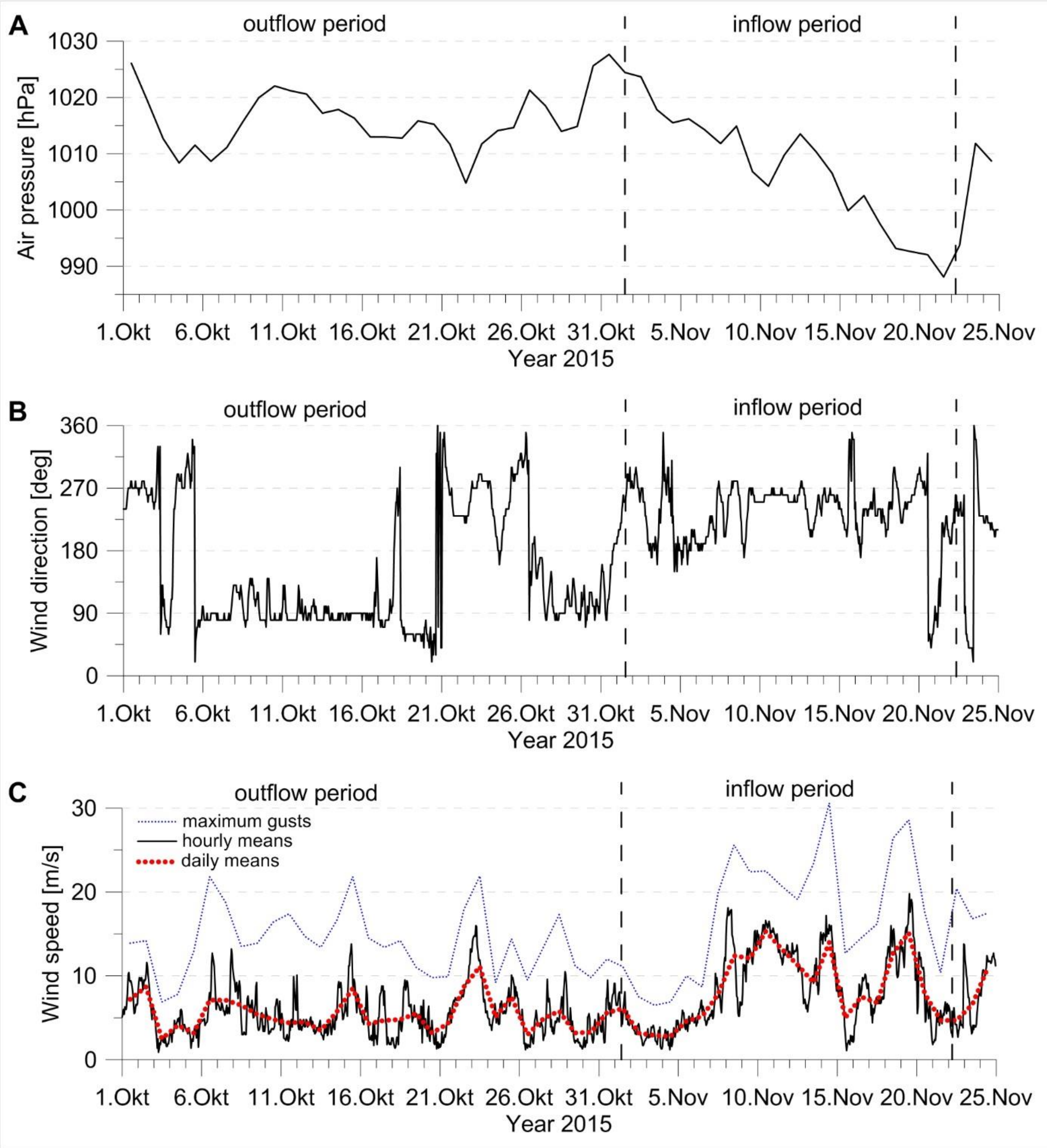


Fig. 3: Air pressure and wind conditions during October-November 2015 at the station Arkona with 15 stormy low pressures crossing the Baltic Sea in a row, a next Major Baltic Inflow happened from 14th to 22nd November (data: DWD, 2016). A) air pressure, B) wind direction, C) wind speed

After a very warm previous month this situation continued in **December**, showing an anomaly of 5.3 K it was again a new record since measurements started. Furthermore the Baltic area was dominated by crossing low pressure cells from the North Atlantic, while central and southern Europe were influenced by extensive high pressures ('Xena'; 'Yvonne'; 'Zita' and 'Brigitte'). After a short drop the sea level rose again up to the 11^{th} December by 42.7 cm (Figure 7a) and a next smaller inflow pulse followed the MBI of November. As a result of the wintery cooling down of water temperatures at the surface of the Kattegat, this inflowing water masses were again a bit cooler than the previous ones, showing a mean of 8°C. At 37 mm, precipitation was halfway too low compared to the average of 72 mm. The sunshine duration was nationwide at 65 hours (164 %). The German Baltic Sea coast followed this national trend of warm and dry weather. The temperature anomaly recorded at Arkona was 4.2 K, Rostock and Schleswig at 5.4 K and in Ückermünde 5.7 K. Rainfall varied strongly, with too wet values in Schleswig (106 mm; 134 %) and Arkona (81 mm; 188 %) as well as much too dry areas (Rostock: 39 mm; 80 %; Ückermünde: 34 mm; 83 %). Arkona registered a sunshine duration of 46 hours (121 %), but in the south of Germany at the mountain Zugspitze the maximum of 190 hours was measured.

2.3 Summary of Some of the Year's Significant Parameters

An annual sum of 382 800 J/m² of **solar radiation** was recorded at Gdynia. Lying in 22^{nd} place in the upper mid range of a series of comparative data begun in 1956 (FEISTEL et al., 2008), this value is higher than the long-term average of 373 754 J/m², on a level with 2010. The sunniest months were June and July. At 59 506 J/m², June comes in the mid range in the long-term comparison (Table 1), but still fell well short of the peak value of 80 389 J/m² in July 1994, which represents the absolute maximum of the entire series. The year's lowest value was 4755 J/m² in December, lying in sixteenth place above the long-term average of 4361 J/m².

With a **warm sum** of 182.3 Kd (Table 2), recorded at Warnemünde, the summer 2015 is ranked in the upper midrange over the past 68 years on 21^{st} position and far below the previous year of 236.9 Kd on 10^{th} place. The 2015 value exceeds the long-term average of 151.3 Kd, but is within the standard deviation, meaning that the year can be classed as an ordinary one. Average monthly temperatures in July and August were above the long-term average, whereas all other months showed values below the average. Especially August was far above and is ranked as 7^{th} warmest in the time series since 1948.

With a **cold sum** of 19.8 Kd in Warnemünde, the winter of 2014/15 is the seventh warmest winter in the long-term data series. The months December to March were all far too warm and November and April showed balanced values compared with the average (Table 2). January 2015 was exceptional warm with a cold sum of 0 Kd, leading together with the years 1975, 1983 and 1988 the ranking since 1948.

Table 1: Monthly averaged weather data at Arkona station (Rügen Island, 42 m MSL) from DWD (2015). *t*: air temperature, **Δ***t*: air temperature anomaly, *h*: humidity, *s*: sunshine duration, *r*: precipitation, Frost: days with minimum temperature below 0°C, Ice: days with maximum temperature below 0°C. Solar: Solar Radiation in J/m² at Gdynia station, 54°31‘ N, 18°33‘ O, 22 m MSL from IMGW (2016). Percentages are given with respect to the long-term mean. Maxima and minima are shown in bold

Month	*t*/°C	Δ*t*/K	*h*/ %	*s*/ %	*r*/ %	Frost	Ice	Solar
Jan	2.9	1.7	89	89	164	**11**	-	5021
Feb	**2.1**	1.0	86	**155**	**41**	**11**	**1**	12606
Mrz	4.4	1.6	85	118	127	**1**	-	24342
Apr	7.2	1.2	81	118	58	-	-	44165
Mai	10.4	0.0	82	97	119	-	-	57887
Jun	13.7	-0.5	80	105	67	-	-	**59506**
Jul	16.5	**-0.6**	**79**	101	106	-	-	59203
Aug	**18**	0.7	83	122	67	-	-	58992
Sep	14.8	0.7	80	123	91	-	-	31833
Okt	10.5	0.5	83	89	74	-	-	18694
Nov	7.5	2.0	**90**	**70**	**250**	-	-	5796
Dez	6.5	**4.2**	86	121	188	2	-	**4755**

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

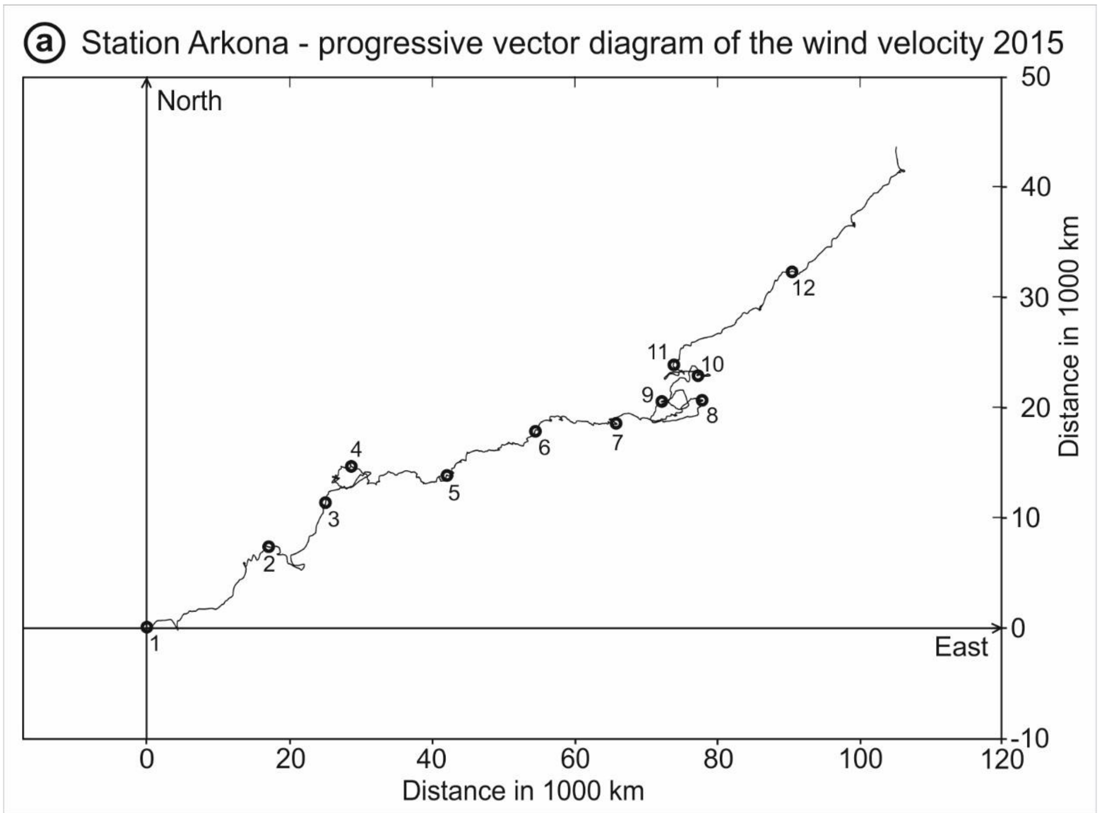
Monat	KS 2014/15	Mittelwert	Monat	WS 2015	Mittelwert
Nov	3	2.5 ± 6.2	Apr	0	1.0 ± 2.5
Dez	12.4	21.7 ± 28.0	Mai	0	5.6 ± 6.8
Jan	0	39.5 ± 39.5	Jun	13.4	23.1 ± 14.6
Feb	4.4	31.4 ± 38.1	Jul	65.4	57.3 ± 36.4
Mrz	0	8.5 ± 12.0	Aug	96.7	52.3 ± 31.9
Apr	0	0 ± 0.2	Sep	6.8	11.5 ± 12.0
			Okt	0	0.4 ± 1.2
Σ 2014/2015	19.8	103.6 ± 85.6	Σ 2015	182.3	151.3 ± 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 $t = 16°C$

Monat	KS 2014/15	Monat	WS 2015
Nov	0	Apr	0
Dez	4.3	Mai	0
Jan	0.9	Jun	3
Feb	2.9	Jul	33.1
Mrz	0	Aug	63.2
Apr	0	Sep	4.7
		Okt	0
∑ 2014/2015	8.1	∑ 2015	104

Figures 4 to 6 illustrate the **wind conditions** at Arkona throughout 2015. Figure 4 illustrates wind developments using progressive vector diagrams in which the trajectory develops locally by means of the temporal integration of the wind vector. For the 2015 assessment (Figure 4a), the long-term climatic wind curve is shown by way of comparison (Figure 4b); it was derived from the 1951-2002 time series. The 2015 curve (107 000 km eastwards, 44 000 km northwards) roughly follows the curve for the climatic mean (52 000 km eastwards, 25 000 km northwards), but showed doubled distances. This can be attributed to the dominating west to southwest winds during the year (Figure 5b, 6). According to the wind-rose diagram (Figure 6), these winds account for about 70 % of the annual sum; easterly winds for a further 20 %. The mean wind speed of 7.2 m/s (Figure 5a) just falls short above the long-term average of 7.1 m/s (HAGEN & FEISTEL, 2008). Comparing the east component of the wind (positive westwards) with an average of 3.3 m/s (Figure 5b) with the climatic mean of 1.7 m/s (HAGEN & FEISTEL, 2008), the intensified westerly winds become clear. With an average speed of 1.38 m/s, the north component of the wind (positive southwards) shows an increased value over the long-term average of 0.8 m/s. As a result of frequent changes in the direction of the wind and low intensity, the curve for 2015 shows strong wind vector compensation for the months August to October compared with the average for 1951-2002 (Figure 4a, b). The trend towards prevailing SW winds that began in 1981 and continues today (HAGEN & FEISTEL, 2008) is evident over the year.

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



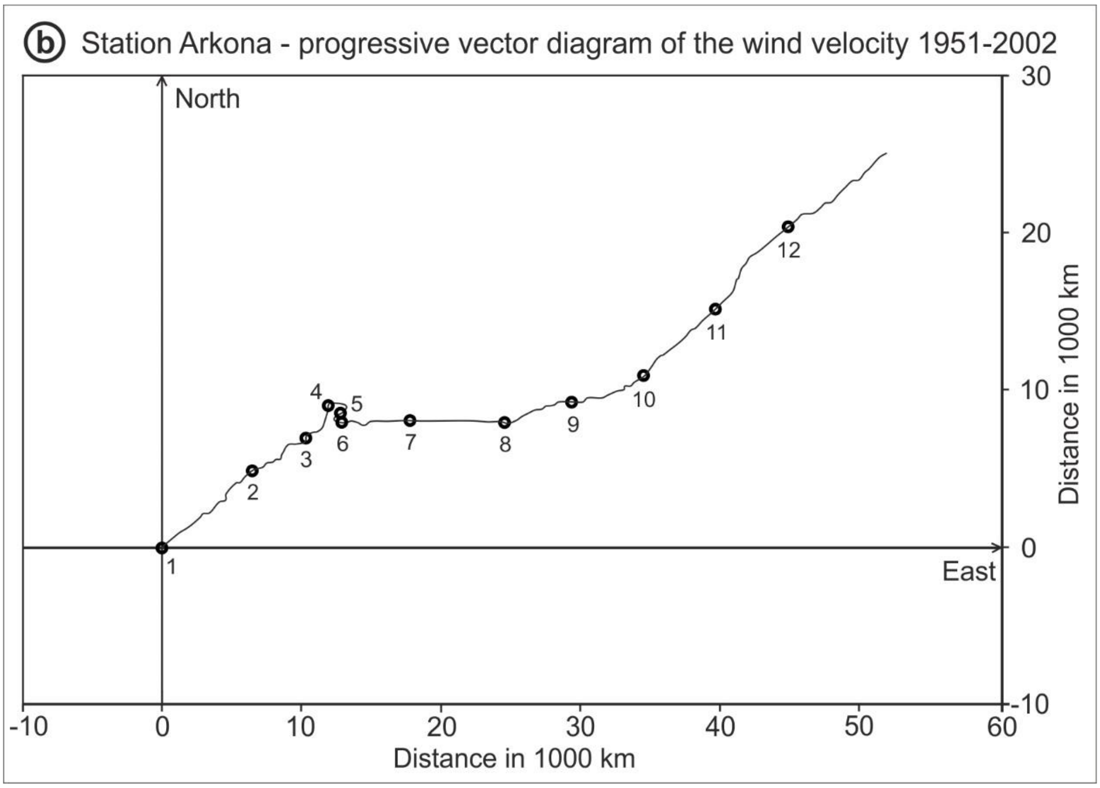


Fig. 4: Progressive vector diagram of the wind velocity at the weather station Arkona, distance in 1000 km, positive in northerly and easterly directions. The first day of each month is encircled. a) the year 2015 (from data of DWD, 2016) b) long-term average

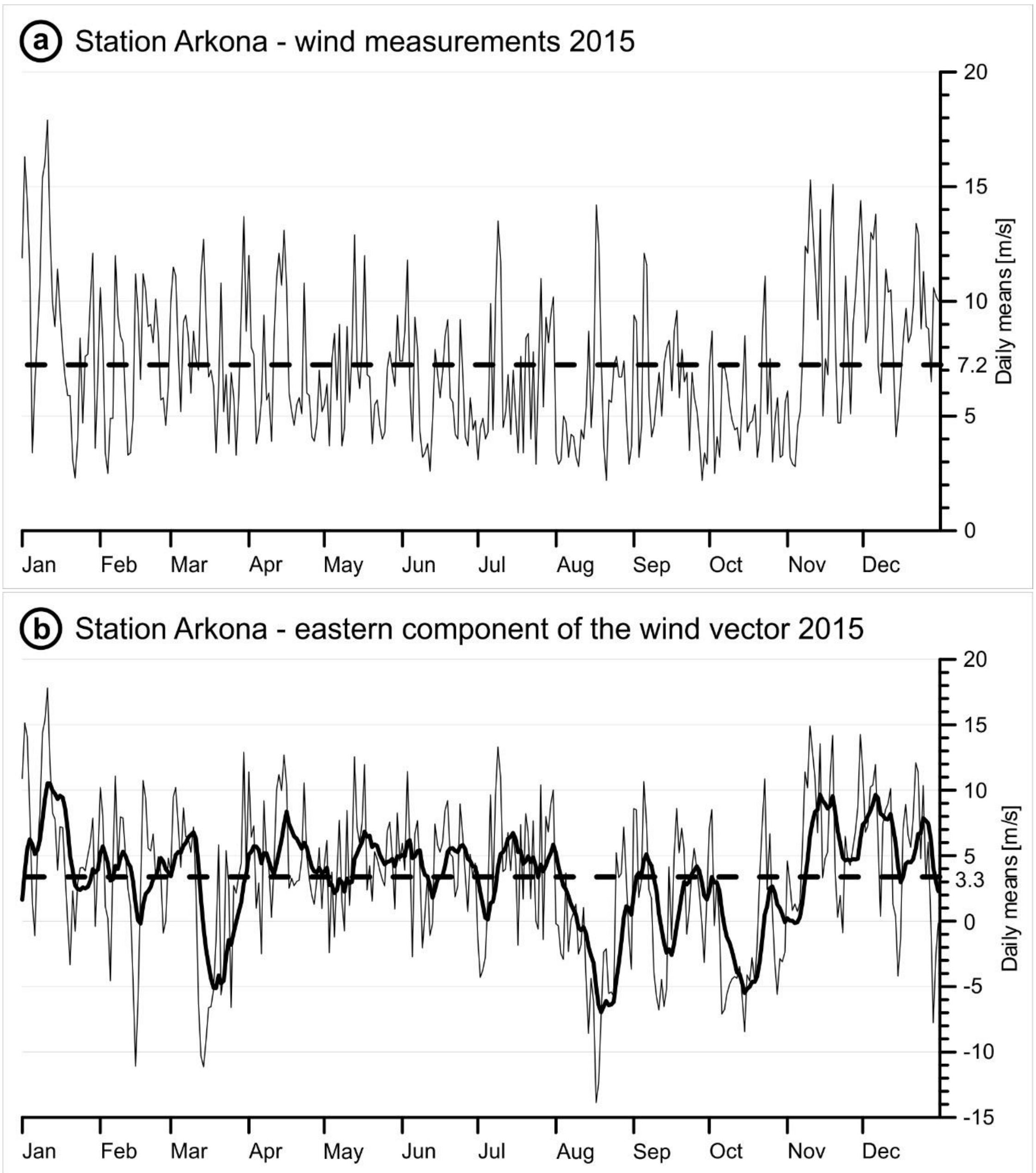


Fig. 5: Wind measurements at the weather station Arkona (from data of DWD, 2016). a) Daily means of wind speed, in m/s, the dashed line is the annual average of 7.2 m/s. b) Daily means of the eastern component (westerly wind positive), the dashed line is the annual average of 3.3 m/s. The line in bold is filtered with a 10-days exponential memory.

Wind development in the course of the year reveals rather an unusual distribution of stronger winds, as daily averages of more than 10 m/s (>5 Bft) were often exceeded, even in the summer months from May to August (Figure 5a). January 11th (gale "Elon") showed the greatest daily average of 17.9 m/s from western direction, with gusts up to 28.3 m/s. The annual mean wind speed of 7.2 m/s is slightly higher than 2014's 6.7 m/s (NAUSCH et al., 2015). Previous years showed following annual mean values of 7.0 m/s (2013), 7.1 m/s (2012) and 7.3 m/s in the year 2011 (NAUSCH et al., 2012, 2013, 2014). Maximum wind speeds in excess of 20 m/s (>8 Bft) were recorded as hourly means only in the night of 10th-11th January and in the late evening of 21st March. In 2014 this value was exceeded only on 9th January (NAUSCH et al., 2015). From 9th to 12th January, the gale "Elon" swept across the Baltic Sea from the west, reaching a top speed of 21.9 m/s – a value falling well short of previous peak values in hourly means of 30 m/s in 2000; 26.6 m/s in 2005; and 25.9 m/s (hurricane 'Xaver') in December 2013. This is clearly illustrated by the wind-rose diagram (Figure 6) in which orange and red colour signatures indicating values greater than 20 m/s did only slightly occur.

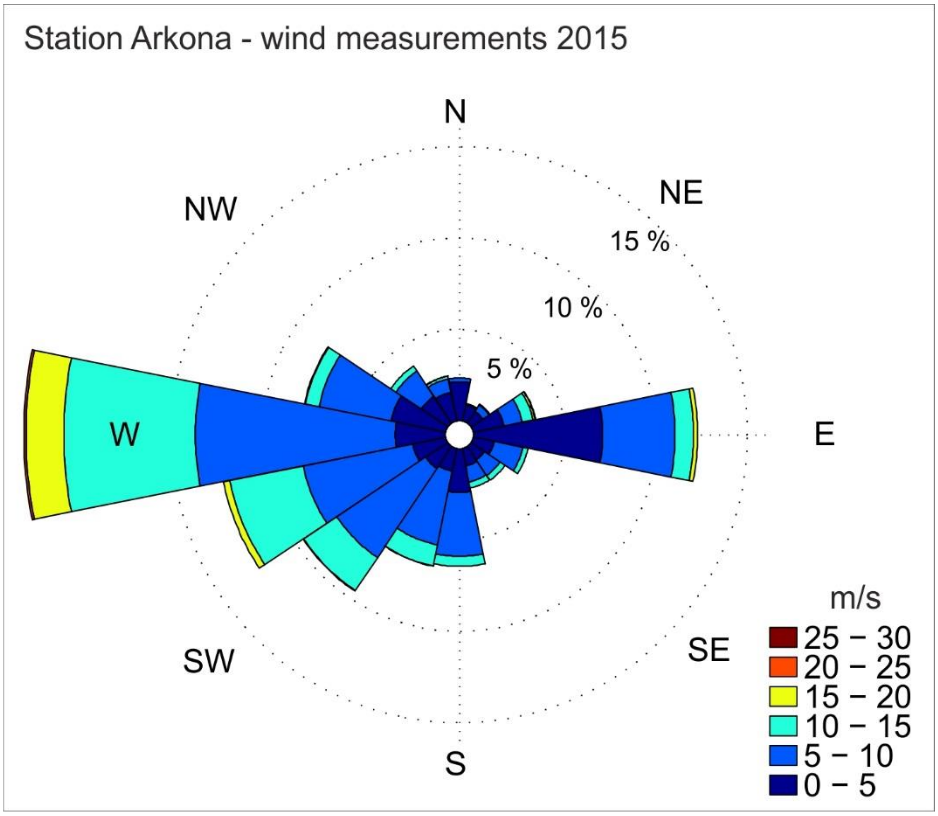


Fig. 6: Wind measurements at the weather station Arkona (from data of DWD, 2016) as windrose plot. Distribution of wind direction and strength based on hourly means of the year 2015

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

In the course of 2015, the Baltic Sea experienced five inflow phases with volumes estimated between 141 km³ and 270 km³. Rapid increases in sea level that are usually only caused by an inflow of North Sea water through the Sound and Belts are always of special interest here. Such rapid increases are produced by storms from westerly to north-westerly directions, as the clear correlation between the sea level at Landsort Norra and the filtered wind curves illustrates (Figures 5b, 7b). Filtering is performed according to the following formula:

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

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

Early in the year on 11th January, the gauge at Landsort Norra recorded a high water mark of 64.5 cm MSL (Figure 7a) as a result of gale-force winds of deep pressure "Elon" and the shortly preceeding large Major Baltic Inflow of December 2014 (NAUSCH et al., 2015; MOHRHOLZ et al. 2015). The short inflow phase induced by gale "Elon" and gale "Felix" raised the sea level from 19.9 cm MSL to 64.5 cm MSL in the time span 7th to 12th January by 44.6 cm. With the empirical approximation formula:

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

(NAUSCH et al., 2002; FEISTEL et al., 2008), it is possible using the values of the difference in gauge level ΔL in cm and the inflow duration Δt in days to estimate the inflow volume ΔV. The increase in sea level from 7th to 12th January thus yields a volume of 162 km³. After a phase of dominating outflow the tide gauge station Landsort Norra registered a lowstand of -30.9 cm MSL at 22nd March. A next inflow phase of two pulses occurred up to 17th April and sea level rise of 51.41 cm brought again a volume of about 161 km³ into the Baltic Sea. During the summertime the sea level variations were low between 0-20 cm MSL. In August a next outflow period occurred persisting easterly winds (c.f. Figure 5b, 7a) and a lowstand of -26.39 cm MSL was reached at 28th. Afterwards the situation shifted back to westerly winds and deep pressure "Jonas" induced the next smaller inflow of 141 km³ (28th August – 8th September) and its effects can be seen in the Arkona Basin (c.f. Chapter 4). A next longer period of easterly winds followed in the beginning October. Outflow occurred again and the lowest sea level of the year was reached at 15th October (-37.6 cm MSL). The end of the year was dominated by an intensed inflow phase of some smaller pulses and a next Major Baltic Inflow of moderate intensity. From 1st to 19th November the sea level rose by 77.5 cm at Landsort Norra (-24.99 to 52.51 cm MSL) indicating a total volume of about 270 km³. Salinity and current velocity data of the MARNET stations at the Darss Sill and in the Arkona Basin in the western Baltic Sea showed a main inflow period from 14th to 22nd November, where highly saline water (>17 g/kg) was transported over the sills. A salt transport rate of 1.5 Gt and highly saline water volume 76 km³ was derived. Smaller pulses in the end of October and beginning December surrounded this event. The propagation of this three inflow pulses occurring in autumn and early winter can be traced nicely by their water temperature, showing mean temperatures of about 12, 10 and 8°C (October, MBI in November and December event). In conclusion are intensified water exchange processes recorded in the last two years and some inflow pulses which were able to reach the bottom water of the central Baltic Sea followed the large event of December 2014 (MOHRHOLZ et al., 2015; NAUMANN, 2016; NAUMANN et al., in review).

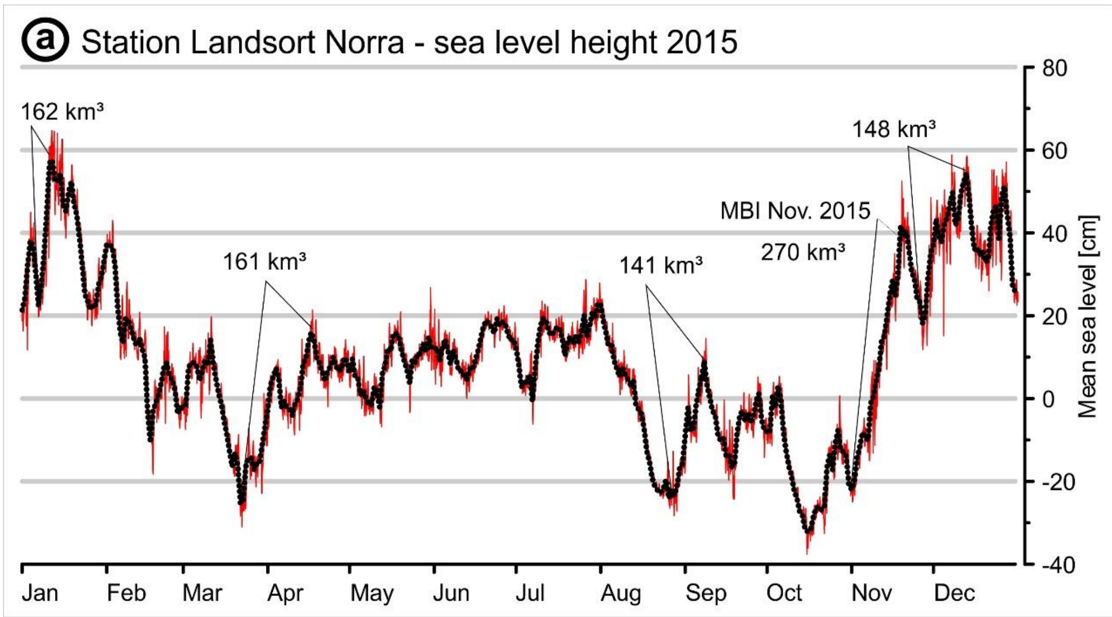


Fig. 7a: Sea level at Landsort as a measure of the Baltic Sea fill factor (from data of SMHI, 2016)

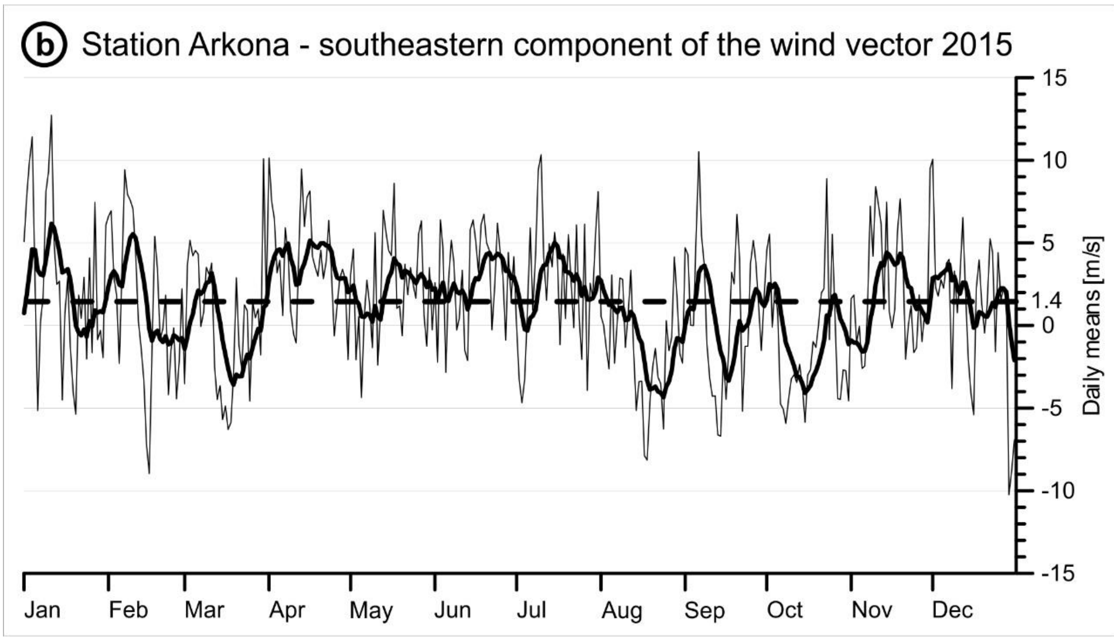


Fig. 7b: Strength of the southeastern component of the wind vector (northwesterly wind positive) at the weather station Arkona (from data of DWD, 2016). The bold curve appeared by filtering with an exponential 10-days memory

3. Water Exchange through the Entrances to the Baltic Sea/ Observations at the Measuring Platform "Darss Sill"

While the monitoring station at the Darss Sill had been supplying complete time series of all parameters during the year 2014, technical problems resulted in substantial data gaps in 2015. Due to difficulties during the deployment of the platform's instrument chain on one of the regular maintenance cruises in March, the sensors were accidentally not positioned at the correct water depths, and therefore, although continuously recording, provided data only at some unspecified water levels in the surface layer. This resulted in corrupted data for temperature, salinity, and oxygen from 11th March to 27th April. No ADCP data are available for the period from 20 May to 25 June due to a malfunctioning of the instrument. Beyond these data gaps, however, all instruments recorded complete time series. As usual, in addition to the automatic oxygen readings taken on the observation mast, discrete comparative measurements of oxygen concentrations were taken at the depths of the station's sensors by means of the Winkler method (cf. GRASSHOFF et al., 1983); the oxygen readings were corrected accordingly.

3.1 Statistical Evaluation

Due to the large contiguous data gap of more than 1.5 months (see above), a reliable statistical analysis could not be performed for the year 2015. The corresponding Tabs. 4 and 5, as well as Figs. 8 and 9, that are standard components of this report, are nevertheless supplied for completeness. Some of the characteristics of the time series will be discussed in the following sections.

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

	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	-	-	-	-	-	-

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

	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	–	–	–	–	–	–

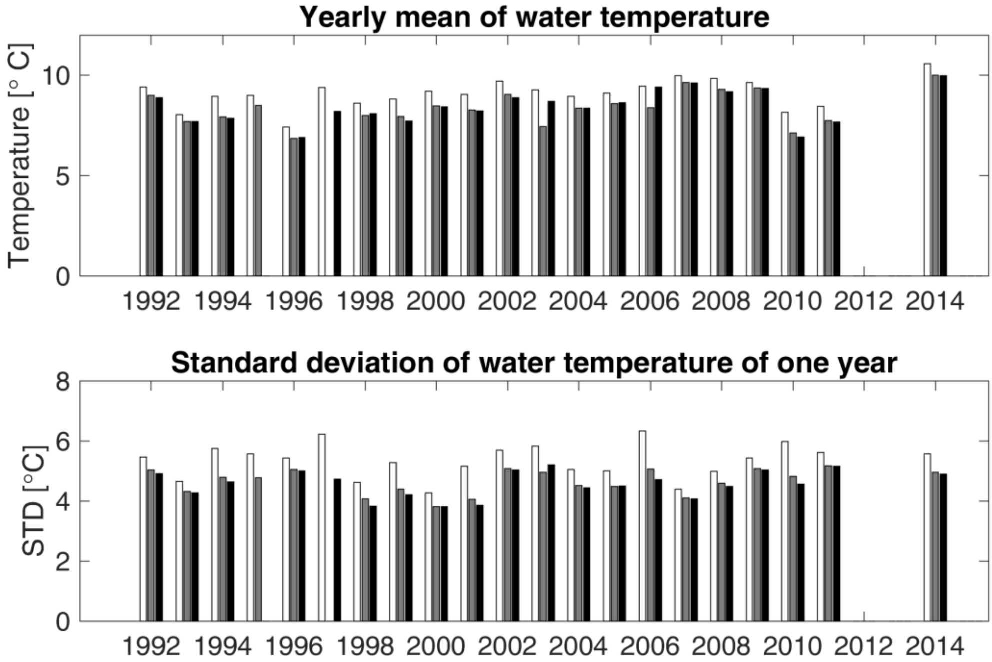


Fig. 8: Mean and standard deviation of water temperature taken over one year in the surface layer (7 m, white bars) and the bottom layer (17 m, grey bars and 19, black bars) at the Darss Sill

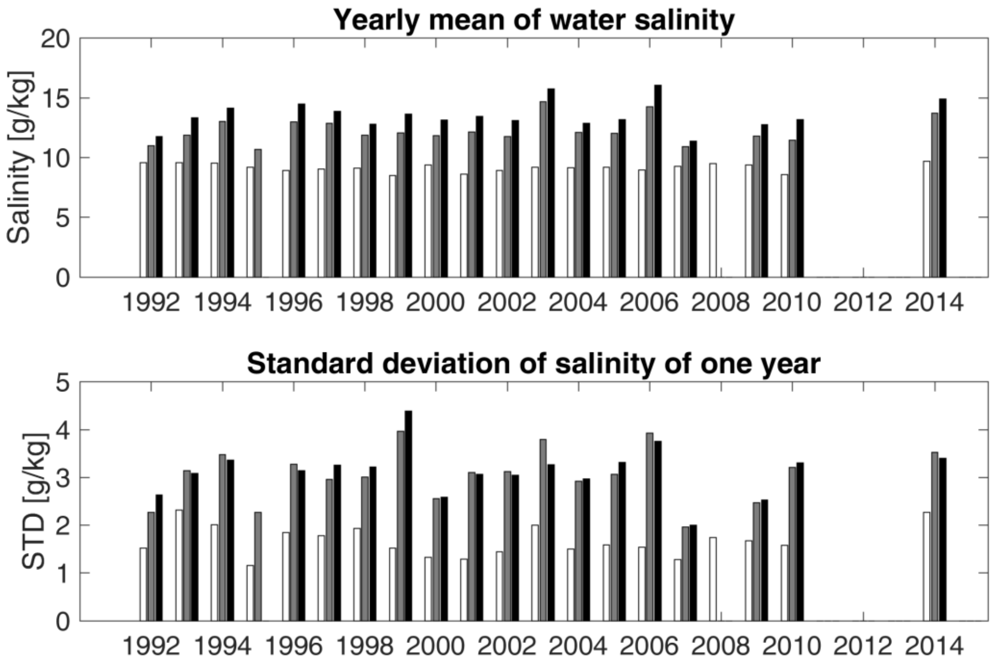


Fig. 9: Mean and standard deviation of salinity taken over one year in the surface layer (7 m, white bars) and the bottom layer (17 m, grey bars and 19, black bars) at the Darss Sill

3.2 Warming Phase with Moderate Inflow Events in January, March and August

Figure 10 shows the development of water temperature and salinity in 2015 in the surface layer (7 m depth) and the near-bottom layer (19 m depth). As in recent years, the currents shown in Figure 11 were temporally integrated in order to characterise the baroclinic (depth-variable) component, here plotted as a 'progressive vector diagram' (pseudo-trajectory). This integrated view of the velocity data filters short-term fluctuations, and allows long-term phenomena such as inflow and outflow events to be identified more clearly. According to this definition, the current velocity corresponds to the slope of the curves shown in Figure 11 with positive slopes reflecting inflow events. Note that, starting from 25 June, the integrated velocities shown in Figure 11 contain an unknown shift in transport due to the data gap mentioned above. From this point on, the integrated transports shown in Figure 11 are no more directly comparable to previous years.

As described in the previous report of this series, water properties at the Darss Sill during the last weeks of the year 2014 were determined by the Major Baltic Inflow 2014, rated as one of the largest events of this type since the beginning of the records. The remnants of this exceptional event were still evident during the first week of the year 2015, when salinity up to 19 g/kg were recorded by the near-bottom sensors of the monitoring platform. Heavy westerly winds during storm system "Olan" (see Section 2) triggered a second, smaller inflow across the Darss Sill between 9th and 14th January (Figures 7 and 11). Salinity during this event reached 20 g/kg, temperatures were around 6°C, and oxygen concentrations reached the saturation level across the entire water column (Figures 10 and 12). As discussed in more detail in the following section, the effect of this event could be clearly identified also at the MARNET platform in the Arkona Basin, where it prolonged the period of exceptionally high near-bottom salinity induced by the major inflow in December.

The following months until approximately end of March where characterized by falling water levels at the Landsort gauge (Figure 7), only shortly interrupted by some minor inflows that had, however, no discernible effect on the water mass properties in the deeper basins. During the second half of March, water levels reached the second lowest mark of the year, thus preparing the following inflow period. Increasing westerly winds (Figure 5), rising water levels at Landsort (Figure 7), and eastward current velocities at the observation platform on the Darss Sill (Figure 11) suggest a moderately strong inflow pulse in the following period until beginning of April. Unfortunately, due to the data gap in the salinity and temperature records mentioned above, the properties of the inflowing waters (temperature, salinity, oxygen content) cannot be constrained very precisely. Nevertheless, observations at the MARNET platform in the Arkona Basin, discussed in more detail in the next section, reveal a rapid increase of near-bottom salinity up to at least 15 g/kg (Figure 13), indicating the arrival of the inflow waters. However, also at this station, a small data gap in April precludes any exact quantification of water mass modifications in the bottom layer. Oxygen concentrations in the Arkona Basin prior to the event were already close to saturation, which would suggest that the inflow did not lead to any important changes in the near-bottom oxygen content. It did, however, certainly increase the density of the near-bottom waters, and therefore their potential to ventilate the deeper basins of the southern and central Baltic Sea.

During the following summer months, water levels at the Landsort gauge nearly stagnated (Figure 7), and both the long-term decrease in salinity (Figure 10) and the small transports (Figure 11) observed at the MARNET platform suggest that no further significant inflow activity occurred until end of August. Surface-layer temperatures remained unusually low during the summer period, exceeding the threshold of 17°C only during a few days at the end of August and beginning of September. The maximum yearly temperature in the surface layer was 17.6°C, measured at 7 m depth on 2nd September. An interesting feature observed during the summer period are the short but intense cold temperature anomalies that affected the entire water column and had a duration of a few days, respectively. The most prominent examples of such events, associated with temperature drops of up to 5°C in each case, occurred beginning July, and beginning and mid of August (Figure 10). Similar events were also detected in previous years, and may be explained as follows. During short periods with winds from northerly to easterly directions that usually precede these events, cold upwelling filaments are created at the German coast, in particular near the island of Hiddensee that forms a well-known upwelling hot-spot for these wind directions. These filaments are then advected by the outflowing water masses across the Darss Sill, where they are detected by the sensors of the MARNET observational platform. It is likely that these upwelling filaments, containing waters from below the thermocline, were comparably nutrient-rich, and may therefore have formed patches of enhanced primary production.

The only significant inflow event occurring during the warm season was a moderate inflow pulse triggered by strong westerly winds during the last week of August after the water level at Landsort had reached one of the lowest values of the year (Figure 7). The velocity records at the monitoring station (Figure 11) indicate a purely barotropic inflow event (occasionally interrupted due to variable winds) that resulted in an overall water level rise at Landsort of approximately 0.3 m. Salinity at the Darss Sill exhibited a rapid increase on 26th August (Figure 10), whereas at the same time oxygen concentrations collapsed down to values around 20 % of the saturation point, although only for a short period (Figure 12). After a few days, oxygen concentrations relaxed back to values above 90 % in each case. This at first glance paradoxical behaviour is easily explained by the fact that the warm, oxygen-depleted bottom waters from the Belt region usually arrives first at the Darss Sill, followed by the oxic water masses imported from the Kattegat region. Similar phenomena have been observed also during previous summer inflows. As shown in the following section, this inflow did not have a pronounced effect on the oxygen content of the Arkona Basin. However, it did result in increasing bottom salinity, and, above all, in a rapid increase in bottom temperatures that may have increased the sedimentary oxygen demand.

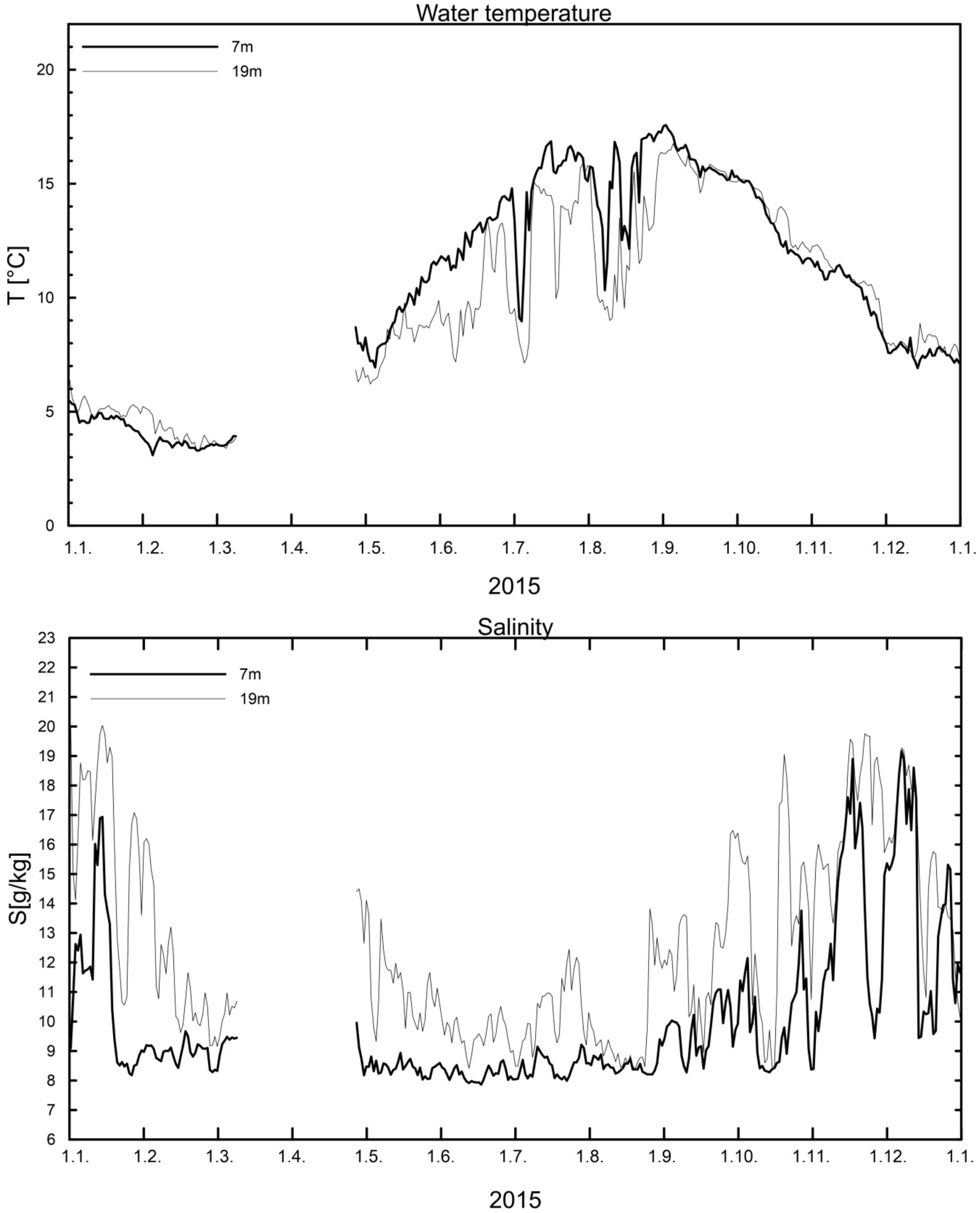


Fig. 10: Water temperature (above) and salinity (below) measured in the surface layer and the near bottom layer at Darss Sill in 2015

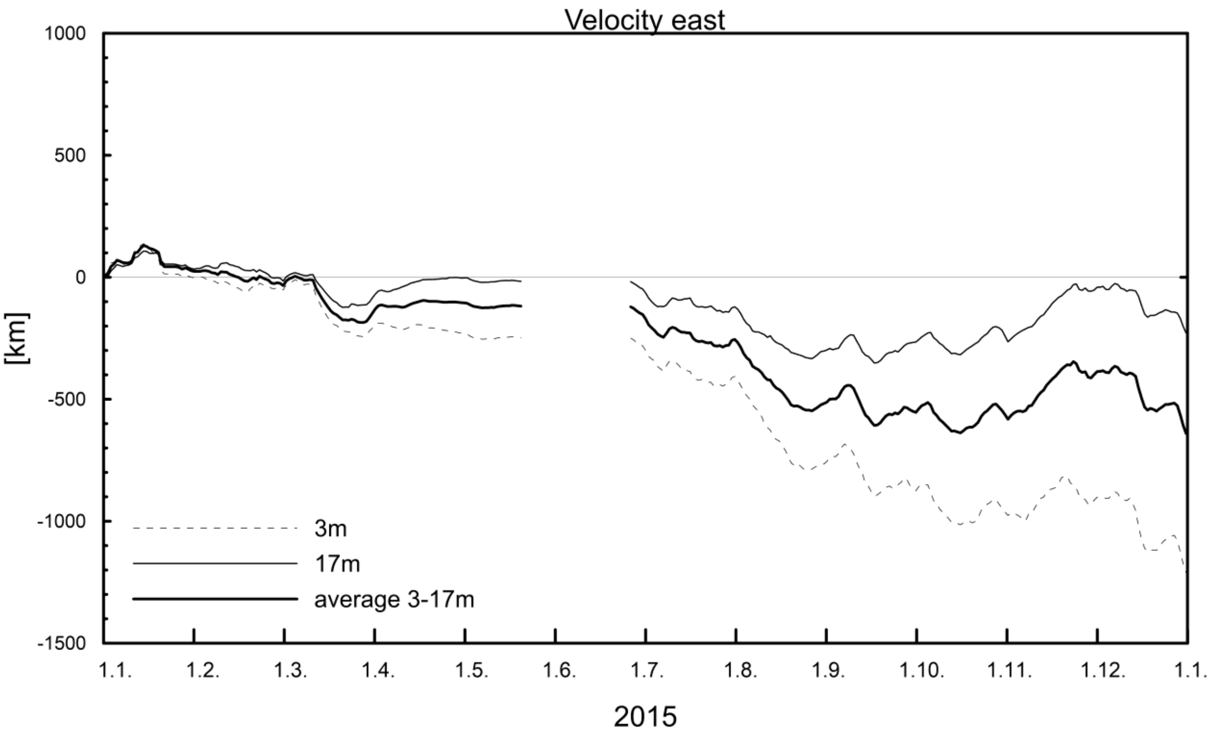


Fig 11: East component of the progressive vector diagrams of the current in 3 m depth (solid line), the vertical averaged current (thick line) and the current in 17 m depth (dashed line) at the Darss Sill in 2015

3.3 Cooling Phase due to the Major Baltic Inflow in November

Simultaneous with the inflow event at the end of August, changing weather conditions initiated the cooling period during which surface temperatures at the Darss Sill gradually decreased from 18°C down to approximately 8.5°C by the end of the year. The second half of September was characterized by relatively low winds from West, accompanied by a longer period of baroclinic inflow (Figure 11) of saline waters with moderate oxygen concentrations between 60-80 % of the saturation value (Figure 10 and 12). The two main events of the fall season, however, were two large barotropic inflows, the second of which was characterized as a Major Baltic Inflow. The preconditions for these events were established during longer period with easterly winds, generating permanent outflow conditions since beginning of October, which ultimately resulted in the lowest water levels of the year at the Landsort gauge around mid of October (Figure 7).

The first, weaker event was then triggered by westerly winds in mid of October, and became evident at the monitoring station by a sharp increase in bottom salinity on 18th October (Figure 10), and, two days later, by the passage of oxygen-depleted waters from the Belt Sea with concentrations below 25 % of the saturation value (Figure 12). As water temperatures were still high (Figure 10), it is likely that the reasons for this short-term collapse of the oxygen concentrations are analogous to those explained above in the context of the warm inflow event from end of August. During the course of this event, oxygen concentrations increased again to values close to the saturation level, and bottom salinity reached values of slightly more than 19 g/kg. The fact that the inflowing salt water was largely confined to the bottom layer hints at the small amount of high-salinity waters imported by this event. This is confirmed by the velocity records (Figure 11), showing that the inflow was of purely barotropic nature and relatively short duration: already on 28th October, velocities at the Darss Sill turned back to outflow conditions. The water level at Landort was still slightly below the neutral value at this time.

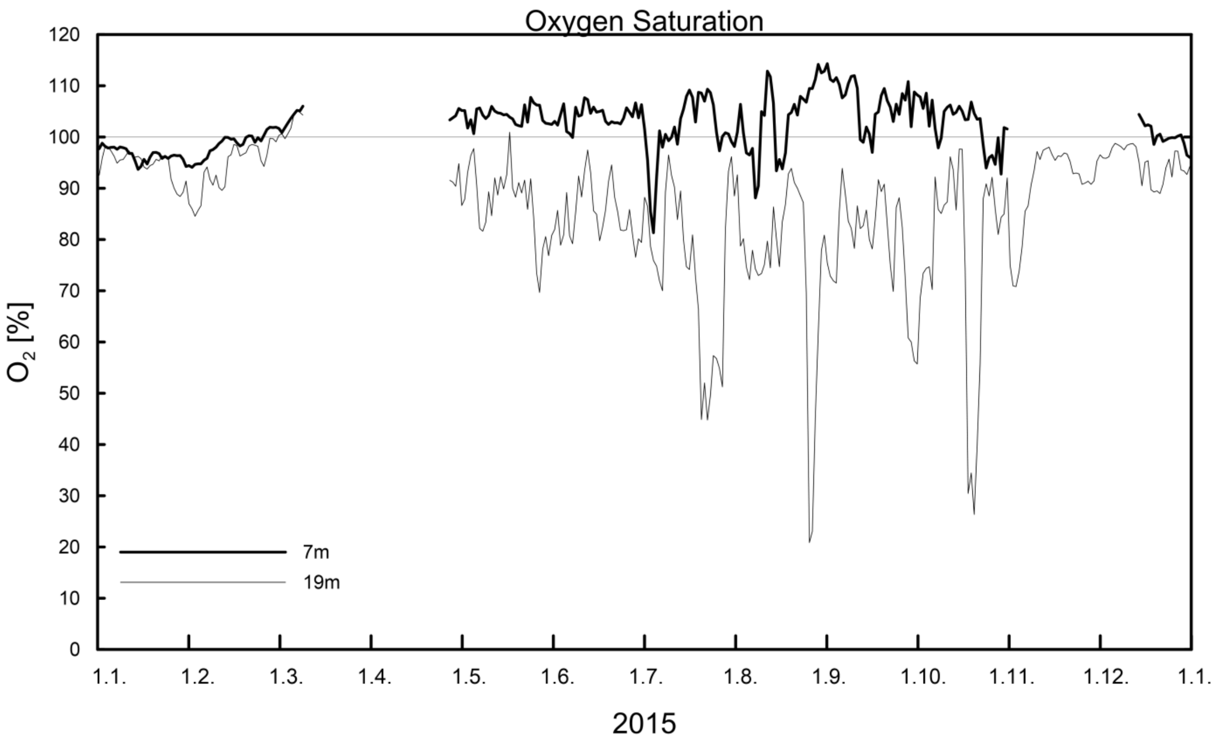


Abb. 12: Oxygen saturation measured in the surface and bottom layer at the Darss Sill in 2015

After a short outflow phase with sinking water levels at Landsort, easterly winds nearly ceased towards the end of October, and, on 1st November, the largest inflow event of the year 2015 started. While during its first phase, this inflow was largely driven by the baroclinic pressure difference across the Danish Straits, westerly winds reached more than 15 m/s already in the second week of November (see Figure 3), thereby providing an additional driving force for the inflowing waters. Bottom currents at the Darss Sill (Figure 11) showed nearly continuous inflow conditions over a period of more than three weeks until 24th November, whereas surface waters continued to flow out of the Baltic Sea during the initial inflow phase until 6th November. The two-layer flow during the initial phase is also mirrored in a two-layer structure of salinity with high salinity confined to the near-bottom regions, and outflowing brackish waters near the surface (Figure 10). This clearly shows that the initial period of the inflow, characterized by low-wind conditions, was largely determined by the baroclinic pressure gradient resulting from the density differences of the saline Kattegat and brackish Baltic Sea waters. Such “baroclinic” inflows were found to occur in previous years mostly during calm summer conditions but were rarely observed during the winter season.

The situation, however, changed completely when westerly winds picked up in the second week of November. Starting from 7th November, also the surface currents flipped to inflow directions, and after a short time even exceeded the near-bottom speeds (Figure 11). During this time, the inflow became fully barotropic, the water column was nearly well-mixed, and surface and bottom salinity reached maximum values of more than 19 g/kg (Figure 10). Oxygen concentrations increased from values below 70 % observed during the initial baroclinic phase of the inflow to saturation levels. This barotropic main phase of the inflow event lasted until 20th November, after which winds became variable in direction and wind speeds decayed. During its final phase, the inflow continued as a weak, baroclinically driven flow until it completely ceased on 24th November.

Water levels remain high at the Landsort gauge also after this Major Baltic Inflow (Figure 7), which explains that despite the strong westerly winds characterizing the following month of December, no significant amounts of saline waters were imported into the Western Baltic Sea (Figure 11). The year 2015 ends at the Darss Sill with oxygen levels close to saturation throughout the water column, and relatively low salinity between 11 and 12 g/kg.

3. Observations at the Buoy "Arkona Basin"

The dynamics of saline bottom currents in the Arkona Basin was investigated in detail some years ago in the framework of the projects "QuantAS-Nat" and "QuantAS-Off" (Quantification of water mass transformation in the Arkona Sea), funded by the German Research Foundation (DFG) and the Federal Ministry for the Environment (BMU). Data from these projects included the first detailed and synoptic turbulence and velocity transects across bottom gravity currents passing through a channel north of Kriegers Flak during a number of medium-strength inflow events (ARNEBORG et al., 2007; UMLAUF et al., 2007; SELLSCHOPP et al., 2006). In a pilot study, BURCHARD et al. (2009) investigated the pathways of these haline intrusions into the Arkona Basin in 2003 and 2004. They identified the channels north of Kriegers Flak and the Bornholm Channel as zones of greatly intensified mixing, and validated their model results using data from the MARNET monitoring network as published in this report series every year. The theoretical analysis of these data revealed a surprisingly strong influence of Earth's rotation on turbulent entrainment in dense bottom currents, leading to the development of new theoretical model that take rotation into account (UMLAUF & ARNEBORG, 2009a, b, UMLAUF et al., 2010). The correct representation of the turbulent entrainment rates in numerical models of the Baltic Sea is known to be essential to predict the final interleaving depth and ecosystem impact of the inflowing bottom gravity currents in the deeper basins of the central Baltic Sea.

The Arkona Basin monitoring station is located almost 20 nm north-east of Arkona in 46 m water depth. As in the previous two years, the station again provided complete series of measurements of temperature, salinity, and oxygen concentrations with the exception of a small data gap from 12th to 29th April. As described in Section 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 13 shows the time series of water temperature and salinity at depths of 7 m and 40 m, representing the surface and bottom layer properties. Occasionally, also data from the deepest sensor at 43 m depth (not shown in the figure) will be discussed. Corresponding oxygen concentrations, plotted here as saturation values, are shown in Figure 14.

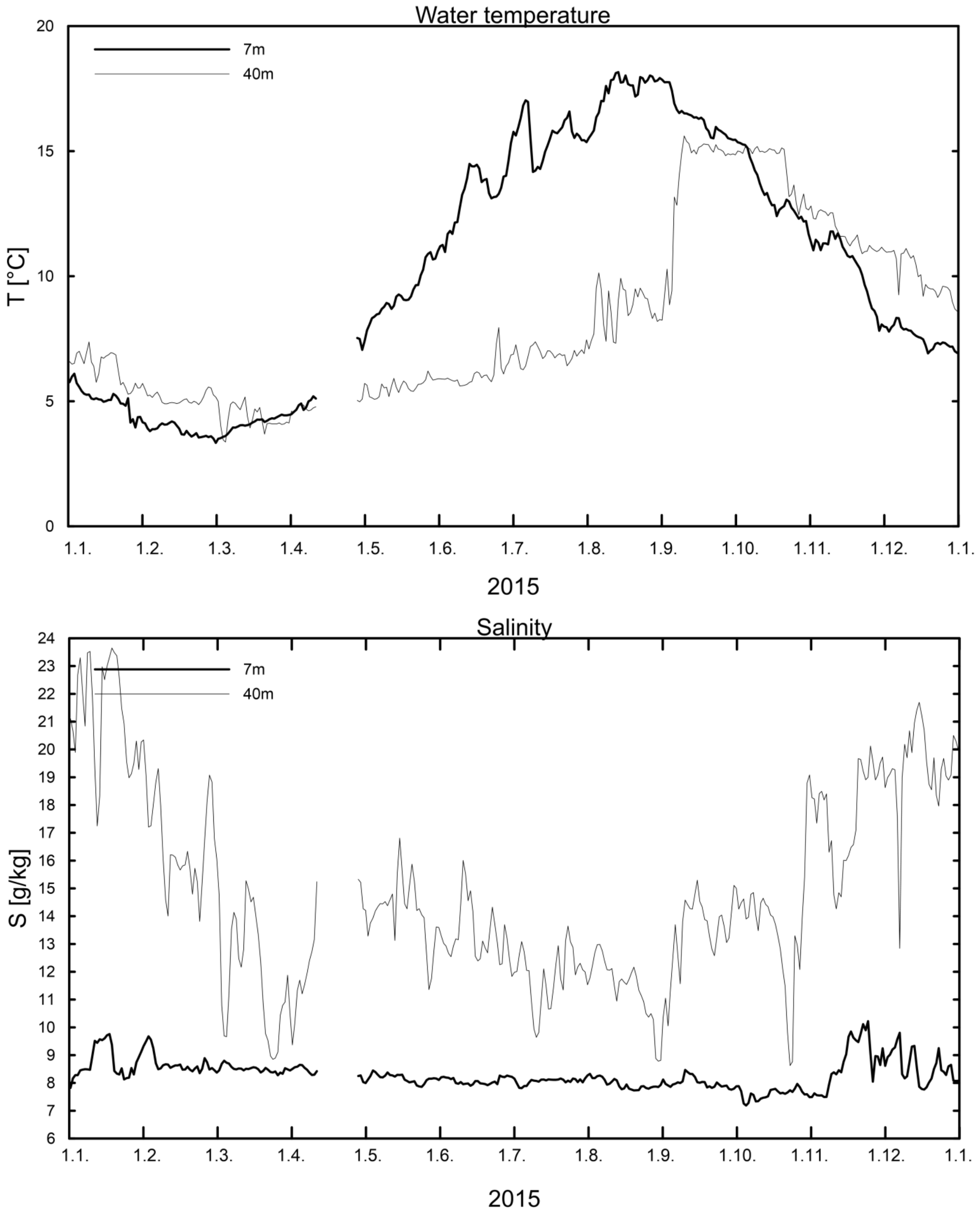


Fig. 13: Water temperature (above) and salinity (below) measured in the surface layer and near bottom layer at the station AB in the Arkona Basin in 2015

The annual cycle of the surface-layer temperature in Figure 13 shows that the lowest temperatures of the year were recorded beginning of March with the annual minimum temperature of 3.4°C (daily mean) recorded on 3rd March. This value is substantially larger than those observed in the previous year 2013 (0.9°C) and 2014 (2.4°C), which mirrors the relatively mild winter 2014/2015. As in other years, the minimum bottom temperatures were reached with a three to four week delay, reflecting the time scale for lateral transport through the Danish Straits rather than the effect of local atmospheric cooling. Starting from the beginning of March, surface temperatures at the monitoring station gradually increased, and reached a first maximum during a phase with mild weather conditions beginning of June. During this short maximum, the threshold of 15°C was exceeded for the first time in 2015, although only for the duration of a few hours before temperatures dropped again due to increasing winds and falling atmospheric temperatures. During the entire summer period, surface-layer temperatures above 17°C were found only during a short temperature peak around 5th July, and then again for a period of approximately three weeks in August, when temperatures fluctuated around 18°C. In summary, the cold summer of the year 2015 was clearly reflected in the surface temperatures of the Arkona Basin, which remained significantly below the levels of the previous warm years with temperatures above 21° C at this location. The autumn cooling phase started at the beginning of September, approximately 3 weeks later compared to the previous year, and was only shortly interrupted by two warming events in October and November. The mild December significantly reduced the cooling rate of the previous months, explaining the relatively high temperatures of approximately 7°C at the end of the year.

Water mass properties in the lower part of the water column during the first months of the year were still largely determined by the aftermath of the record-breaking Major Baltic Inflow from December 2014. As described in the previous section, this event was followed by a smaller inflow pulse in January that is reflected in the continuously high salinity in the bottom waters of the Arkona Basin (Figure 13). Note that maximum salinity of almost 24 g/kg significantly exceeded those observed at the station Darss Sill (below 22 g/kg during all phases of the inflow), pointing at the importance of high-salinity waters intruding via the Drogden Sill. The largest daily mean value of the year (and also the largest value found during the entire Major Baltic Inflow 2014) was 24.7 g/kg, observed on 5 January at the deepest sensor in 43 m depth (not shown in Figure 13).

The temperature of the bottom waters in the Arkona Basin, which forms a useful indicator to track the inflowing water masses on their way towards the deeper basins of the southern and central Baltic Sea, was generally in the range 5.5 – 7.0°C. During the second, smaller inflow pulse arriving around mid of January in the Arkona Basin, temperatures varied between 6.5°C and 7°C. This latter event was strong enough to also modify the surface layer salinity, which increased from 8 g/kg to slightly less than 10 g/kg in mid of January (Figure 13); oxygen concentrations were close to saturation during the entire period (Figure 14). In the period following this smaller inflow pulse, bottom salinity gradually decreased, only briefly interrupted by a few short-term fluctuations, until end of March, when values had decayed to less than 10 g/kg. This indicates that, by this time, all dense inflow water had left the Arkona Basin via the Bornholm Channel, and started its decent towards the deeper basins of the central Baltic

Sea. The temporal evolution shown in Figure 13 suggests that the time scale for the drainage of saline bottom waters after a Major Baltic Inflow is in the order of a month. During the following period of rising water levels at Landsort (Figure 7) and a moderate inflow event starting mid of March (see Section 3), bottom salinity recovered again to values around 15 g/kg.

The following summer months were characterized by weak inflow activity, followed by a longer outflow period in August that resulted in an overall long-term decay of bottom salinity. The bottom layer, isolated from direct atmospheric forcing by the stable halocline, exhibited unusually low temperatures of less than 7°C during the summer period before end of July, and less than 10°C before end of August (Figure 10). Note, for comparison, that in the previous, more typical year the threshold of 10°C was exceeded already mid of June. Late-summer oxygen concentrations in the near-bottom region generally fluctuated around 50 % of the saturation value, and did never fall below the threshold of 20 %. The fact that, despite the collapsing inflow activity, no anoxia developed in the lower layers of the Arkona Basin during the summer months may therefore be at least partly explained by the well-known exponential decrease of microbially-mediated degradation rates at low temperatures.

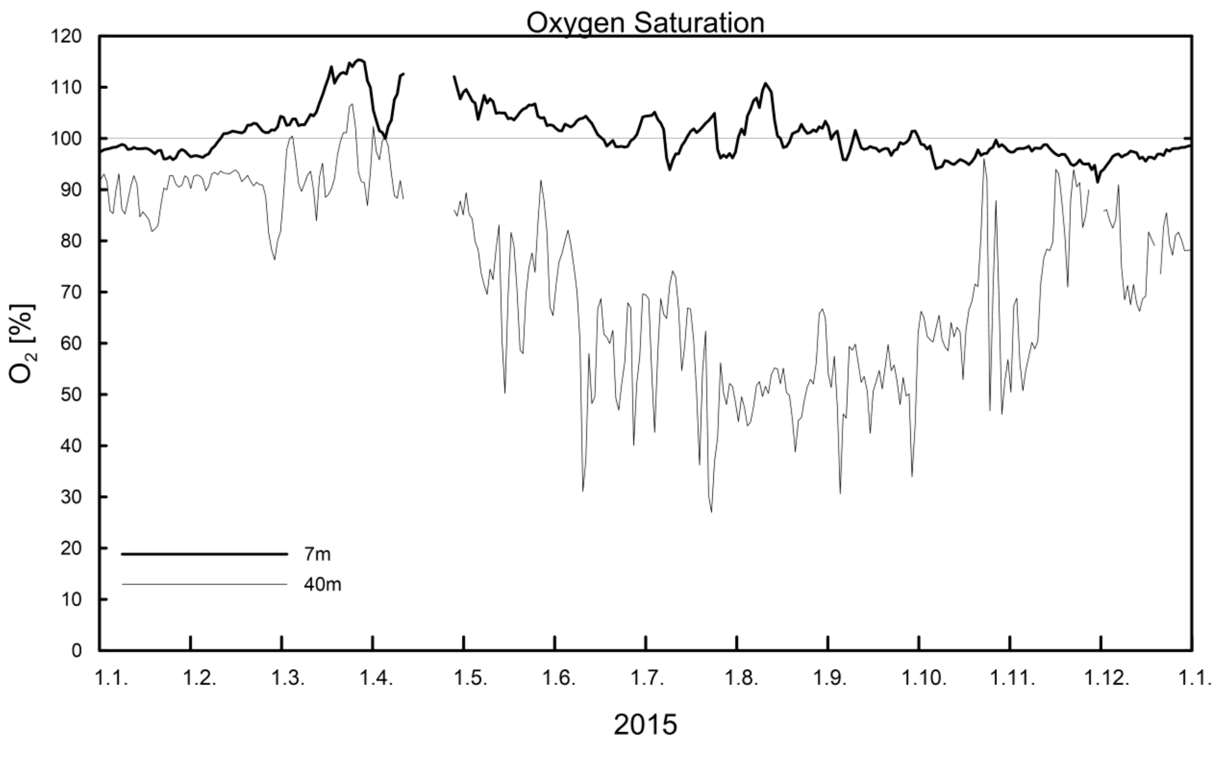


Fig. 14: Oxygen saturation measured in the surface and bottom layer at the station AB in the Arkona Basin in 2015

The situation changed, however, radically at the beginning of September, when the warm waters of the medium-intensity inflow event described in the previous section arrived at the Arkona monitoring platform. Bottom temperatures increased by more than 5°C within a few days, and salinity reached values close to 15 g/kg (Figure 13). The imprint of this inflow event on the near-bottom oxygen concentration is, however, hardly discernible in Figure 14, despite the fact that oxygen concentrations near the saturation point were observed for this inflow event at the station Darss Sill (Figure 12). Beyond the dilution effect, it is likely that the increasing microbial oxygen demand associated with the higher temperatures of the inflowing waters partly compensated the imported oxygen surplus.

The signatures of the two inflow events in the following fall period (see Sections 2 and 3) can clearly be distinguished also in the bottom waters of the Arkona Basin. The waters of the medium-intensity inflow in October arrived at the monitoring platform on 23 October, as can be most clearly seen in a rapid drop of the bottom temperatures from approximately 15°C down to 12.5-13°C (Figure 13). In parallel, salinity at the lowermost sensor (43 m depth, not shown in Figure 13) increased to values above 20 g/kg, and oxygen concentrations to values above 90 % saturation. After the reversal from inflow to outflow conditions at the Darss Sill, however, both salinity and oxygen concentrations rapidly collapsed again, pointing at the relatively small water volume associated with this inflow.

The inflow event in November, classified as a Major Baltic Inflow in Sections 2 and 3, had a more profound impact on the deep-water properties of the Arkona Basin. As the temperatures of the inflowing waters were around 10°C at the Darss Sill (see Figure 10), and therefore comparable to the local deep-water temperatures in the Arkona Basin, this inflow event did not leave a clear temperature imprint. However, based on the rapid increase of salinity at intermediate depths (sensor at 20 m depth, not shown), the arrival of the first inflow waters from this event can be dated to 11th November. The sensors located in the bottom layer recorded increasing trends for both salinity (Figure 13) and oxygen (Figure 14) starting from 19th November, suggesting a delayed arrival of the densest water masses in the bottom layer. Within a few days after the arrival of the first inflow waters, oxygen concentrations in the bottom layer reached saturation levels, and bottom salinity increased to values above 21 g/kg at the deepest sensor (43 m depth), comparable to the maximum values found at the Darss Sill (Figure 10). The large volume of the intruding water masses is evident from the fact that salinity of up to 17 g/kg were recorded high up in the water column at only 20 m depth, and that a marked increase in salinity could be identified even in the surface waters (Figure 13). It is therefore likely that the waters from this second Major Baltic Inflow within a time span of less than a year will have a major impact on the deep-water properties in the basins of the central Baltic Sea. These expected changes will be described and quantified in the next edition of this report series.

It should be noted that the major inflow described above was followed by a considerably smaller event in December (see Sections 2 and 3) that is most clearly evident from an increase in the near-bottom salinity above 21 g/kg at the deepest sensor. This value is substantially larger than the maximum salinity of around 19 g/kg found at the Darss Sill for this inflow (see previous section), once more pointing at the relevance of the alternative inflow pathway across the Drogden Sill. The inflow volume for this event was much smaller compared to the Major Baltic Inflow in November but, in particular in view of the high salinity, may further intensify its long-term impact.

5. Observations at the Buoy "Oder Bank"

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

The Oder Bank monitoring station (OB) is located approximately 5 nm north-east of Koserow/Usedom at a water depth of 15 m, recording temperature, salinity, and oxygen at depths of 3 m and 12 m. Following the gradual replacement of the oxygen sensors at the other MARNET stations, optode sensors from Aanderaa (Norway) are in use also at station OB since 2010. These optical oxygen measurements were validated with the help of water samples taken during the regular maintenance cruises using the Winkler method. After the winter break, the monitoring station OB was brought back to service on 12th March 2015, more than two months earlier compared to the previous year. Starting from that date, the station provided continuous time series of all parameters until 14th December, when it was again demobilized to avoid damage from floating ice.

Temperatures and salinity levels at OB are plotted in Figure 15; associated oxygen readings are shown in Figure 16. Similar to the other MARNET stations, the maximum temperatures that were reached during the summer period were considerably smaller compared to the record-setting years 2010, 2013, and 2014, when temperatures of up to 23°C were observed at station OB. In 2015, the maximum daily mean temperatures in the surface layer exceeded the threshold of 20°C only twice (on 5th July and 16th August), and the maximum hourly mean temperature, reached on 5th July, was only 20.9°C. As in the previous years, surface temperatures at the monitoring station OB were significantly larger compared to those at the deeper and more energetic stations in the Arkona Basin and the Darss Sill (see Figs. 10 and 13), which reflects the shallower and more protected location of this station.

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

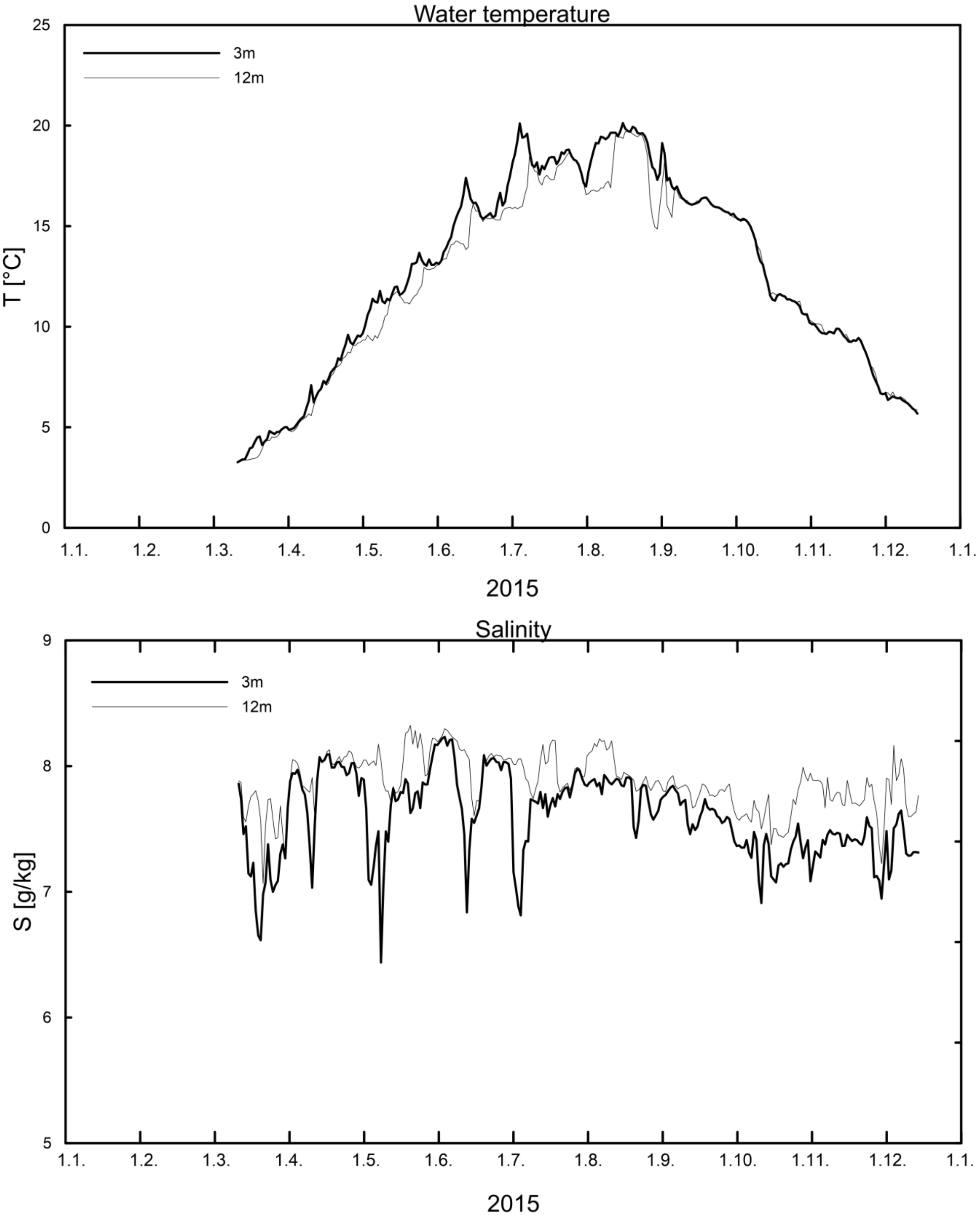


Fig. 15: Water temperature (above) and salinity (below) measured in the surface layer and near bottom layer at the station OB in the Pomeranian Bight in 2015

Distinct events of this type were observed in 2015 in May, June, and July. On 5th July, e.g., the daily mean of the surface salinity, typically fluctuating around values of 8 g/kg during this time of the year, rapidly dropped to 6.8 g/kg. This resulted in a stabilization of the water column, suppressing the mixing of water between the upper and lower layers. As a result, the surface layer rapidly heated up to the yearly maximum temperatures of slightly above 20°C (see above), while in the insulated lower layer temperatures stagnated. A strong wind event with daily mean wind speeds exceeding 12 m/s on 9th July induced a rapid mixing of the water column, and therefore set the endpoint of this stratification event. Similar patterns lead to the generation of the surface-salinity maxima, and associated temperature maxima, observed on 9th May and 13th June. It is worth noting that in 2015, the summer months also exhibited a few stratification events that were triggered by the upwelling of salty (thus dense) waters in the lower layer, e.g. in May, July, and August. Although upwelling is governed by different physical processes compared to the freshwater-induced events described above, it leads to a comparable increase in stratification, and thus to an analogous decoupling of the lower and upper part of the water column (Fig. 15). An event of this type in August was responsible for the evolution of the second temperature maximum in mid of August, where temperatures again increased to values above 20°C.

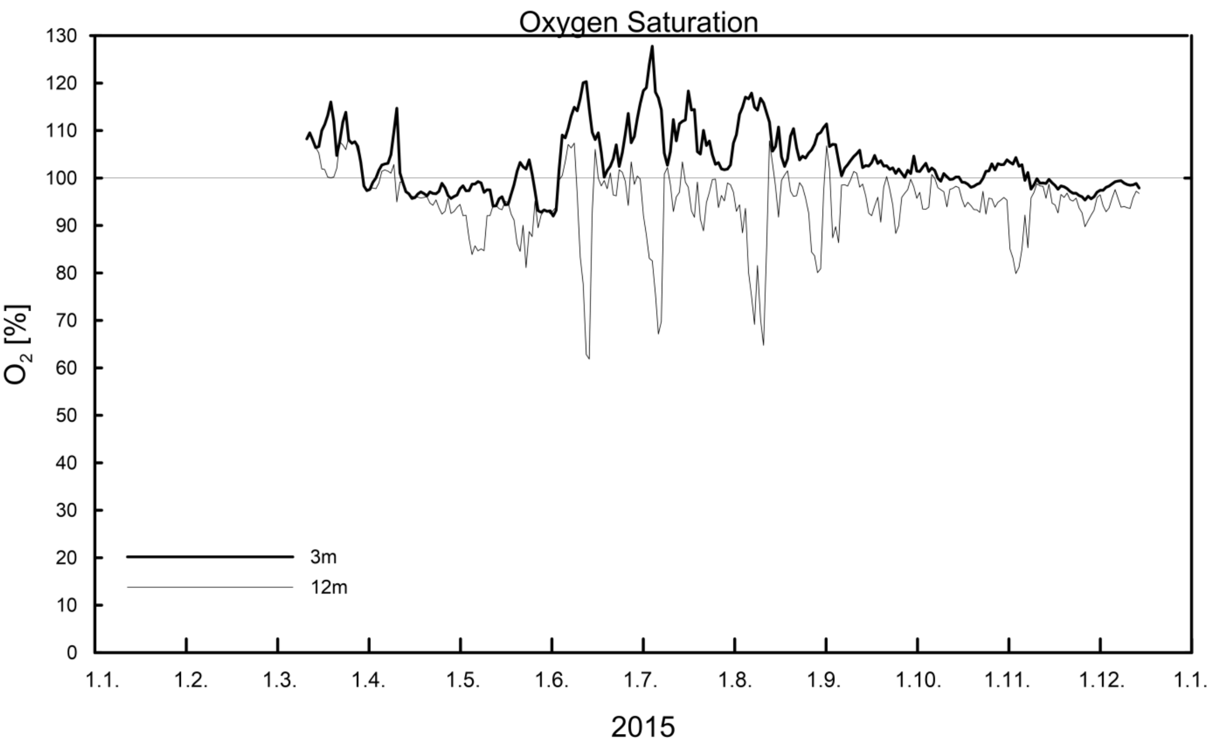


Fig. 16: Oxygen saturation measured in the surface and bottom layer at the station OB in the Pomeranian Bight in 2015

From an ecological perspective, by far the most important consequence of the suppression of turbulent mixing during these events is the decrease in near-bottom oxygen concentrations due to the de-coupling of the bottom layer from direct atmospheric ventilation. The impact of these events on the oxygen budget of the Pomeranian Bight is revealed by Figure 16, showing oxygen concentrations at depths of 3 m and 12 m. For all stratification events, a distinct negative correlation can be identified between increasing oxygen saturation in the surface layer and a decrease in the near-bottom layer, reflecting the effects of primary production and sedimentary oxygen demand, respectively. Examples of such events include the stratification periods in June, July and August that were mirrored in hourly mean oxygen concentration below 60 % (14^{th} June, 7^{th} July, and 12^{th} August). Interestingly, the pronounced stratification events observed at the beginning of May (Fig. 15) left no significant imprint on the near-bottom oxygen concentrations. It is likely that this points at reduced microbial respiration rates due to the still low water temperatures in spring time. All in all, the minimum near-bottom oxygen concentrations during the summer months were somewhat larger compared to the previous year, and therefore again far above the anoxic conditions observed during the record-breaking year 2010 (NAUSCH et al. 2011a).

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

6. Hydrographic and Hydrochemical Conditions

6.1 Water Temperature

6.1.1 The Sea Surface Temperature (SST) derived from Satellite Data

The development of Sea Surface Temperature (SST) of the Baltic Sea in 2015 was investigated using data of the US 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 investigations are discussed in SIEGEL et al. (2008). The annual assessment of the development of SST in the Baltic Sea is summarised in NAUSCH et al. (2015) and in HELCOM Environment Fact Sheets (SIEGEL & GERTH, 2015). Reflections on long-term development of SST since 1990 are presented in SIEGEL et al. (1999, 2006, 2008) and SIEGEL & GERTH (2010). The heat and cold sums of air temperature in Warnemünde (Chapter 2, Table 2) as well as data from MARNET stations (BSH/IOW) were include in the interpretation.
The year 2015 was after 2014 the second warmest since 1990 and approximately 0.9 K above average for the period 1990-2015 and 0.3 K colder than 2014. Except for the summer month

June-August, all other months contributed to this annual mean. SST anomalies of up to +2 K characterized nearly the entire Baltic from January to May, due to one of the mildest winters in air-temperature since 1948. January – March and October belonged to the warmest months since 1990. In the Gotland Sea (GS), March was the coldest month of the year, but in Arkona Sea (AS) and Bothnian Sea (BoS) it was February. February and March were rather similar and both the coldest months since 1990. February 18th-24th was the coldest week of the year. The SST increase in late spring was not as pronounced as usual, particularly in June leading to negative anomalies for the monthly mean SST. A warming phase from June 20th to July 5th and following deep pressure influence combined with wind, made July 5th to the warmest day in the western Baltic (WB) and in the GS. This caused negative anomalies for July. In August, SST increased particularly in the Gulf of Bothnia interrupted by wind events. August 19th, became the warmest day of the year in the northern Baltic Sea. August anomalies were in the southern and western Baltic slightly negative and in the northern Baltic positive. As in long-term average, August was the warmest month. From September to December, positive anomalies slightly increased that November and December became the warmest months since 1990.

The cold and heat sums of air temperature of Warnemünde (Table 2, Chapter 2) give information about the severity of winter and the course of summer. The winter 2014/15 was with a cold sum of 19.8 K d one of the warmest since 1948. The months of December and November 2014 contributed with about 78 % to this cold sum and February 2015 with only 22 %. The heat sum for summer 2015 (182.3 K d) was approximately 50 K d lower than 2014, but exceeded the long-term average (151.3 K d). July and August exceeded only slightly the long-term means. November and December were so mild that no daily mean temperature below zero has occurred (Chapter 2).

The anomalies of monthly mean SST for the entire Baltic Sea in Figure 17 are the basis for the discussion of the overall thermal development in 2015. The seasonal development of monthly mean temperatures in the central areas of the Arkona, Gotland and Bothnian Seas is shown in Figure 18 in comparison to the long-term monthly means for 1990-2015.

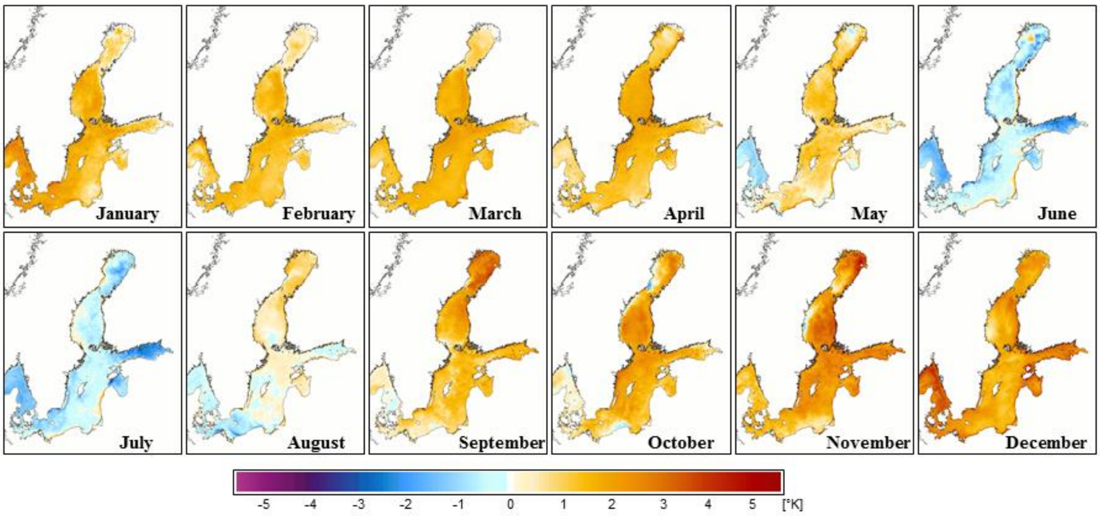


Fig. 17: SST- Anomalies of the monthly mean temperature of the Baltic Sea in 2015 referring to the long-term means 1990-2015

Daily means of SST were the basis for the detailed description of the temperature development. Positive anomalies of 1.5 – 2 K characterized the winter 2014/2015 from November to April in the entire Baltic and from September to December 2015. January to March and November to December belonged each to the warmest months since 1990.

Beginning of January, the SST was in the open parts of the western Baltic (WB) and of the Gotland Sea (GS) around 5°C. The AS cooled down to 3-4°C mid-February and the GS to around 3°C beginning of March. The northern Bothnian Bay (BoB) cooled down faster than the Baltic Proper and the WB. Thus January 24 developed to the day of maximum ice cover in the entire Baltic Sea (Fig. 19, SCHMELZER, 2015).

In the AS and BoS the mean SST of February and March were rather similar and the annual minimum (Fig. 18). Only in the Gotland Sea, the March was slightly colder.

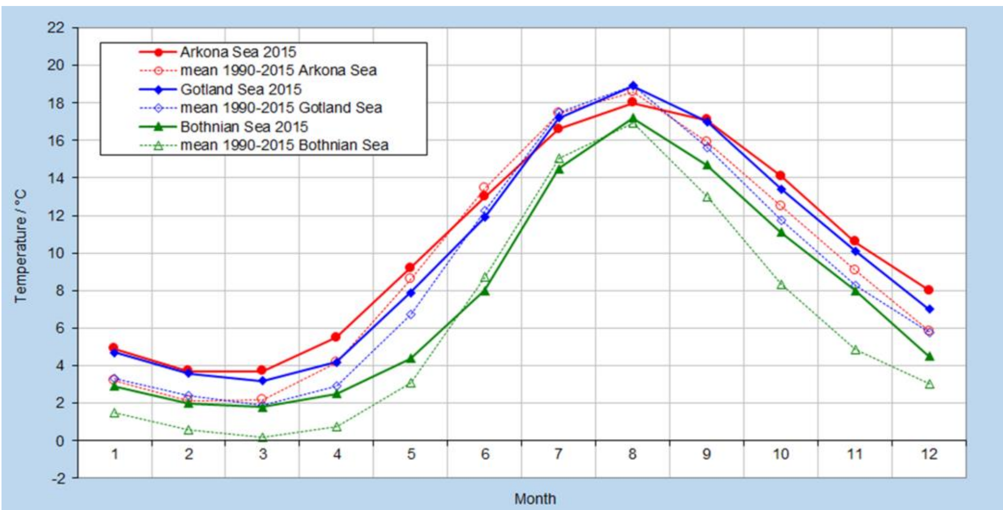
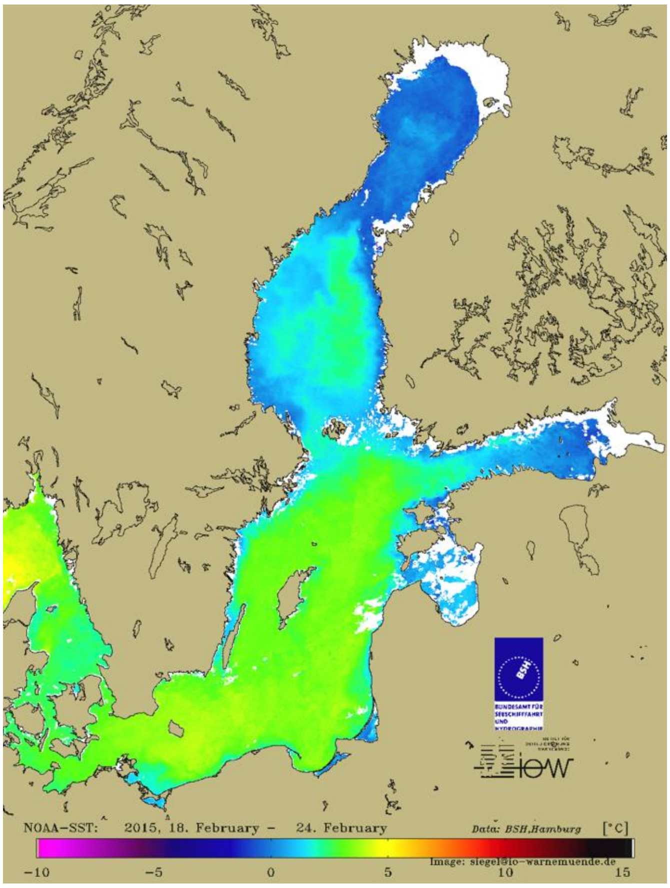


Fig. 18: Seasonal course of sea surface temperature in the central Arkona-, Gotland- and Bothnian Sea in 2015 in comparison to the mean values of the last 26 years (1990-2015)



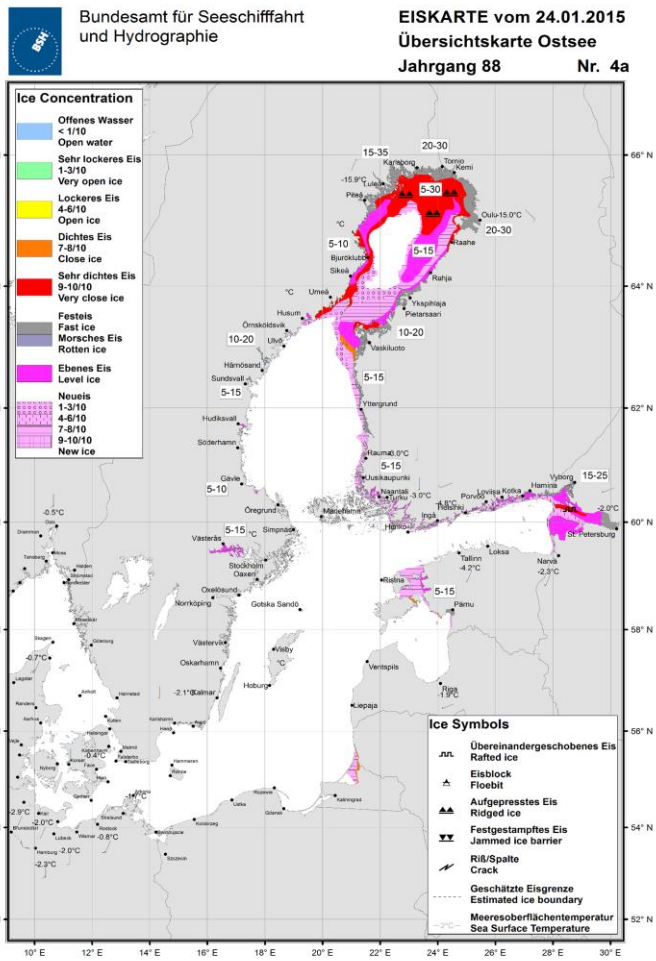


Fig. 19: Weekly mean SST of the Baltic Sea for 18th – 24th February (coldest week) and maximum ice coverage of the year 2015 on 24th January

Because of the strong changing cloud coverage, it was difficult to define the coldest day and the coldest week. Figure 19 shows the week February 18th-24th selected as the coldest week in the entire Baltic with SSTs of 2 - 4°C except the colder BoB and inner Gulf of Finland (GoF). The transect of mean SST in February in relation to long-term average (1990-2015), previous year, and range of variation (Fig. 20) reflect the impression from Figure 17. SST of entire Baltic is higher than the long-term mean values, but does not exceed the variation range.

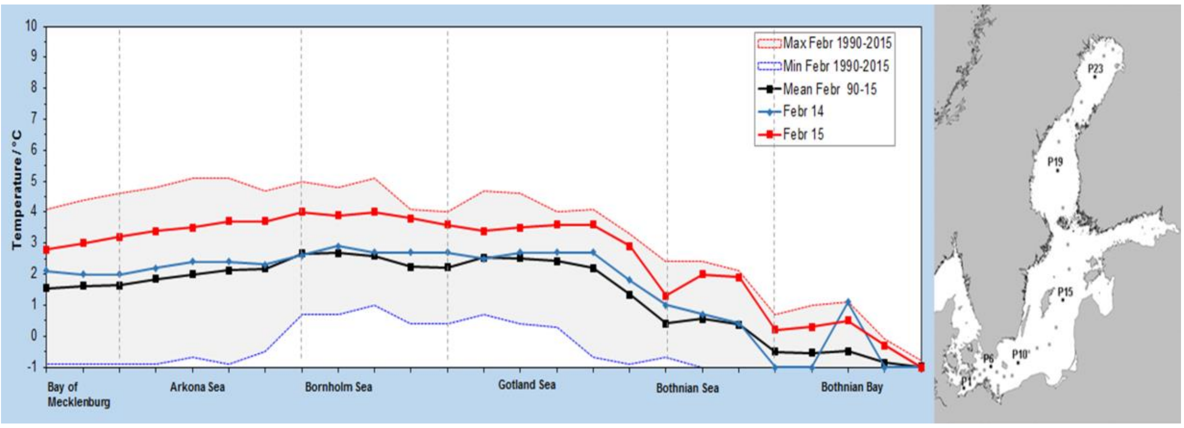


Fig. 20: Temperature distribution along the transect through the central basins of the Baltic Sea in February 2015 in comparison to the previous year, the long-term mean value of 1990-2015 and the variation range

Slight warming started around March 5th in the Bornholm Sea (BS) before it continued in the entire WB. The situation was rather stable until March 25th followed by a stronger warming and reaching end of March 5°C in the WB and about 4°C in the GS.

Until April 10th, the SST increased only slightly in the WB before a stronger warming occurred from the west and influenced the GS and BoS. End of April the SST reached values of approximately 8-9°C in the Mecklenburg Bight (MB), 7-8°C in the AS, 5-6°C in the GS and about 3°C in the BoS. This led to monthly anomaly of +1 to +2 K in the entire Baltic Sea.

Further heating in May in the AS was not as pronounced as normal. SST of the AS approached the long-term mean values, the mean temperatures of the GS and BoS show nearly the same anomalies as in the months before. End of May, the SST was 7-8°C in the AS, 5-6°C in the GS and about 3°C in the BoS similar to the values end of April.

In June and July, the anomalies are slightly negative with 0 to -1 K in the entire Baltic Sea, but in the GoF the mean temperatures are lower and the anomalies between -1 and -2 K in both months (Fig. 17). The typical warming in June was much slower than in the long-term means (Fig. 18). Reason was a stagnation in the first decade of June. Around June 10th, a first warming occurred, but the second starting from June 20th extended also to northern parts. By the end of June, SST reached 15-18°C in WB, 15-16°C in GS and about 12-13°C in BoS.

This warming intensified during a low wind period from July 1st to 5th followed by changing meteorological conditions that July 5th reached SSTs of up to 20°C in the WB and up to 22°C in the southern GS and developed there to the warmest day of the year (Fig. 21). The GoBo and the GoF were excluded from this warming.

The central parts of BoS and Gulf of Finland had only 13-15°C and BoB 10-13°C. Strong westerly winds with maximum of Beaufort 8 starting from July 6 as measured at the MARNET Station “Arkona Basin” mixed the surface water and reduced the SST to 15-17°C particularly in the southern and western Baltic. In the following days, the temperature increased more in the northern parts. Thus, the entire Baltic had similar temperatures of 15-18°C until the end of the month. Passages of low-pressure systems with changing wind and cloud conditions prevented further warming. This resulted in monthly mean SSTs of July just below the long-term average for 1990-2015, presented in Figure 22 together with the previous year, and the range of variation. Anomalies of up to -2 K occurred only in the Gulf of Finland due to the long lasting westerly wind and induced upwelling there (Fig. 17). In the first decade of August, SST increased during lower wind periods in the entire Baltic before a wind event starting from August 13th stopped further warming and reduced SST on the following days slightly. Between August 10th and 12th, a maximum SST of August reached values of 18-20°C in the western and central Baltic Sea and 16-18°C in the Gulf of Bothnia. From August 15, the high-pressure system “Isabel” (Chapter 2) dominated the weather in the Baltic region and particularly the northern parts. The image from August 19th in Figure 21 shows a rather homogeneous SST distribution in the entire Baltic Sea. Approximately 18°C represent the highest SST of the year in the northern Baltic Sea.

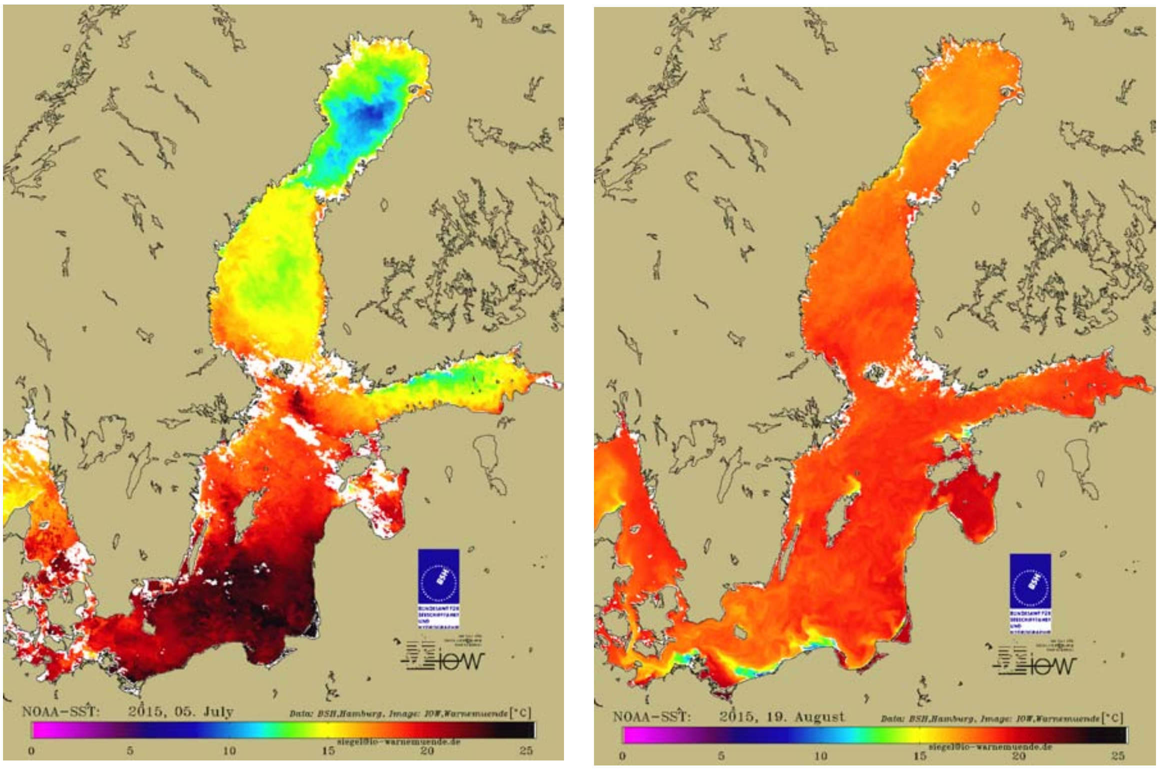


Fig. 21: SST of the Baltic Sea on July 5th, the warmest day of year 2015 in the southern Baltic Sea and on August 19th, the warmest day in the northern Baltic with rather homogeneous distribution and strong upwelling along the southern coast

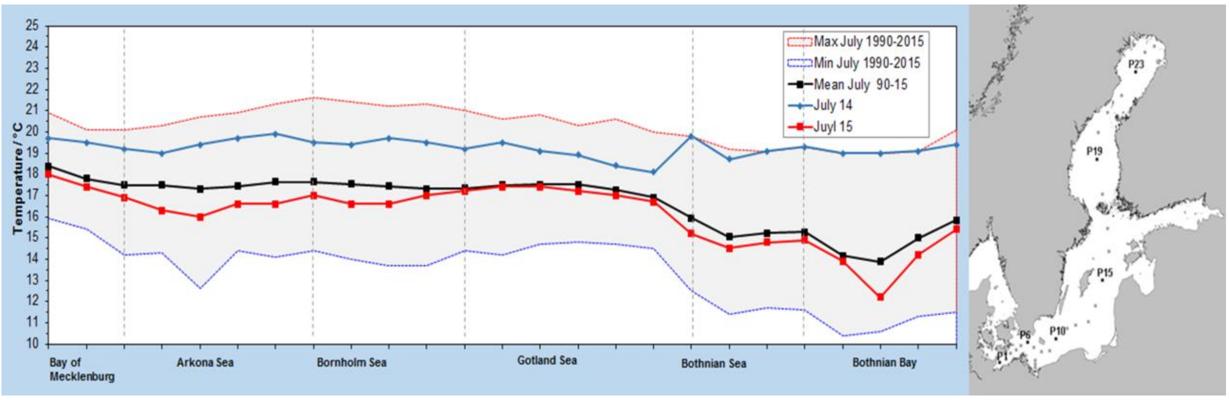


Fig. 22: Temperature distribution along the transect through the central basins of the Baltic Sea in July 2015 in comparison to the previous year, the long-term mean value of 1990-2015 and the variation range

The easterly winds, recorded in AS continued until August 25th, induced strong upwelling at the southern coasts and reduced SST dramatically. The cores of upwelling areas had partly less than 10°C. Mixed upwelled water is leaving the Baltic Sea. SSTs of 16-18°C end of August in central parts of the entire Baltic Sea led to monthly mean values of 17-19°C. The monthly averages of August are in the southern and western Baltic slightly below and in the northern parts above the long-term means (Fig. 17). As in the long-term average, the August was clearly the warmest month of the year 2015 (Fig. 18). After the August 25th, changes to westerly winds and cloud coverage induced upwelling in the northern Baltic, stopped the upwelling at the southern coasts and reduced slightly the SST throughout the Baltic.

Beginning of September, the SST decrease became stronger until September 8th. For 10 days, a stagnation followed with temperature of 16-17°C in WS, western GS and GoF, 17-18°C in the eastern GS and 13-16°C in the GoBo. Around September 20th, the SST decreased by 1°C in all regions, which was then stable until the end of the month. That resulted in monthly mean values of 16-18°C in the central and western part and of 13-16°C in the GoBo. The cooling was not as strong as in other years. The anomalies increased to the north and reached values of + 3 K in BoB (Fig. 17).

Further cooling started in October in the northern Baltic where westerly winds induced upwelling, which cooled the BoB until October 4th down to 7-10°C. Particularly from October 7th, strong easterly winds influenced the southern parts, induced upwelling and reduced the SST. From October 13th, the entire Baltic cooled down again and the next phase started around October 20th. Upwelling due to westerly winds in the north and due to easterly winds in the south dominated the SST until the end of the month, resulting in SSTs between 7 and 10°C in the north and between 9 and 13°C in central and western parts. The long lasting upwelling cells are only slightly visible in the anomalies (Fig. 17). Cores of the upwelling cells showed slight negative anomalies and otherwise positive with values up to approximately +2 K in the northern GB and in the GoBo. October 2015 was the second warmest since 1990.

In November, westerly to southwesterly wind with five events of 8 Beaufort did not decrease the SST as expected. Strongest reduction took place around November 20th and at November 28th. End of November 4-6°C were observed in the GoBo and 6-9°C otherwise. This development

causes monthly averages of 5-11°C and positive anomalies nearly in the entire Baltic, smaller values in south (0 to +1 K) and +1 to +3 K in the north (Fig. 18). With these temperatures, November 2015 was the warmest November since 1990.
In December, three main cooling phases took place, but the SST did not decrease strongly.
In the central and western Baltic, the SST reached end of December values of 5-7°C, only 1-2K less than end of November. In the GoBo, the SST reduced to 2-5°C and in the coastal areas of northern BoB sea ice formed. With this development, December 2015 was the warmest since 1990 and still exceeded December 2000.

Overall, 2014 was the second warmest year since 1990 (Fig. 24). The annual temperature average throughout the Baltic Sea was about 1 K higher than the long-term average, and only 0.2 K below the warmest year 2014. January to April and September to December contribute with 1.5 – 2 K above the long-term averages particularly to this high value. January - March belonged to the warmest months, and November and December were the warmest months since 1990, which was also due to the mild air-temperature without any daily mean value below 0°C. The resulting temperature trend was 0.6 K per decade.

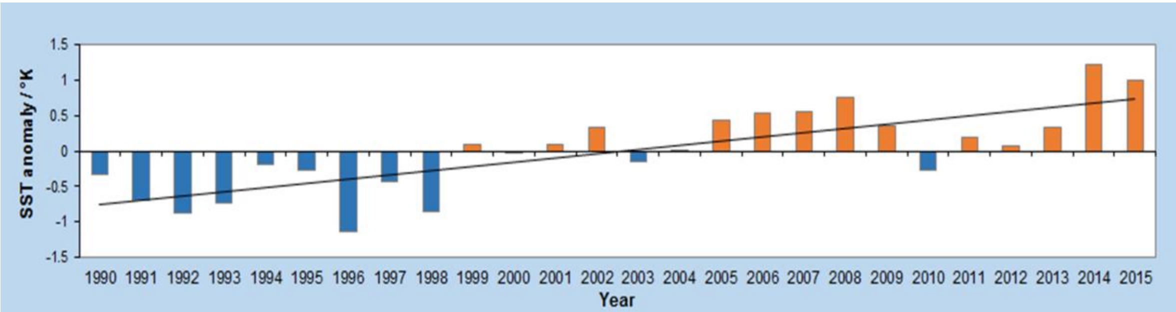


Fig. 24: Anomalies of the annual mean temperature of the entire Baltic Sea during the last 26 years (1990-2015)

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 2015, 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 29.

The surface temperature of the Baltic Sea is mainly determined by local heat flux between the sea surface and the atmosphere. In contrast, the temperature signal below the halocline is detached from the surface and the intermediate winter water layer and reflects the lateral heat flows due to salt-water inflows from the North Sea and diapycnal mixing.

In the central Baltic, the development of vertical temperature distribution above the halocline follows with some delay the annual cycle of atmospheric temperature (cf. chapter 2). The winter of 2014/2015 was unusually mild. This is reflected by the 2nd smallest ice coverage since 1720. From January to April 2015, temperatures clearly exceeded the long-term means (cf. chapter 2). Thus, the cooling of sea surface during winter time was significantly reduced in the western and central parts of the Baltic. The spring started with SST well above the long term mean. However, during May to July the mean temperatures switched to values below the long term mean for this season. However, in August the temperatures were again well above the long term mean and remained higher than the climatological mean till end of the year 2015.

The deep water conditions in the central Baltic in 2015 were mainly controlled by the extreme Christmas MBI of December 2014. This event transported about 198 km³ of saline water carrying 4 Gt of salt into the Baltic (MOHRHOLZ et al., 2015). The impact of this MBI became effective in January 2015. This event was followed by two small and medium MBI in March and November 2015 (cf. chapters 2 and 3). Also a portion of these inflows reached the deep water of the Baltic's central basins, and prolonged the ecologically significant changes of the 2014 Christmas MBI.

At the beginning of February 2015 the temperature distribution along the Baltic Talweg revealed the weak cooling in the surface layer. As a result of the very mild January, surface temperatures decreased in the shallow areas of the western Baltic Sea to values about 3 to 3.2°C. Only in the Mecklenburg Bight surface temperature below 3°C was observed at station TF0011 (2.65°C). Surface temperatures in the adjacent Arkona Sea were still around 3.4°C. This value was well above the density maximum with the result that further cooling forced temperature driven mixing. In the central Baltic, the deep convection associated with cooling largely homogenized the surface layer and the former winter water layer. The thermocline at station TF271 in the eastern Gotland Sea was found at a depth of 55 m. The vertical temperature gradient down to the halocline at a depth of about 70 m was weak, however. With 3.8°C, the surface temperature at station TF271 still exceeded the temperature of the density maximum. Further cooling thus preserved the deep vertical convection, and contributed to further homogenization of the surface layer. Generally, the surface temperatures in the central Baltic of 3.5°C and above were unusual high in February 2015. In contrast, in February 2014 the SST in was close to 1°C and below in the Belt Sea, and about 2.7°C in the central Baltic.

The temperature distribution below the halocline reflects the impact of the inflow events of saline water from the North Sea. The small late summer inflow during August/September 2014 and the Christmas MBI 2014 dominated the temperature distribution in the western Baltic. Waters of the minor inflow in late summer 2014 have flushed the halocline of the Bornholm Basin with extreme warm water of 14°C in October / November 2014. This water was mixed up in January 2015 with slightly cooler water of the Christmas MBI 2014. The mixed water body depicted the highest temperatures in the entire Baltic in February 2015. The warm water filled the eastern part of the halocline in the Bornholm Basin and the bottom layer of the Slupsk

Furrow. It was characterised by temperature above 8°C, with maximum value of about 10°C. The former deep and bottom water masses of the Slupsk Furrow were shifted eastwards. Patches of this water masses were observed at the entrance of the eastern Gotland Basin. The deep water in the Gotland Basin was still unaffected by the spreading of warm water. Here the bottom temperature at station TF 0271 was at 6.7°C.
The major part of the Christmas MBI 2014 waters has passed the Bornholmgat, and filled the entire Bornholm Basin below the sill depth of the Slupsk Sill (55m). The bottom temperature in the Bornholm Basin was about 7.2°C.

In normal years, relatively low surface temperatures are still observed during the monitoring cruise in March. As a result of the abnormally warm air temperatures in winter 2014/2015, the surface temperature of the western Baltic was above the February temperatures, and in the central Baltic Sea SST remained at the level of early February. The maximum temperature of 4.5°C was observed at the entrance to Kiel Bight (station TF361). Other areas of the western and central Baltic Sea were also comparatively warm with surface temperatures of 4.3°C in the Arkona Basin, 4.3°C in the Bornholm Basin, and 3.5°C in the eastern Gotland Basin. The minimum SST of 3.0°C was observed at station TF0285 in the northern Gotland Basin. Surface temperatures in the western and central Baltic clearly exceeded those of the density maximum. The onset of seasonal warming has established weak temperature stratification in the western Baltic.
In the second half of March 2015 a small MBI imported about 65 km³ of cold, saline water into the Baltic. This inflow water filled the area west of the Darss Sill as cool bottom water body with temperatures of about 4°C. The temperature of bottom water in the Arkona Sea was slightly higher at 4.7°C. The inflow water from the Christmas MBI 2014 has completely passed the Bornholmgat. A large fraction of this water mass is still present in the deep layers of the Bornholm Basin where the temperature is about 7.0°C. The warm water in halocline of the Bornholm Basin and in the deep water layer of the Slupsk Furrow has cooled due to further mixing with the MBI water. Maximum temperature in the halocline has decreased from 10°C in February to 8.5°C in March. The former deep waters from the Bornholm Basin and the Slupsk Furrow have reached the eastern Gotland Basin. Due to its high density the water replaced the bottom water, which led to a temperature increase from 6.7°C to 7.0°C between February and March 2015.
The inflow process into the eastern Gotland Basin causes an uplift of the old water masses. The 6°C isotherm rose from a depth of 100 m at the beginning of February to 93 m in March. In the same period, the 5°C isotherm remains nearly constant at 78 m. The uplift of water in the eastern Gotland Basin forced also a northward spreading of old intermediate water to the Farö Deep. Here the bottom temperature increased from 6.17°C to 6.38°C. Concurrently, the 6°C isotherm rose from a depth of 156 m to 120 m.

Between March and May, the surface water of Baltic warmed noticeably due to increasing air temperatures and solar radiation. Surface temperatures ranged between 10.5°C in the Mecklenburg Bight, 8.2°C in the Arkona Basin, 8.0°C in the Bornholm Basin, and 6.8°C in the eastern Gotland Basin. Seasonal thermal stratification was well pronounced in the entire western and central Baltic, and blocked the direct interaction between the atmosphere and the

layer of winter water (30-70 m). Compared to the previous years, the intermediate layer was extremely warm in 2015. Usual winter water temperatures are about 2°C, controlled by the temperature of maximum density of surface water. In the eastern Gotland Sea, the minimum temperature of intermediate winter water was in May 4.05°C. It exceeded also the previous year value by 1.0 K. Similar conditions were observed throughout the central Baltic. Due to the mild winter 2014/2015 the surface water never fell below the temperature of density maximum. And thus, the usual convective mixing in spring was not observed in 2015.
The warm water body in the halocline of the Bornholm Basin was mixed up nearly completely with the cool inflow water from the MBI 2014 and the March 2015 inflow. The major part of this water body has reached the eastern Gotland Basin. In beginning April the inflow water from the MBI 2014 was detected at the bottom of the eastern Gotland Basin. Compared to March 2015 the bottom temperature decreased by -0.1K to 6.87°C. The arrival of high density water caused a further uplift in the basin, and spreading of warm intermediate water to the Farö Deep. The bottom temperature in the Farö Deep increased to 6.50°C. And the 6°C isotherm rose to depth to 103 m, reaching the same depth level as in the adjacent eastern Gotland Basin.

By the end of July 2015, typical summer thermal stratification had become established throughout the Baltic Sea. The seasonal thermocline lay at depths between 20m and 30m, and separated the strongly warmed layer of surface water from the cool winter intermediate water. In the basins of the central Baltic Sea, minimum temperatures in the intermediate water were around 4.2°C, making it on average 0.8 K warmer than in 2014. The layer of winter water was also identifiable in the Bornholm Basin with core temperatures of 5.2°C in July.
Although the surface temperatures in spring were well above the long term mean, the cool weather in May, June and July caused a normalization of surface temperatures. Surface temperatures in the western Baltic Sea were well below 20°C. At station TF213 in the Bornholm Basin, 15.63°C was recorded on 27th July. Surface temperatures were relatively low in the central Baltic Sea, too: 16.24°C was recorded at station TF271 in the eastern Gotland Basin. However, a calm period in the beginning of August caused a rapid warming of the shallow surface layer. Till 12th August the surface temperature at station TF271 rose to 19.5°C in a 10m thick layer.
After the inflow in March 2015 no significant amount of saline water entered the Baltic. Thus, the temperature distribution in deep water of central Baltic Basins remained nearly unchanged since May 2015. Only a slight increase in bottom temperature of the Farö Deep to 6.58°C was observed. Also local diapycnal mixing caused minor changes and flattening of temperature gradients. In the western Baltic the bottom layer temperature increased due to quasi permanent baroclinic leakage of saline water from the Kattegat into the Arkona Basin. There the bottom temperature increased from 5.1°C in May to 6.0°C in July. The Slupsk Furrow lost significant amounts of warm and saline waters due to overflow of the Sill towards the eastern Gotland Basin. The 6°C isotherm sunk down to the depth level of the eastern sill.

Due to heavy wind conditions during the November monitoring cruise the Talweg transect of the Baltic could not be covered completely. There are no data for a larger section between the Slupsk Furrow and the eastern Gotland Basin. However, the most important changes were detected.

The temperature distribution in early November 2015 revealed autumnal erosion of the thermocline in the surface layer. The temperature in the surface layer, extending to a depth of 35 m to 45 m was well above 10°C. In the Arkona Basin surface temperature of 11.8°C was observed. Towards the central Baltic Sea it fell to 10.7°C (station TF271). As a result of the warm autumn, the water temperature above the halocline clearly exceeded the previous year's values. The deepening of thermocline reduced the thickness of the intermediate winter water layer in the central Baltic to layer of 30 m to 35 m thickness, with minimum temperatures of 4.8°C (station TF271). No layer of winter intermediate water was present in the Bornholm Basin.

In late October 2015 a minor barotropic inflow was observed (cf. chapter 2). It was followed in early November 2015 by a moderate MBI, which transported about 75km³ of warm and saline water into the Baltic. At the time of the cruise the tip of the October inflow has already passed the Bornholmgat, where the water influenced the thermal stratification. The maximum temperature of 13.35°C was observed at 57 m. Due to the low salinity of this inflow, it was sandwiched in the halocline of the Bornholm Basin. As the warm inflow water in the deeper layers of the Arkona Basin depicted almost the same temperature as its still relatively warm surface layer, only a very slight vertical temperature gradient was observed in the Arkona Basin. The waters of the November inflow were found in the Belt Sea and also at the bottom of the Arkona Basin. Here the temperature of the inflow water was about 11.8°C. It was expected that this MBI will reach at least the eastern Gotland Basin in the first months of 2016.

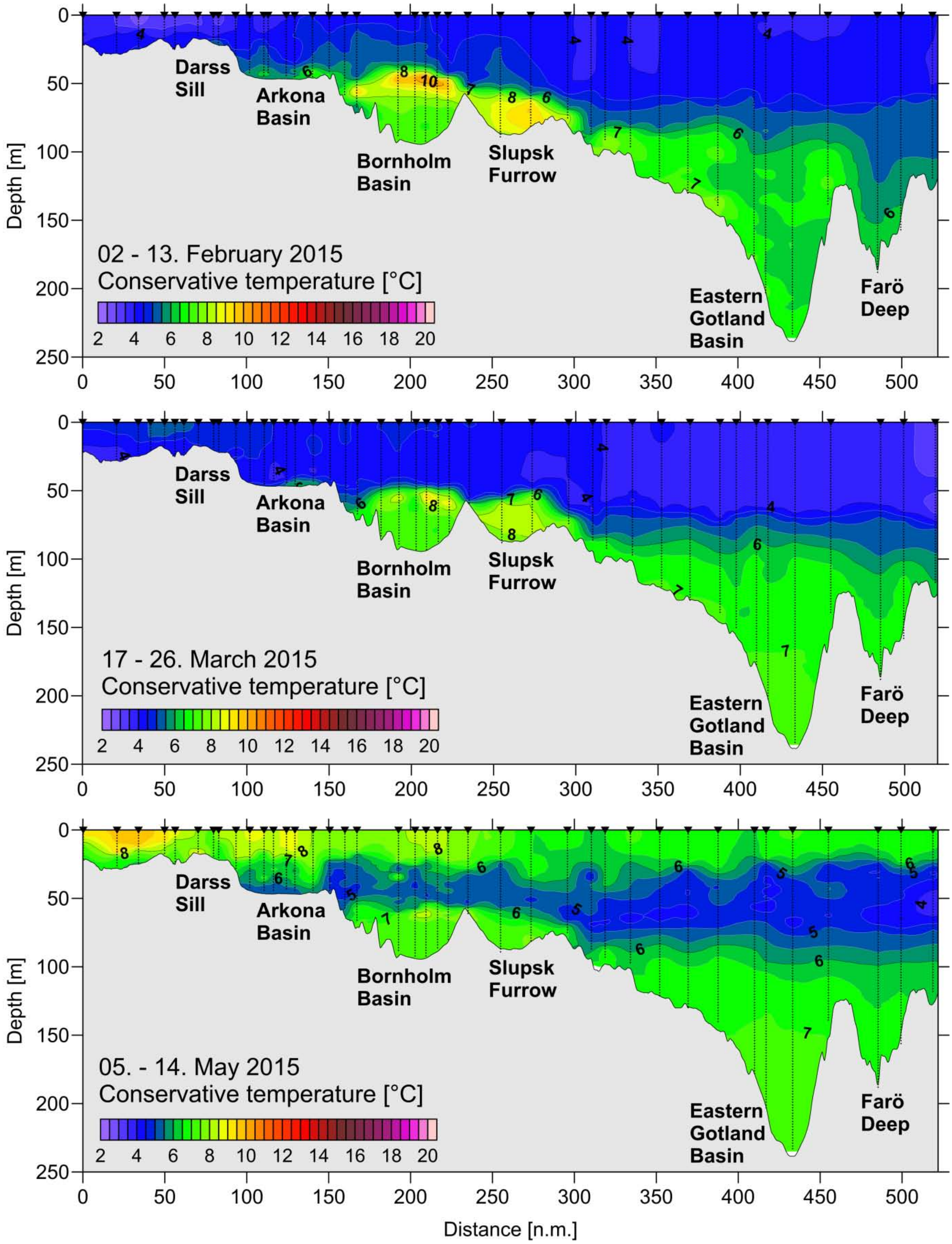


Fig. 25a: Temperature distribution along the Talweg transect through the Baltic Sea between Darss Sill and northern Gotland Basin

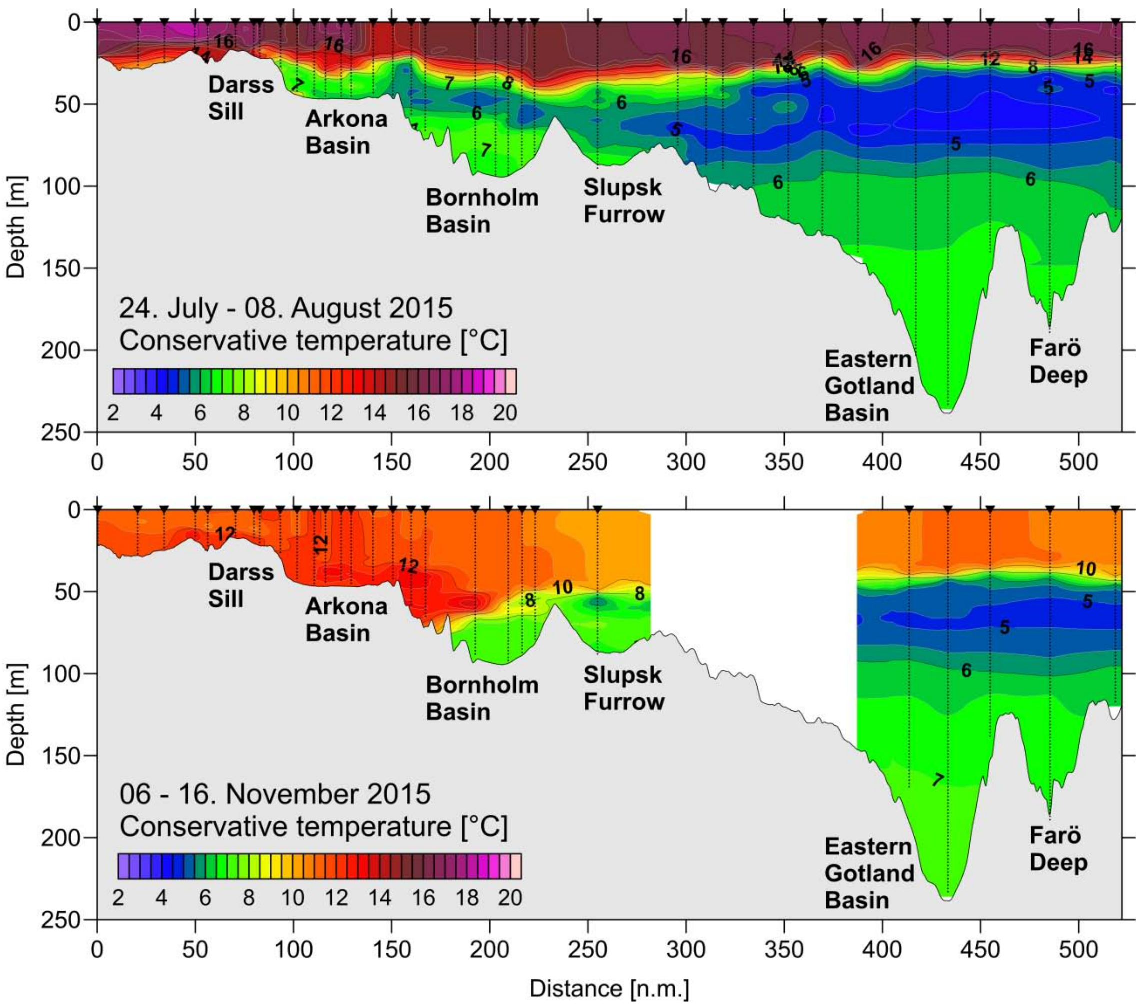


Fig. 25b: Temperature distribution along the Talweg transect through the Baltic Sea between Darss Sill and northern Gotland Basin

As part of its long-term monitoring programme, IOW has operated hydrographic moorings near station TF271 in the eastern Gotland Basin since October 2010. In contrast to the Gotland Northeast mooring, operational since 1998 and from where the well-known 'Hagen Curve' is derived, the mooring at TF271 also collects salinity data. The gathered time series data allow the description of the development of hydrographic conditions in the deep water of the Gotland Basin in high temporal resolution. This time series greatly enhances the IOW's ship-based monitoring programme. Figure 26 shows the temperature profile at five depths in the deep water of the eastern Gotland Basin in 2015. Given the heterogeneous character of the inflowing bodies of water from the Christmas MBI 2014, high variability of temperature was observed during the active inflow phase till May 2015.

Before first inflow waters arrived in the eastern Gotland Basin the temperature in deep water ranged only from 5.88°C near the bottom to about 6.0°C at 140 m depth. First patches of the old halocline water from Bornholm Basin and Slupsk Furrow deep water, pushed eastward by the December 2014 MBI, reached the eastern Gotland Basin mid of January 2015. They caused a temperature increase in all deep water layers. Maximum temperatures of about 7.5°C were observed near the sea bed in February 2015. In the layers above the temperature increase was lesser. End of February near the bottom a significant drop in temperature was observed. It marked the time when the former old deep and bottom water from the Bornholm Basin entered the deep layers of the eastern Gotland Basin. The original inflow water of the Christmas MBI 2014 arrived at the mooring position in the beginning of April 2015. It caused a nearly uniform temperature between 190m and the bottom, which was present throughout the rest of 2015. Temporal fluctuations in this were low. The inflow process in the layer between 140m and 160 m was finished end of April, indicated by the maximum of temperature. The subsequent negative trend in temperature was caused by diapycnal mixing with overlaying cooler water masses.

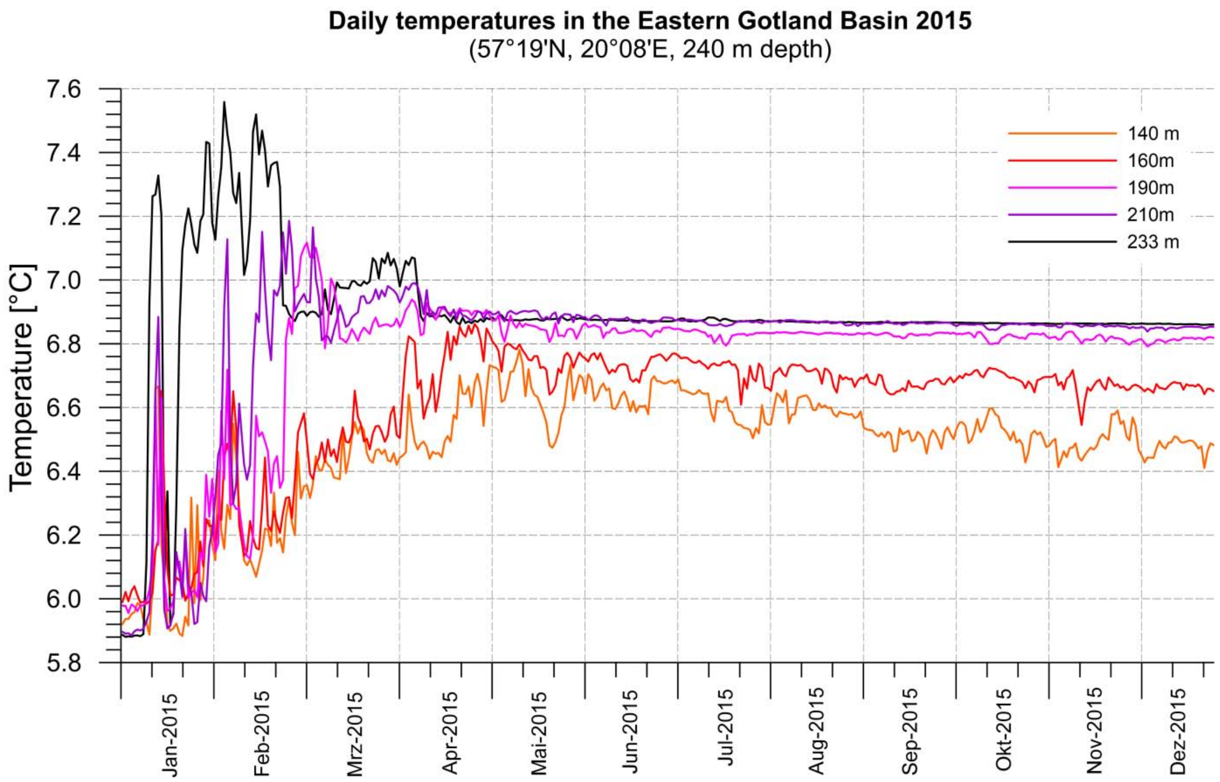


Fig. 26: Temporal development of deep water temperature in the Eastern Gotland Basin (station Tf271) from January to December 2015 (daily averages of original data with 10 min sampling interval)

Table 6 summarises the annual means and standard deviations of temperature in the deep water of the central Baltic based on CTD measurements over the past five years. The overall negative trend observed till 2014 in the central Baltic basins was stopped by the series of inflow events, namely the Christmas MBI 2014. In 2015 deep water temperatures increased in all basins. The strongest increase of 0.68°C and 0.64°C was detected in the Gotland Deep and the Farö Deep. Both basins are located in the direct pathway of inflowing saline water. The impact on the Landsort Deep and the Karlsö Deep was less pronounced. Till end of 2015 the real inflow waters have not reached the western Gotland Basin. The standard deviations of temperature fluctuations in 2015 were high in the Gotland Deep and Farö Deep. The stronger fluctuations observed there are attributable to high inflow activity and the deep-water renewal associated with it. The enhanced variability, found also in the Landsort Deep, was caused most probably by the advection of former eastern Gotland Basin deep water.

Table 6: Annual means and standard deviations of selected hydrographic parameters in the deep water of the central Baltic Sea: IOW- and SMHI data (n= 5-15)

Water temperature (° C; maximum in bold)

Station	Depth/m	2011	2012	2013	2014	2015
213 (Bornholm Deep)	80	6.48 ±0.69	6.40 ±0.40	5.55 ±0.78	6.99 ±1.29	**7.01 ±0.08**
271 (Gotland Deep)	200	6.43 ±0.00	6.42 ±0.01	6.33 ±0.03	6.11 ±0.19	**6,79 ±0,19**
286 (Fårö Deep)	150	**6.42 ±0.07**	6.14 ±0.08	5.83 ±0.05	5.69 ±0.04	6.33 ±0.25
284 (Landsort Deep)	400	**5.95 ±0.09**	5.70 ±0.06	5.46 ±0.11	5.27 ±0.06	5.46 ±0.30
245 (Karlsö Deep)	100	**5.44 ±0.07**	5.15 ±0.12	5.22 ±0.07	5.00 ±0.04	5,03 ±0.06

Salinity (maximum in bold)

Station	Depth/m	2011	2012	2013	2014	2015
213 (Bornholm Deep)	80	14.68 ±0.45	15.16 ±0.49	15.16 ±0.24	16.06 ±0.41	**18.86 ±0.25**
271 (Gotland Deep)	200	12.20 ±0.03	12.13 ±0.04	12.00 ±0.04	12.06±0.11	**12.95 ±0.35**
286 (Fårö Deep)	150	11.69 ±0.16	11.52 ±0.06	11.28 ±0.17	11.36 ±0.08	**11.93 ±0.22**
284 (Landsort Deep)	400	**10.65 ±0.02**	10.50 ±0.03	10.43 ±0.05	10.37 ±0.08	10.63 ±0.33
245 (Karlsö Deep)	100	**9.98 ±0.11**	9.61 ±0.12	9.76 ± 0.18	9.58 ±0.11	9.64 ±0.17

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

Station	Depth/m	2011	2012	2013	2014	2015
213 (Bornholm Deep)	80	**0.78 ±0.83**	1.68 ±1.45	1.62 ±1.05	2.07 ±1.47	3.60 ±1.75
271 (Gotland Deep)	200	-3.98 ±0.51	-4.81 ±0.50	**-5.30 ±0.83**	-2.94 ±2.38	0.93 ±0.80
286 (Fårö Deep)	150	-1.57 ±0.30	-2.20±0.38	-1.95 ±1.46	**-2.35 ±0.53**	-0.87 ±0.20
284 (Landsort Deep)	400	-1.06 ±0.31	**-1.24 ±0.30**	-1.11 ±0.24	-1.02 ±0.68	-0.86 ±0.18
245 (Karlsö Deep)	100	**-1.36 ±0.58**	-0.17 ±0.44	-0.72 ±0.73	-0.85 ±0.52	-0.87 ±0.51

6.2 Salinity

The vertical distribution of salinity in the western and central Baltic Sea during IOW's five monitoring cruises is shown in Figure 27. Salinity distribution is markedly less variable than temperature distribution, and a west-to-east gradient in the surface and the bottom water is typical. Greater fluctuations in salinity are observed particularly in the western Baltic Sea where the influence of salt-water inflows from the North Sea is strongest. The duration and influence of minor inflow events is usually too small to be reflected in overall salinity distribution. Only combined they can lead to slow, long-term changes in salinity. In 2015 the evolution of salinity distribution was mainly controlled by the extreme Christmas MBI 2014, which caused a significant increase in deep water salinity of the central Baltic. The salinity distributions shown in Figure 27 are mere 'snapshots' that cannot provide a complete picture of inflow activity. 2015 saw several minor inflows and a moderate MBI in November, which were recorded at different phases during IOW monitoring cruises. Three of the five data sets show an inflow event in the western Baltic. Based solely on these monitoring cruises, however, it is not possible to produce meaningful statistics on inflow events.

At the beginning of February the major fraction of the Christmas MBI 2014 waters has passed the Arkona Basin and filled the Bornholm Basin up to the sill depth of the Slupsk Sill. The salinity at the bottom of the basin was about 19.8 g/kg. The former deep water was uplifted and drained eastward into the Slupsk Furrow where it raised the halocline above the eastern sill depth. In the centre of the Arkona Basin, a 10 m to 15 m-thick salty bottom layer was observed that contained saline water of the small inflow in January 2015 (cf. chapter 2). Bottom salinity in the Arkona Basin at this time measured a maximum of 22.8 g/kg. West of the Darss Sill high saline water covered the lower part of the water column.
After a long period of stagnation, salinity in the deep water of the central Baltic Sea was

relatively low at the beginning of 2015, although some amounts of water from the minor inflows in 2014 have reached the eastern Gotland Basin. On the seabed in the Gotland Deep, salinity was only 12.31 g/kg in February 2015. The 12 g/kg isohaline lay at a depth of around 163 m.

By the second half of March first saline waters of a minor inflow were observed. The bottom salinity in the Belt Sea was about 21 g/kg. The former pool of saline water in the Arkona Sea vanished. Here bottom salinity dropped to 15.62 g/kg. In the Bornholm Basin the halocline was still slightly above the sill depth of the Slupsk Sill, pointing to ongoing drainage of saline water into the Slupsk Furrow. There the halocline was uplifted to 55 m. The Slupsk Furrow kept large amounts of saline water from the MBI 2014. However, a fraction of MBI 2014 waters has passed the eastern Sill of the channel and spread toward the eastern Gotland Basin. In the Gotland Deep, inflow of saline water led to a significant increase in bottom salinity to 13.17 g/kg, and caused the 12 g/kg isohaline to rise 20 m to a depth of 143 m. Yet the Farö Deep was not affected by the inflow process. The bottom salinity was only 11.86 g/kg here.

At the beginning of May, the major part of inflow waters from the March inflow has already passed the Arkona Basin. However, there is still a pool of saline water in the Arkona Basin, with bottom salinity of 17.4 g/kg. The halocline in the Bornholm Basin relaxed to the sill depth of the Slupsk Sill. Below the halocline the basin was filled with the high saline waters of the Christmas MBI 2014. The bottom salinity of 19.48 g/kg was nearly constant since March 2015. In the Slupsk Furrow the halocline depicted an eastward slope from 55 m depth near Slupsk Sill to 70 m at the eastern sill of Slupsk Furrow. Large amounts of saline water have left the Slupsk Furrow, drained towards the eastern Gotland Basin. The deep part of the basin was filled up with saline inflow water. The bottom salinity increased to 13.54 g/kg in the Gotland Deep, which is close to the overall maximum value, observed after the extreme MBI in 1951. The 12 g/kg isohaline rose another 17 m to a depth of 130 m. First water started to overflow the sill to the Farö Deep. Here the bottom salinity increased to 12.11 g/kg, and the 12 g/kg isohaline was found at depth of 170 m.

In July no significant changes of salinity distribution were detected in the western Baltic. In the Bornholm Basin mixing with overlaying water caused a slight dilution of deep water. The bottom salinity sunk little to 19.14 g/kg. The inflow process into the eastern Gotland Basin has finished in July 2015. In the Gotland Deep the depth of the 12 g/kg isohaline and the bottom salinity remaining practically unchanged. However, the overflow to the Farö Deep continued until July. The bottom salinity increased further to 12.23 g/kg, and the 12 g/kg isohaline rose 28 m to a depth of 142 m.

At the beginning of November, salinity stratification in the western Baltic was influenced by the minor inflows of October and the inflow of November 2015, visible west of the Darss Sill. Bottom salinity in the Arkona Sea was 23.3 g/kg. The warm October inflow was insufficiently dense to replace the deep water in the Bornholm Basin, and spread along the halocline through the Bornholm Basin halocline. However, due to diapycnal mixing the bottom salinity in the Bornholm Deep decreased to 18.9 g/kg. The saline inflow into the deep water of the central Baltic was finished. Between July and November 2015, the depth of 12 g/kg isohaline has not changed significantly.

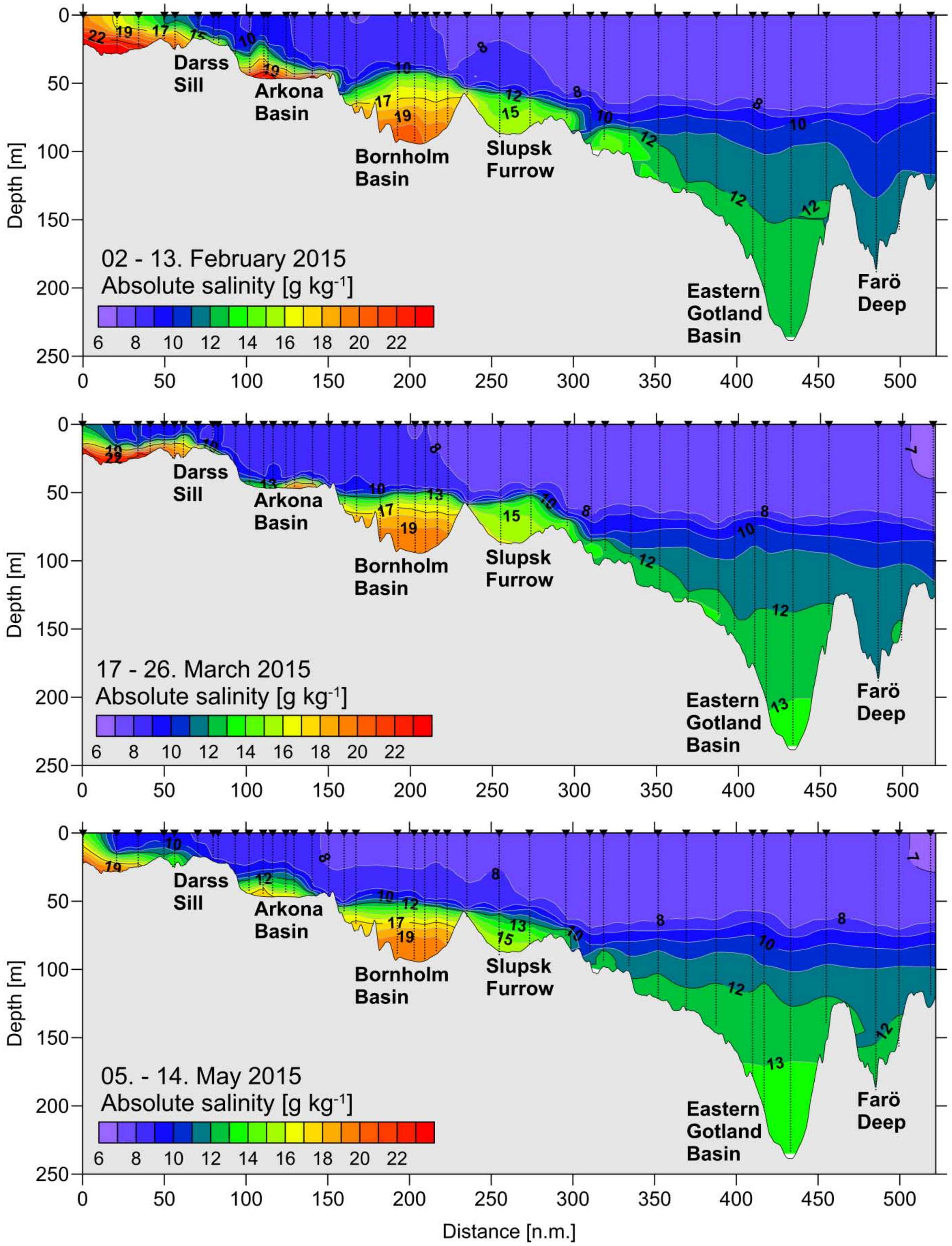


Fig. 27a: Salinity distribution along the Talweg transect through the Baltic Sea between Darss Sill and northern Gotland Basin

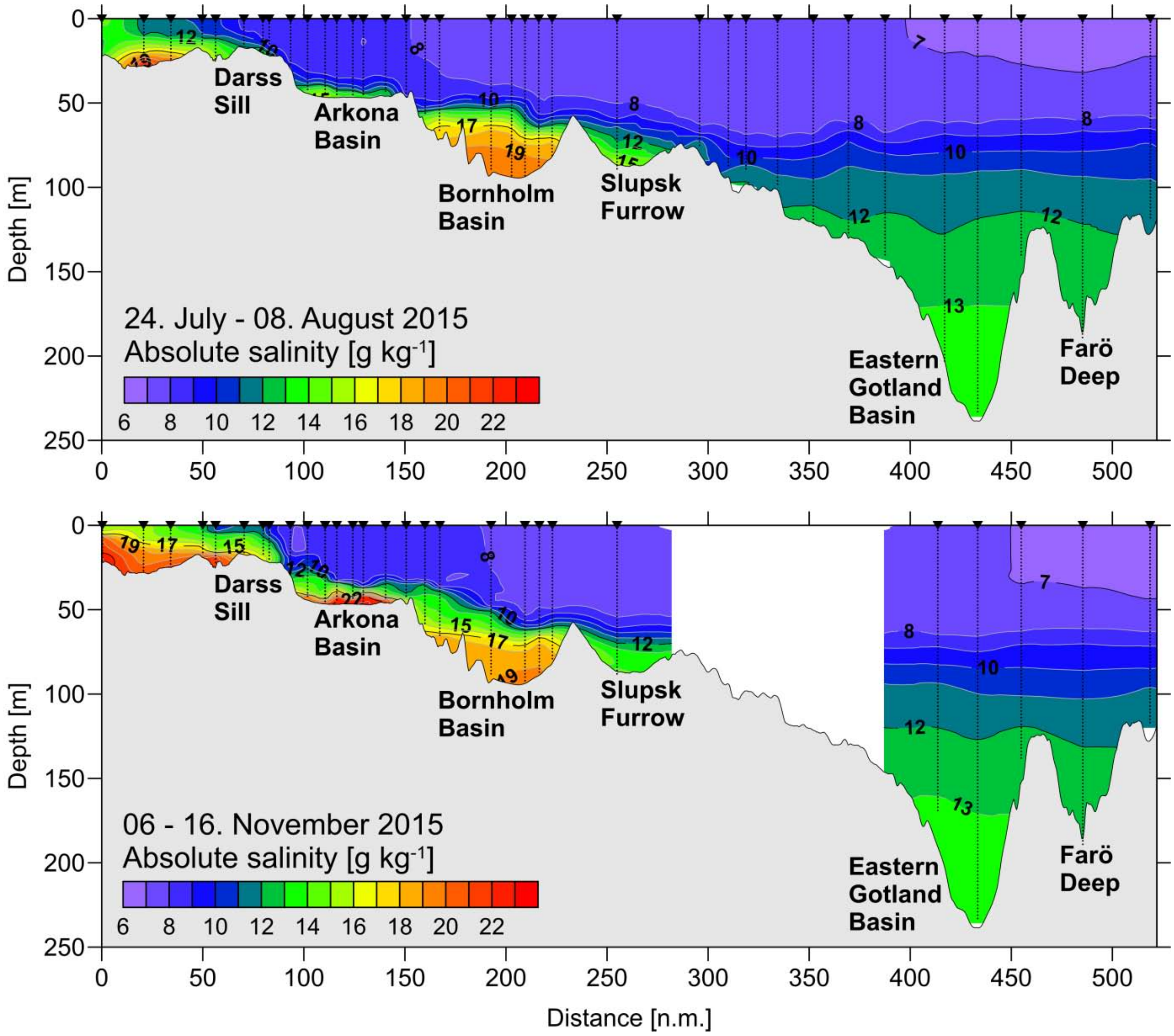


Fig. 27b: Salinity distribution along the Talweg transect through the Baltic Sea between Darss Sill and northern Gotland Basin

Table 6 shows the overall trend of salinity in the deep water of the Baltic in the past five years. Generally, the decline in salinity that has been observed in recent years has stopped in the central Baltic. As a result of the recent series of inflow events the salinity the central Baltic rose significantly. Due to the extreme Christmas MBI 2014 the bottom salinity in the Bornholm Deep, the Gotland Deep and Fårö Deep reached maximum values of the past five year period. The Karlsö Deep and Landsort Deep were exceptions. Since the inflows have not reached the western Gotland Basin only a slight bottom salinity increase was observed at both stations.

No clear trend emerges over the past five years for salinity in the surface layer of the Baltic. Table 7 summarises the variations in surface layer salinity. Compared to values in 2014, surface layer salinity in the eastern Gotland Basin rose slightly in 2015. Concurrently, the surface salinity has decreased in the western Gotland Basin. Standard deviations of surface salinity are roughly on a level with those of the long term average, and thus are in the usual range.

Table 7: Annual means of 2011 to 2015 and standard deviations of surface water salinity in the central Baltic Sea (minimum values in bold, n= 8-25). The long-term averages of the years 1952-2005 are taken from the BALTIC climate atlas (FEISTEL et al., 2008a)

Station	1952-2005	2011	2012	2013	2014	2015
213 (Bornholm Deep)	7.60 ±0.29	**7.23 ±0.11**	7.64 ±0.11	7.28 ±0.12	7.65 ±0.18	7.76 ±0.20
271 (Gotland Deep)	7.26 ±0.32	7.15 ±0.19	7.10 ±0.13	**6.78 ±0.28**	6.87 ±0.17	7.06 ±0.15
286 (Fårö Deep)	6.92 ±0.34	6.96 ±0.24	6.91 ±0.16	**6.64 ±0.29**	6.73 ±0.21	6.74 ±0.25
284 (Landsort Deep)	6.75 ±0.35	6.68 ±0.40	**6.27 ±0.38**	6.52 ±0.12	6.60 ±0.24	6.29 ±0.44
245 (Karlsö Deep)	6.99 ±0.32	6.81 ±0.24	6.97 ±0.21	**6.77 ±0.10**	7.00 ±0.13	6.91 ±0.25

Figure 28 shows the temporal development of salinity in the deep water of the eastern Gotland Basin in 2015, based on data from the hydrographic moorings described above. Concurrently with the first jump in temperature also a weak increase in salinity was observed in January 2015 when first patches of the old halocline water from Bornholm Basin and Slupsk Furrow deep water arrived. End of February a further significant jump in near bottom salinity was observed, indicating the arrival of the former old deep and bottom water from the Bornholm Basin. Until mid of April the salinity in all deep water level increased continuously. The maximum salinity was reached mid to end of April 2015. Than the original inflow water of the Christmas MBI 2014 arrived at the mooring position. From January to end of April the vertical salinity gradient increased from 0.004 g/kg m to nearly 0.008 g/kg m. The strong density stratification will effectively suppress the diapycnal mixing for the near future. Till December 2015 only a week decrease of deep water salinity was observed. As with temperature, the salinity time series reveal strong, short-term fluctuations whose amplitude decreases with depth. For the most part, these fluctuations correlate well with the observed temperature variability.

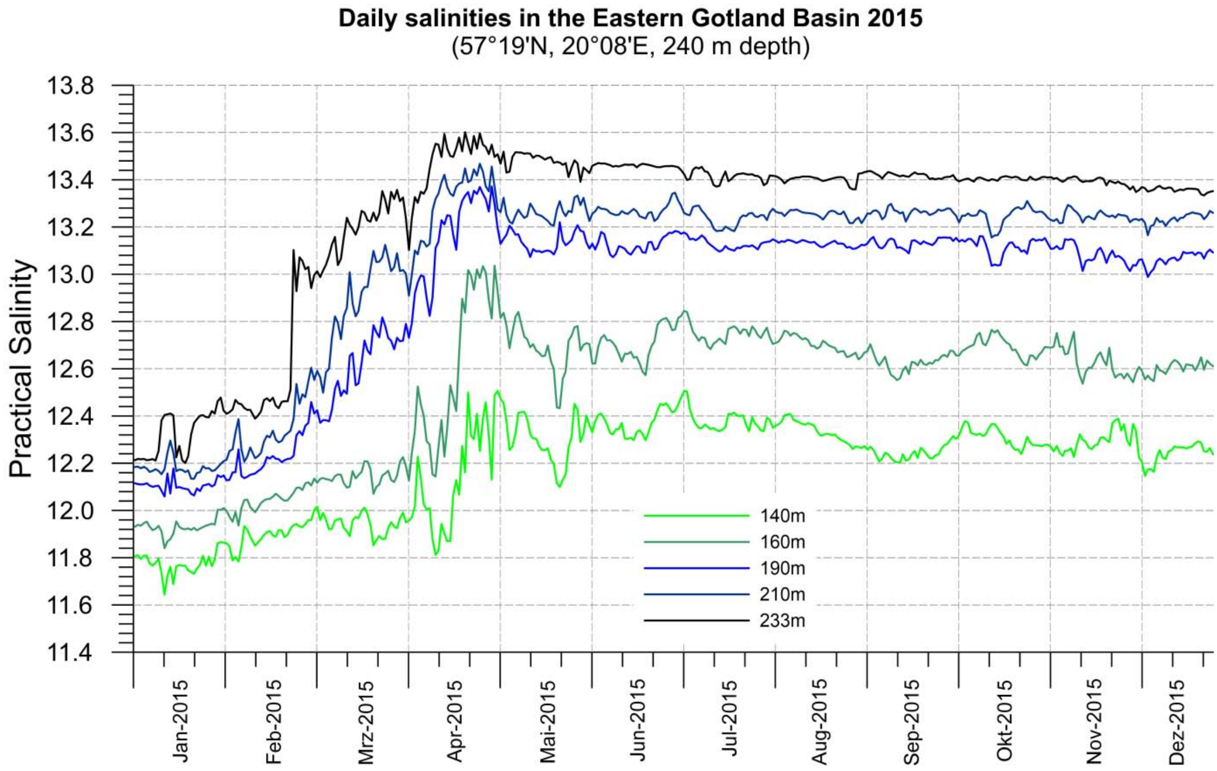


Fig. 28: Temporal development of deep water salinity in the Eastern Gotland Basin (station TF271) from January to December 2015 (Daily averages of original data with 10 min sampling interval)

Figures 25 and 27 depict the Talweg transect of the Baltic in a relatively coarse spatial resolution based on CTD profiles. To investigate the smaller spatial structures a hydrographic transect with a towed undulating CTD (ScanFish) was performed during the cruise in March 2015. Figure 29 displays a section of this transect through the Bornholm Basin. The saline deep water pool in the basin consisted of several water masses and their mixing stages. It illustrates the complexity of the inflow process which has to be recognized for a detailed analysis of the recent sequence of saline inflows. Water with salinity higher than 17 g/kg originated from the Christmas MBI 2014, and filled the deep water layer of the basin. In the eastern part the high temperature in the halocline indicate water masses mixed up from the late summer inflows 2014 and the MBI waters. The halocline water in the western Basin has a low temperature, similar to the surface water. This patch originated from the January 2015 inflow. Overall, the temperature-salinity distribution is very patchy. There exists no "inflow water" with uniform properties. Further transformations will occur during the eastward spreading of the saline water. This explains to a wide extent the large fluctuations in the time series data observed during the active inflow process in the Gotland Deep.

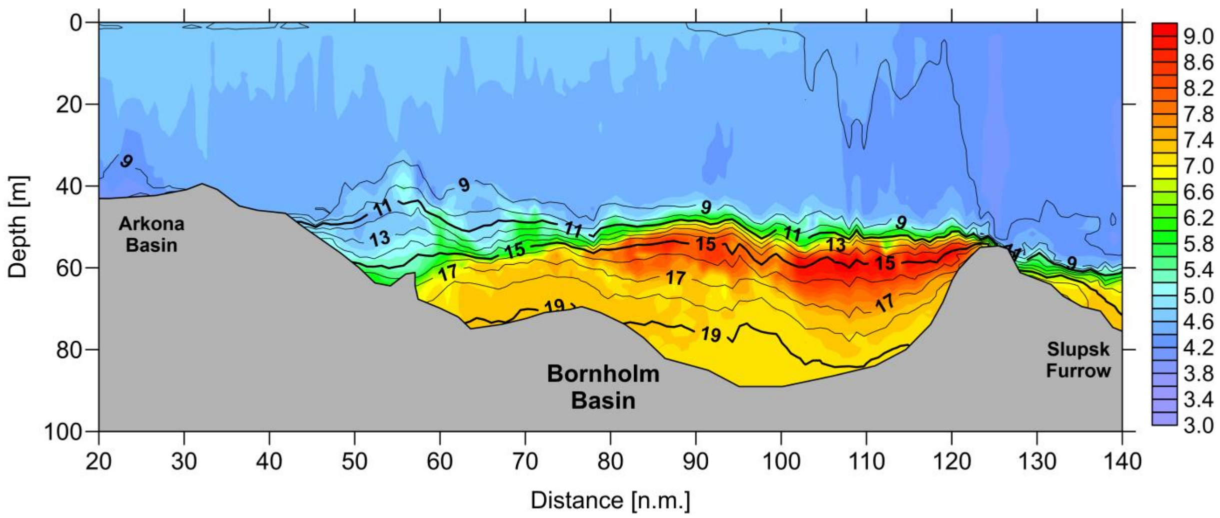


Fig. 29: Temperature (color contour) and practical salinity (isolines) distribution across the Bornholm basin in March 2015. High spatial resolution data obtained with ScanFish measurements.

6.3 Oxygen Distribution

The oxygen supply in the surface layer can be generally considered to be good due to intensive exchange processes with the atmosphere and the primary production by phytoplankton in the euphotic surface layer. Fluctuations in oxygen concentrations are mainly determined by the annual cycles of temperature and salinity, and by seasonally-variable production and consumption processes. Additionally, hydrodynamic processes can play an important role, especially in the highly variable western Baltic Sea. Below permanent or temporary pycnoclines caused by temperature and/or salinity, significant oxygen consumption can occur. As sunlight does not reach these layers, only consumption processes prevail there.

In the mixed surface layer, a typical annual cycle of oxygen concentrations can be observed (MATTHÄUS, 1978, NAUSCH et al., 2008a). The high oxygen solubility at low temperatures in winter and spring causes high oxygen concentrations.

The winter 2014/2015 was mild. Positive anomalies of 1.5 – 2 K characterized the period from November 2014 to April 2015 in the entire Baltic Sea (cf. chapter 6.1.1) causing relative low oxygen values. Highest oxygen concentrations were found in all areas during March/April when temperature is still low but phytoplankton starts to grow. In the further course of the year, the rapid rise in temperature markedly reduces oxygen solubility. Oxygen concentrations in the summer are generally well below 7 ml/l. In all sea areas, the differences between 2014 and 2015 were negligible. Autumnal cooling again caused an increase in oxygen concentrations (Table 8).

Table 8: Annual oxygen cycle in the mixed surface layer (0 – 10 m) in the years 2014 and 2015

	February	March/April	May	July	November
western Baltic					
O_2 (ml/l)	**8.76/8.00**	**7.77/8.81**	**7.89/7.59**	**6.32/6.47**	**6.55/7.29**
std. dev. (ml/l)	0.19/0.19	0.25/0.31	0.27/0.22	0.21/0.10	0.13/0.16
n	5/5	5/5	5/5	4/3	5/5
Arkona Basin					
O_2 (ml/l)	**8.75/8.34**	**9.15/9.29**	**8.40/8.18**	**6.40/6.94**	**6.87/7.18**
std. dev. (ml/l)	0.11/0.06	0.10/0.16	0.11/0.18	0.16/0.14	0.14/0.04
n	13/13	13/13	13/13	13/13	13/13
Bornholm Basin					
O_2 (ml/l)	**8.66/8.32**	**8.67/9.12**	**9.70/8.64**	**6.44/6.56**	**7.01/7.28**
std. dev. (ml/l)	0.09/0.02	0.03/0.11	0.18/0.14	0.06/0.03	0.04/0.06
n	4/4	3/5	4/5	4/5	4/4
eastern Gotland Basin					
O_2 (ml/l)	**8.69/8.51**	**8.78/8.93**	**10.27/8.82**	**7.19/6.77**	**7.34/7.25**
std. dev. (ml/l)	0.05/0.04	0.07/0.04	0.25/0.26	0.23/0.09	0.15/0.02
n	7/9	8/8	9/9	9/9	9/2

To eliminate the influence of temperature and salinity on oxygen solubility, oxygen saturation is often the preferred measure over oxygen concentrations as it greatly improves the comparability of measurements. Figure 30 summarises the oxygen saturation values in the surface layer in 2015 for the western Baltic, the Arkona Basin, the Bornholm Basin and the eastern Gotland Basin. The seasonal development becomes obvious. Due to the dominance of oxygen-consuming processes and low productivity, the surface water in February in all sea areas was slightly undersaturated at 95 to 96 % (Figure 30). The winter 2014/15 was one of the warmest since 1948. Thus phytoplankton development started early. Thus, in March in all four investigated areas saturation was over 100 % whereby the spring bloom in the eastern Gotland Basin was at the beginning and reached its maximum as in the Bornholm Basin in May. In general, no real high spring bloom could be observed. This can be either due to low productivity or we missed the peak due to low sampling frequency. In comparison, in 2014 saturation values between 120 % and 125 % were observed in the Bornholm Basin and the eastern Gotland Basin. However, the extreme saturation levels of between 140 % and 160 % as described for 1994 by NEHRING et al. (1995) were never reached during the last years. The summer period 2015 is characterized by only slight oversaturation around 105 %. This is an indication that no huge cyanobacteria blooms occurred. In the autumn, intensified degradation processes again led to undersaturation between 95 and 100 %. Overall it can be concluded that the annual range of variation in saturation was relatively small, as in previous years. This indicates a healthy oxygen balance in the surface water.

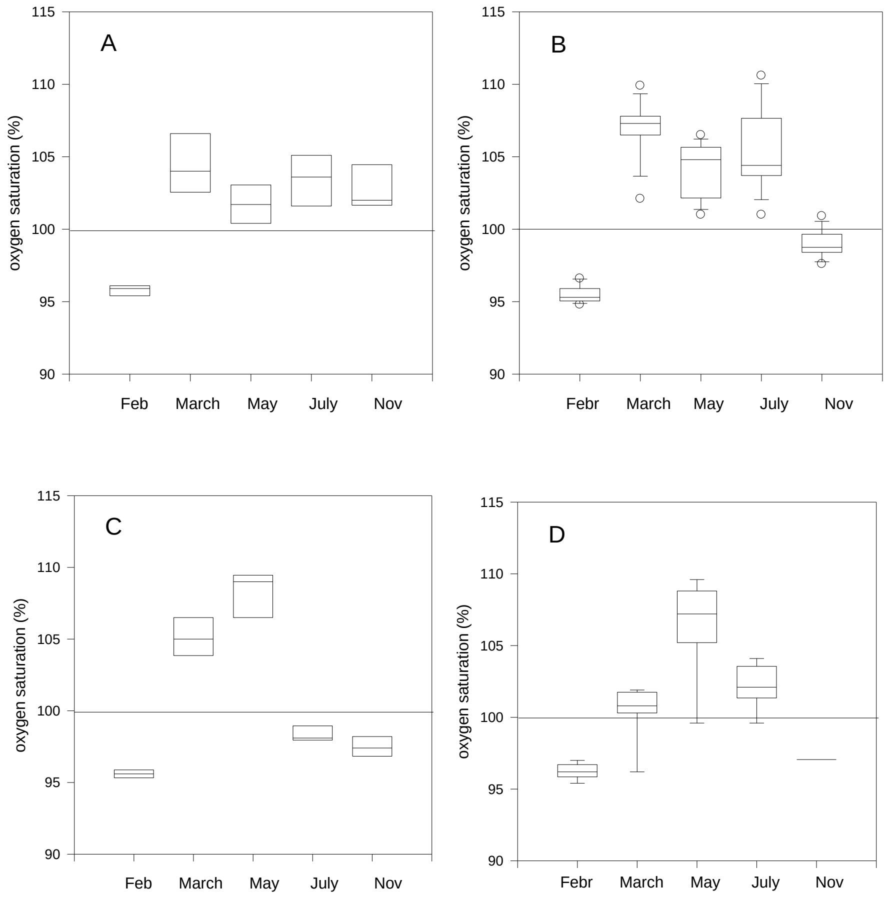


Fig. 30: Box-Whisker- Plots of oxygen saturation (%) in 2015 in the mixed surface layer (0-10 m) of the western Baltic (A), the Arkona Basin (B), the Bornholm Basin (C) and the eastern Gotland Basin (D)

In the western Baltic Sea and in the Arkona Basin, a pronounced annual cycle of oxygen concentration and saturation can be observed in the near bottom layer. Figure 31 compares the year 2015 with the period 2008-2014. During winter time vertical mixing occurs quite often down to the bottom. In addition in 2015 the intensive inflow processes led to repeated renewal of the bottom water and oxygen supply. Thus in the western Baltic, oxygen saturation is quite the same as in the surface layer. In the deeper Arkona Basin still 85 % saturation can be measured. The situation does not change significantly in March. The development of thermal stratification and increased degradation of organic matter lead in the course of the year to a decline in oxygen saturation in near-bottom layers of both sea areas. In May, 72.3 % (western Baltic) resp. 66.3 (Arkona Basin) were measured. Lowest oxygen saturation is normally found in late summer/early autumn before cooling of the water and storm driven mixing increases saturation in November again. Relativ low saturation values of 26.7 % were registered in the western Baltic Sea whereas the situation in the Arkona Basin was comparable with the long term mean. In general, the year 2015 does not deviate considerably from period 2008-2014.

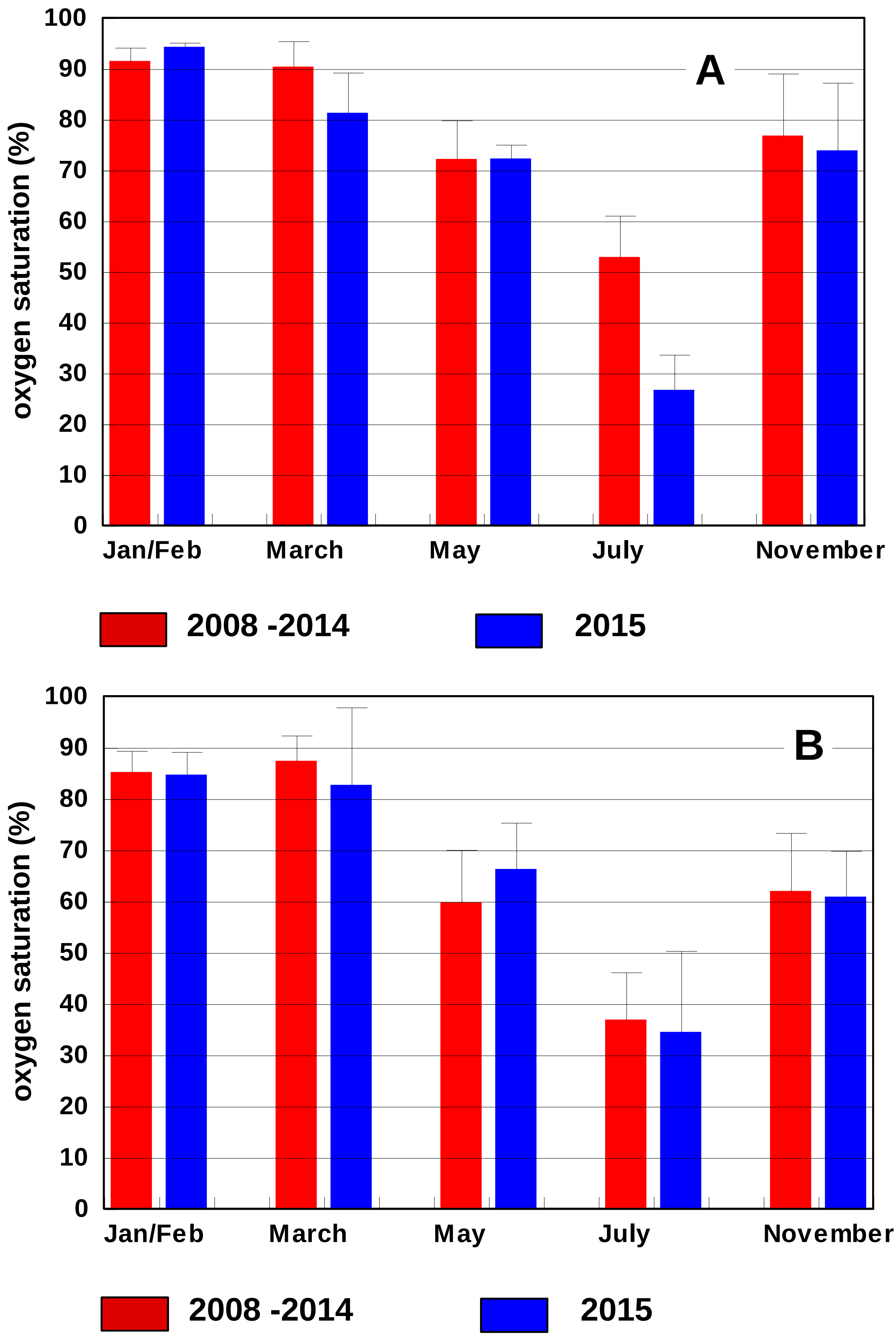


Fig. 31: Oxygen saturation in the near bottom layer in the western Baltic Sea (A) and the Arkona Basin (B) for 2015 in comparison with the period 2008-2014

The period of greatest oxygen depletion is generally observed in late summer / early autumn – the time of the year not covered by IOW cruises. Nevertheless, the Landesamt für Landwirtschaft, Umwelt und ländliche Räume des Landes Schleswig-Holstein (LLUR) has for many years measured near-bottom oxygen concentrations at that time of the year. Investigations in 2015 were conducted from 14th to 29th September. Near-bottom oxygen concentrations were measured at 37 stations, 30 of them at depths >15 m (Figure 32).

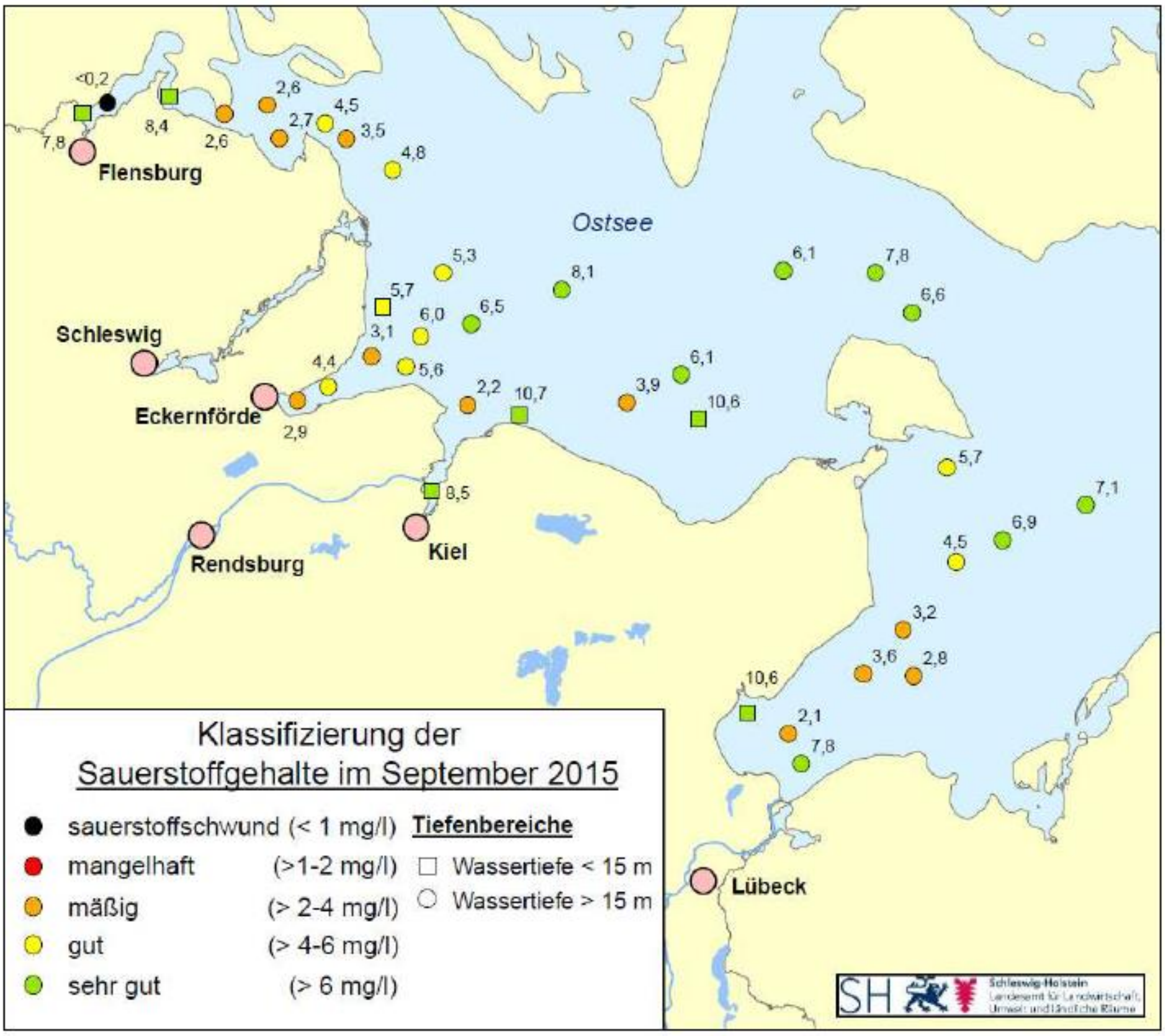


Fig. 32: Oxygen deficiency in the western Baltic Sea in September 2015 (LLUR, 2015) – O2 [mg/l] x 0.7005 = O2 [ml/l

Evaluation of measurements from 2015 at stations with water depths >15 m shows that only 3 % (1 station) of all measurements were classified as *poor* or *inadequate* (<2 mg/l oxygen). The station is located in the inner Flensburg Fjord. At the bottom also hydrogen sulphide could be detected. In 2014 these were 30 %; 2013, the figure had been 36 %; in 2012, as much as 68 % of measurements had been so classified. In 2002, the year with the poorest oxygen conditions so far, their share had been 91 %. The quota of measurements showing *deficient* oxygen conditions (>2 mg/l to 4 mg/l) was some 40 % (2014: 33 %, 2002: 4 %).

According to LLUR, oxygen deficiency in late summer/ early autumn is a phenomenon that was observed in the western Baltic only occasionally until the 1970s. Admittedly, thorough autumn sampling campaigns did not really get underway until the early 2000s. Figure 33 summarises the results of the trend analysis: the percentage share of stations with near-bottom oxygen concentrations ‹2 mg/l shows a slightly declining trend; in 2015, the smallest value in the time series was observed ever. Keep in mind, however, that significant interannual variations exist in the hydrographic conditions, that the sampling time was not identical from year to year, and that the number of sampled stations varied. It must be concluded that further reductions in nutrient inputs are needed if oxygen conditions in the autumn are to improve in the long term.

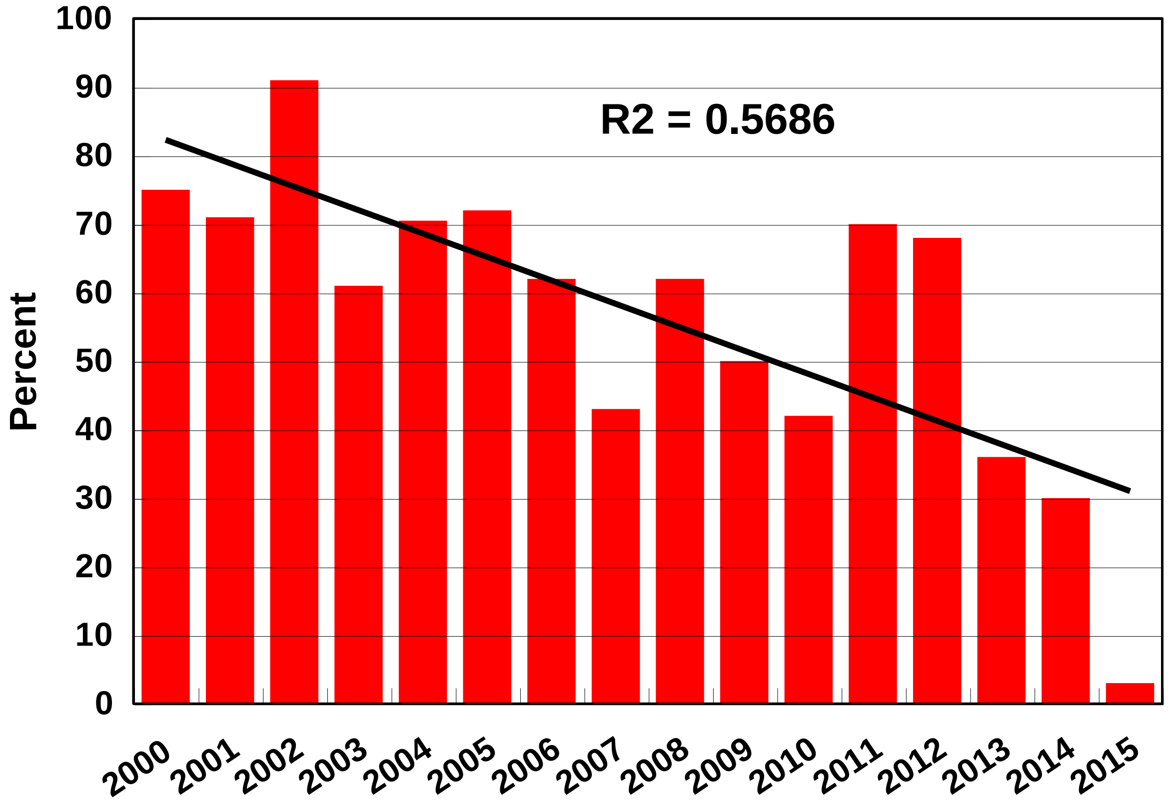


Fig. 33: Percentage of stations with an oxygen content ‹ 2mg/l in the bottom near layer in the western Baltic Sea in autumn – data LLUR

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

In the more easterly, deeper basins of the Baltic Sea, in contrast, deep-water conditions are primarily influenced by the occurrence or absence of strong barotropic and/or baroclinic inflows. Figure 34 shows oxygen conditions along a transect from Darss Sill to the northern Gotland Basin during the five monitoring cruises undertaken in 2015.

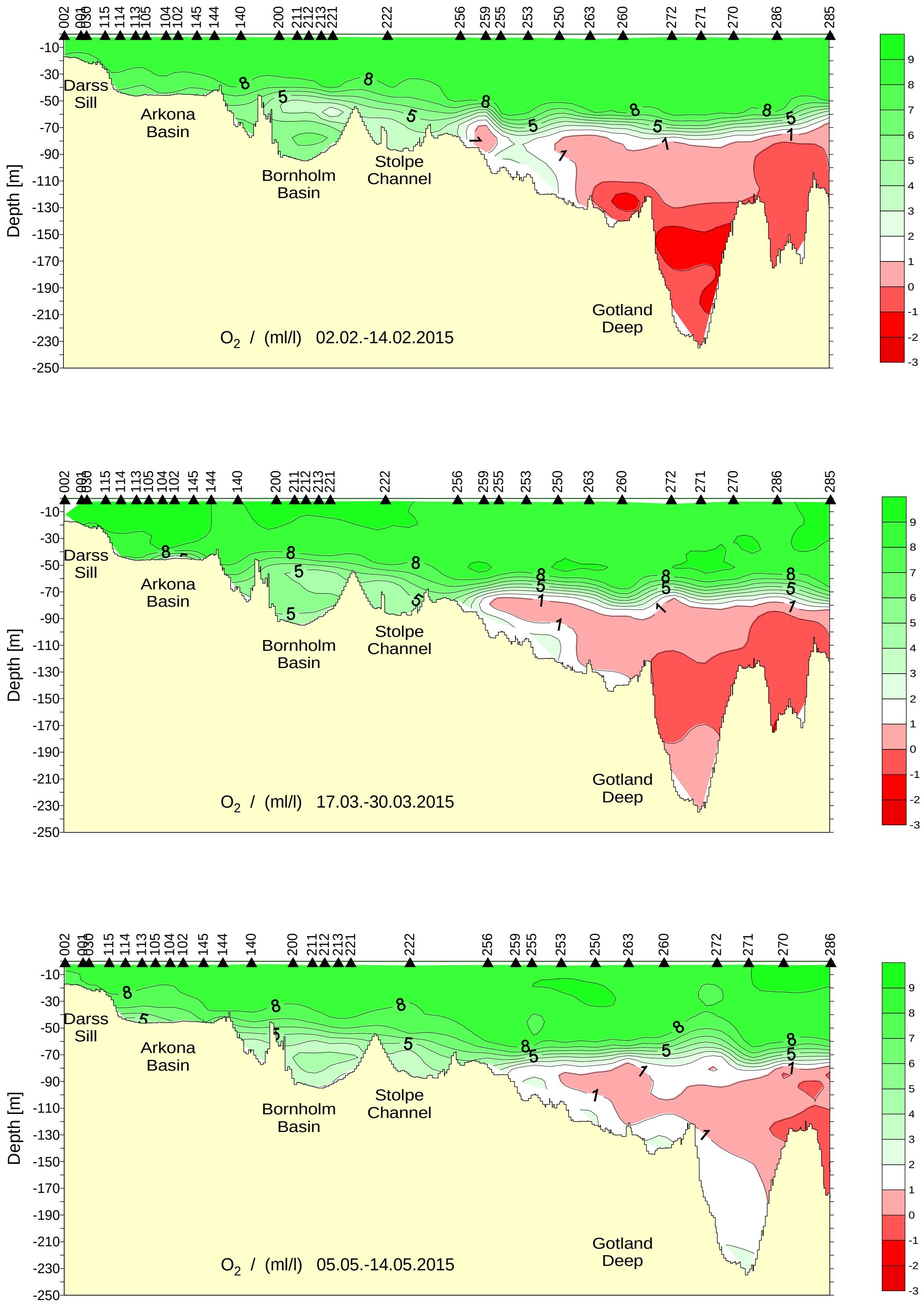


Fig. 34a: Vertical distribution of oxygen resp. hydrogen sulphide 2015 between Darss Sill and northern Gotland Basin

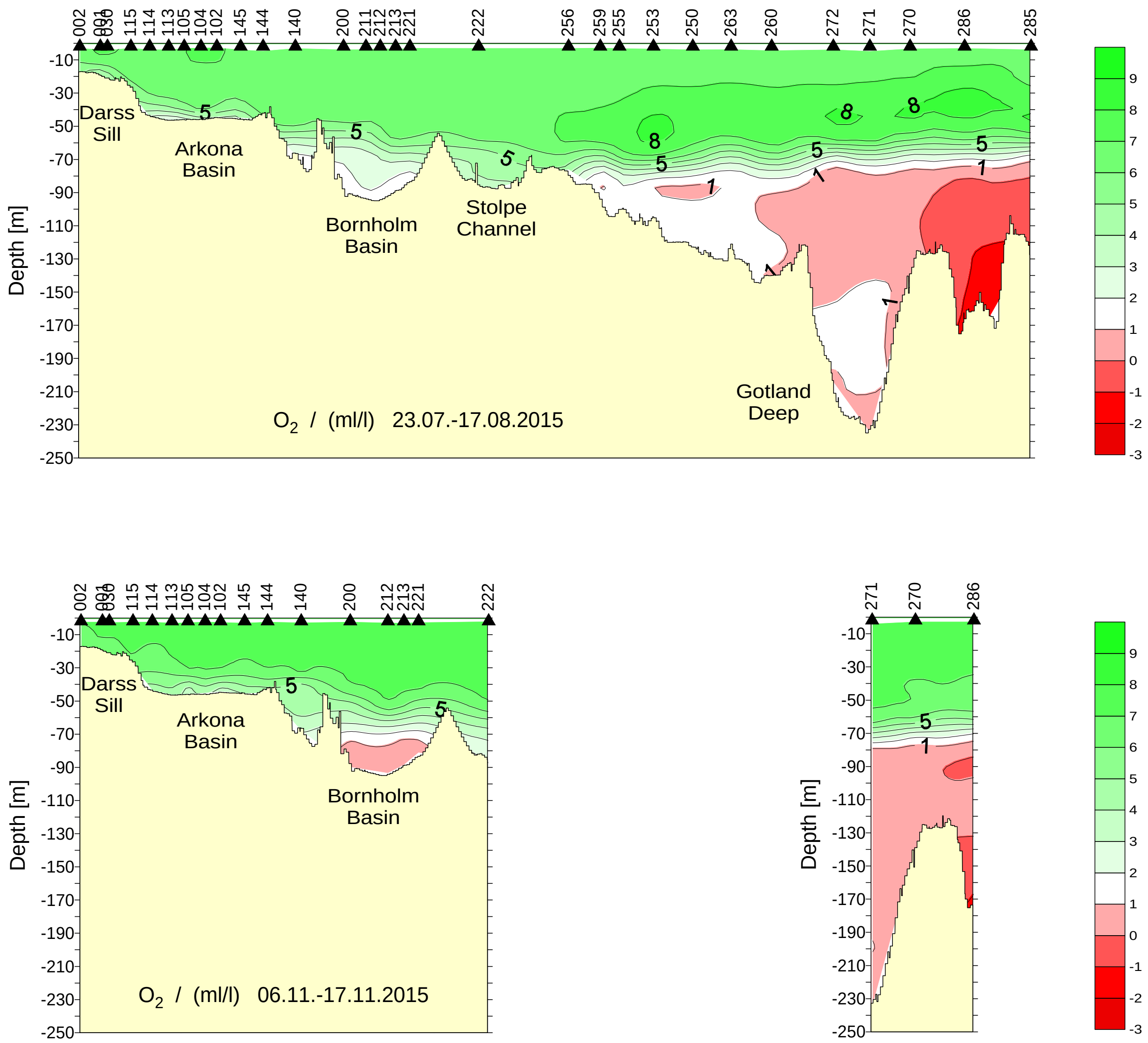


Fig. 34b: Vertical distribution of oxygen resp. hydrogen sulphide 2015 between Darss Sill and northern Gotland Basin

The Bornholm Basin is the westernmost of the deep basins. Barotropic and baroclinic inflows are often able to ventilate its deep water. The situation in 2015 was coined by the Major Baltic Inflow (MBI) of December 2014 which was together with 1913 the third largest on record (MOHRHOLZ et al., 2015). The highly saline water transported huge amounts of well oxygenated water into the basin. Thus, the oxygen content increased in the 80 m horizon of the Bornholm Deep from mid December 2014 (0.31 ml/l) to 5.90 ml/l in the beginning of February 2015. This development can be seen clearly in Figure 35. During the further course of the year oxygen concentrations decreased due to mineralisation processes to 0.77 ml/l in the mid of November. The effects of a further MBI in November 2015 could not yet detected with the last monitoring cruise of the year, but increased the oxygen content on January 30th 2016 to 1.47 ml/l.

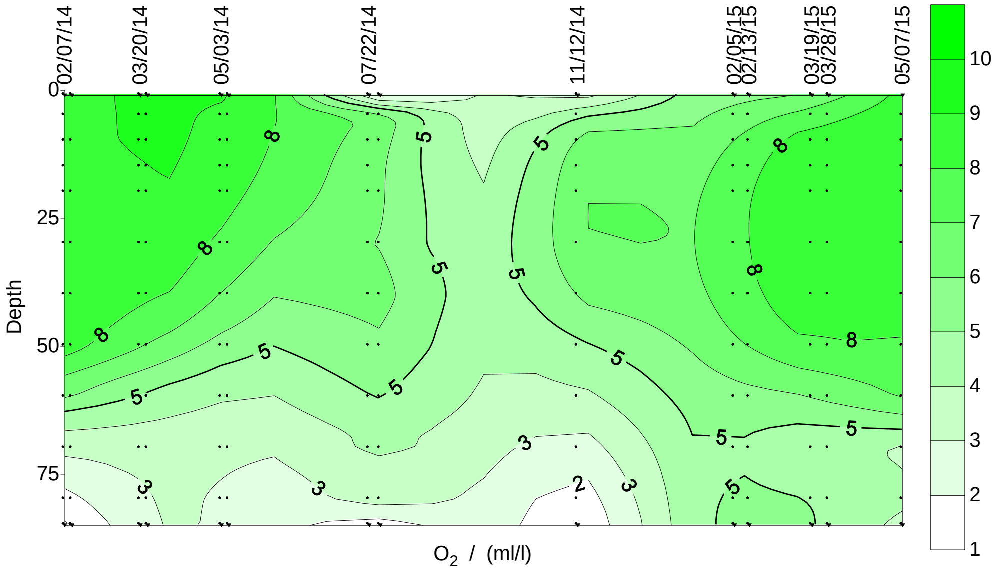


Fig. 35: Oxygen development in the Bornholm Deep between February 2014 and July 2015

However all in all, the annual mean in 80 m depth of 3.60 ml/l is the second highest since 2001 and can be compared with the situation after the MBI of January 2003 (Figure 36). In general it is evidenced by long-term developments that since 2006, predominantly oxic conditions prevailed in the deep water of the Bornholm Basin. Low amounts of hydrogen sulphide have been measured only occasionally, for instance in November 2013. The inflow events in autumn 2013, in February and March 2014 led already in 2014 to relatively good oxygen conditions (NAUSCH et al., 2014) and formed good pre-condition for the MBI of December 2014 (MOHRHOLZ et al., 2015).

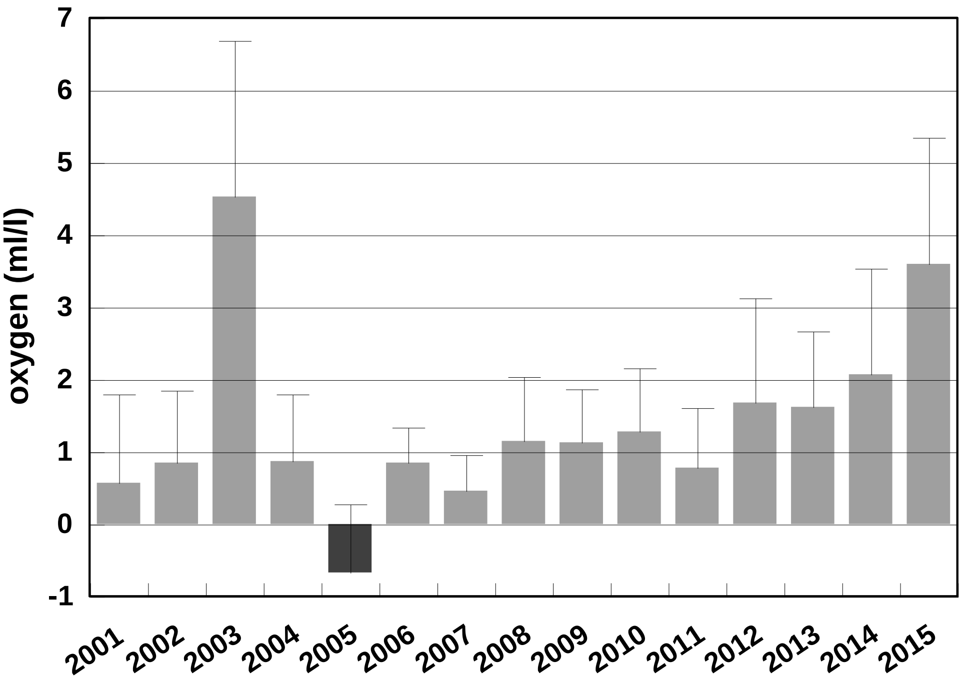


Fig. 36: Annual mean of oxygen concentration at 80 m depth in the Bornholm Deep (station 213) – IOW and SMHI data

The MBI of December 2014 proceeded further into the central basins. Already in March 2015 0.4 – 0.9 ml/l were measured below 170 m in the eastern Gotland Basin (Figs. 34, 37). The inflow events in autumn 2013, in February and March 2014 were able to advance into the eastern Gotland Basin whose deep water they oxygenated repeatedly - if briefly - for the first time since 2003 (NAUSCH et al., 2014). Although none of these three events fulfilled the typical characteristics of a Major Baltic Inflow, comparably large amounts of water, salt, and oxygen were imported into the deep water of the Baltic Sea in combination (a novel form of deep-water ventilation that was described for the first time). The concentrations of hydrogen sulphide measured in the eastern Gotland Basin towards the end of 2014 were thus relatively low. Usually at the end of a long period of stagnation, values between –5 ml/l and –7 ml/l are found, as was the case at the beginning of 2014. Thus, the MBI met relatively favourable conditions in the depth. In April 2015 an additional cruise measured oxygen concentrations up to 3 ml/l. However, all the time an intermediate layer of different thickness remained below the halocline where quite low amounts of oxygen or even traces of hydrogen sulphide remained. It was quite astonishing that despite these "good" pre-conditions oxygen started rapidly to decrease. At 200 m in the Gotland Deep around 1 ml/l remained in the middle of November. An explanation of this rapid and unexpected decrease is still open. However, several inflow events at the turn of 2015/2016 were able to improve the situation again.

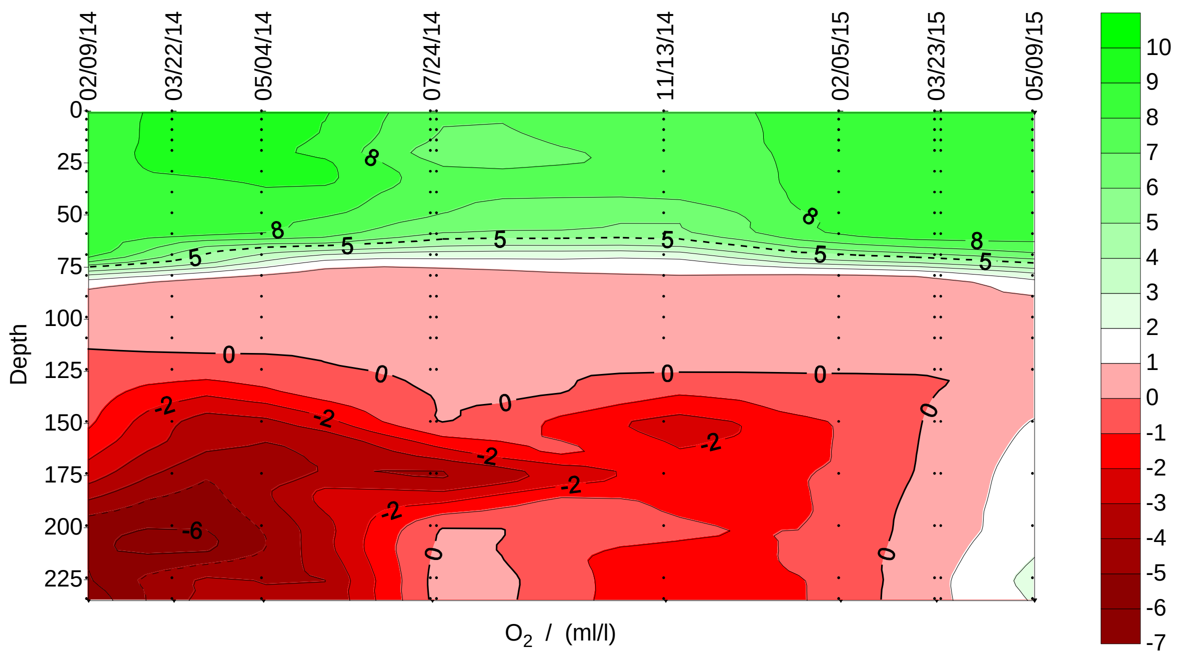


Fig. 37: Oxygen development in the Gotland Deep between February 2014 and July 2015

Surprisingly, the huge amount of highly saline, dense water was unable to ventilate the further north located Farö Deep. However, increasing salinity and temperature values as well as decreasing hydrogen sulphide concentrations may be an indicator that oxygenated water could penetrate to the Farö Deep, partly able to oxidize hydrogen sulphide but be unable to turn the system completely to oxic conditions. On the other hand, the “old” water was pushed away worsen the situation on the entrance to the Gulf of Finland. In the Landsort Deep area the same observation can be done as for the Farö Deep, but in alleviated form, and based only on sparse data.

6.4 Inorganic Nutrients

Eutrophication is still considered to be the most serious anthropogenic threat to the Baltic Sea (HELCOM, 2007). This is also supported by the most recent assessment of HELCOM (HELCOM, 2014):”The entire open Baltic Sea was assessed as being affected by eutrophication. The following coastal areas were assessed by national authorities as being in good ecological status according to WFD requirements: Orther Bucht (Germany), outer coastal Quark (Finland) and outer coastal Bothnian Bay, outer coastal Bothnia Sea, inner and outer coastal Quark (Sweden).” EUTROSYM (1976) gives a common eutrophication definition: “Eutrophication is analogous to the natural aging in the broadest sense of the word the increased supply of plant nutrients (phosphorus and nitrogen compounds) to waters due to human activities in the catchment areas which results in an increased production of algae and higher water plants.” Despite Baltic Sea countries have initiated numerous measures to reduce nutrient inputs, additional reductions are needed. The latest *Updated Pollution Load Compilation* (HELCOM, 2015) reports inputs of 758 000 t nitrogen and 36 200 t phosphorus from the drainage basin in 2010. Atmospheric inputs of nitrogen account for an additional 219 100 t (there are no reliable figures for atmospheric inputs of phosphorus). It should be noted that some 40 % of deposition into the Baltic is attributable to emissions from countries that are not littoral states of the Baltic Sea. If long-term developments from 1995 to 2010 are considered, atmospheric inputs of nitrogen have fallen by some 15 %. With reference to normalised run-off data, inputs of phosphorus from the drainage basin were reduced by 20 % between 1994 and 2010. A reduction of 17 % has been calculated for nitrogen inputs into the Baltic Sea (HELCOM, 2015). Annual amounts of 16 900 t of nitrogen and 490 t of phosphorus are estimated for the German drainage basin.

In Germany, riverine inputs of total phosphorus fell between 1986/90 and 2004/08 by 61 %, mainly due to low loads from point sources. In the same periods, inputs of nitrogen, mainly from non-point sources, fell by only 13 %, half of it due to a reduction in runoff (NAUSCH et al., 2011b). Nevertheless, all German coastal waters and adjacent sea still need to be assessed as eutrophic (HELCOM, 2014).

To evaluate the effects of increased nutrient inputs as well as to evaluate the results of reduction measures undertaken, the monitoring of the nutrient situation is essential. Nutrients are core parameters since HELCOM established a standardised monitoring programme at the end of the 1970s. Nutrient components continue to be the focus of attention both nationally and internationally as its monitoring programme is revised and adapted to the Marine Strategy Framework Directive (MSFD). Investigations mainly include the inorganic nutrients of ammonium, nitrite, nitrate, phosphate and silicate, but total nitrogen and total phosphorus are also measured regularly.

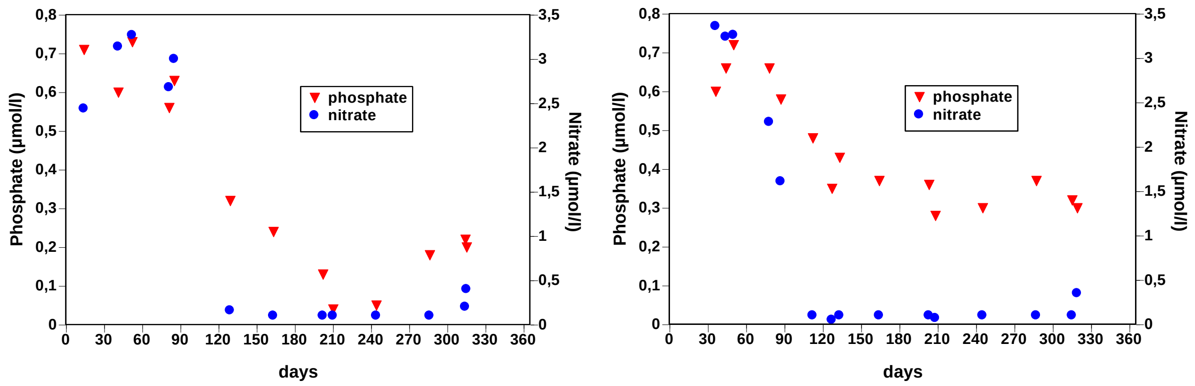


Fig. 38: Annual phosphate and nitrate cycle 2015 in the surface layer (0-10 m) of the eastern Gotland Basin (TF271 - left) and in the Bornholm Basin (TF213 – right)– IOW and SMHI data

In the surface layer of temperate latitudes phosphate and nitrate exhibit a typical annual cycle (NEHRING & MATTHÄUS, 1991, NAUSCH & NEHRING, 1996). Figure 38 illustrates the annual cycle of nitrate and phosphate in the eastern Gotland Sea and in the Bornholm Sea in 2015. In the central Baltic Sea, a typical plateau phase develops during winter time which lasts two to three months (NAUSCH et al, 2008b). Depending on weather conditions, the spring bloom starts in March/early April, normally earlier in the Bornholm Sea compared to the eastern Gotland Sea. Due to the low N/P ration in winter (Table 9), the nitrate reservoir is exhausted latest in the middle of April. Unfortunately, this period is not well covered by measurements in 2015. The spring bloom breaks down due to nitrogen limitation. Nitrate concentrations stay at quite low concentrations until October/November. When the nitrate reservoir is exhausted, around 0.3 µmol/l phosphate remain. Normally, phosphate concentrations decrease further until summer and reach the detection limit in the beginning of July. This typical development can be seen in the eastern Gotland Basin. In autumn, mineralisation processes cause an increase in nutrient concentrations reaching again the winter level in February of the following year. In the Bornholm Sea the development was different. The annual cycle of nitrate was basically as described above for the eastern Gotland Sea. However, the period of minimal nitrate concentrations was developed quite long. The phosphate cycle deviates from the "normal" one. After the spring bloom, phosphate concentrations of around 0.3 µmol/l were measured and did not fell until the beginning of autumn. A similar behaviour could already be observed in 2004 and 2005 (NAUSCH et al, 2005, 2006). Final explanations for this phenomenon could not be given. May be, the intensity of cyanobacteria blooms differed in both areas what has to be verified. Actually, the missing nitrate and plenty of phosphate should foster cyanbacteria blooms if weather conditions are convenient.

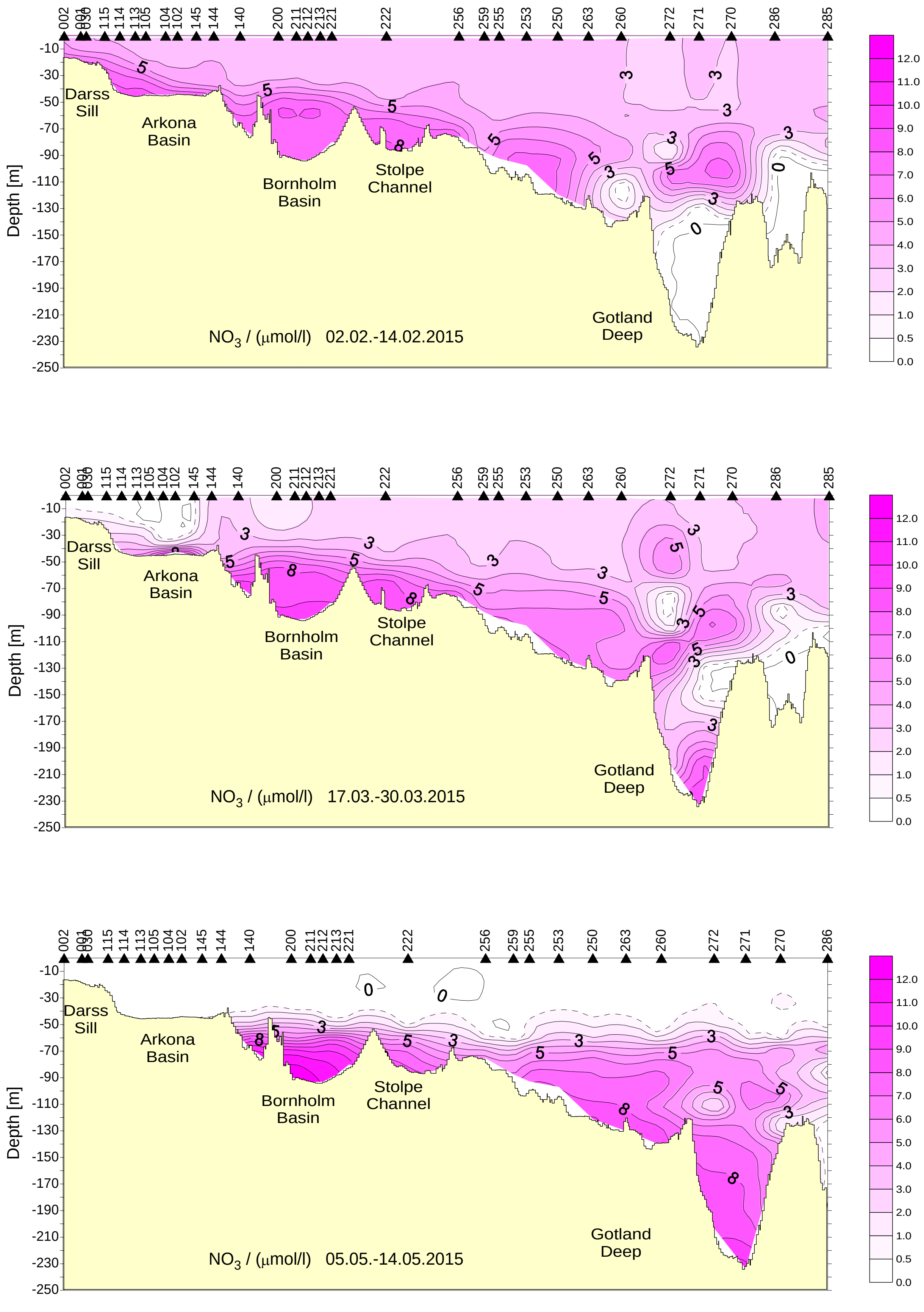


Fig. 39a: Vertical distribution of nitrate 2015 between Darss Sill and northern Gotland Basin

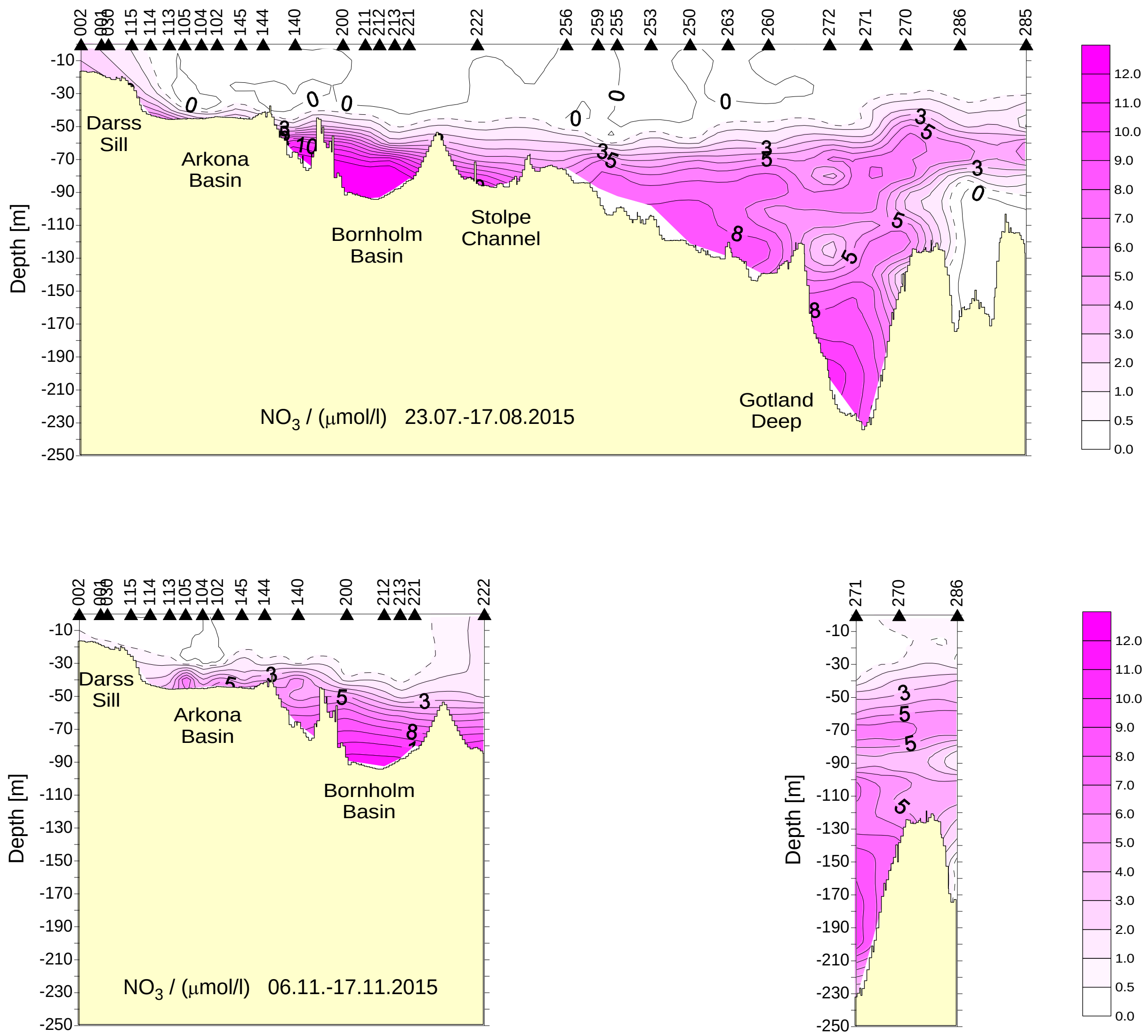


Fig. 39b: Vertical distribution of nitrate 2015 between Darss Sill and northern Gotland Basin

Figures 39 and 40 illustrate the horizontal and vertical distribution of nitrate and phosphate along the transects from the Darss Sill to the northern Gotland Basin for the five monitoring cruises performed in 2015. Table 9 summarises winter nitrate and phosphate values; they are in the range of previous years. However, the great variability in the measured values is remarkable. Even a correlation analysis of the ten-year data series for 2004 to 2013 reveals no significant changes for all investigated sea areas (NAUSCH et al., 2014). This means that the reductions in nutrient concentrations that have already been observed in coastal waters have not yet been observed in the open sea (NAUSCH et al., 2011b).

The N/P ratio can be determined from their relative concentrations. Generally the values are well below the Redfield ratio of 16:1 (REDFIELD et al., 1963); with values around 9, ratios in the western Baltic are still higher than the N/P ratios in the central Baltic.

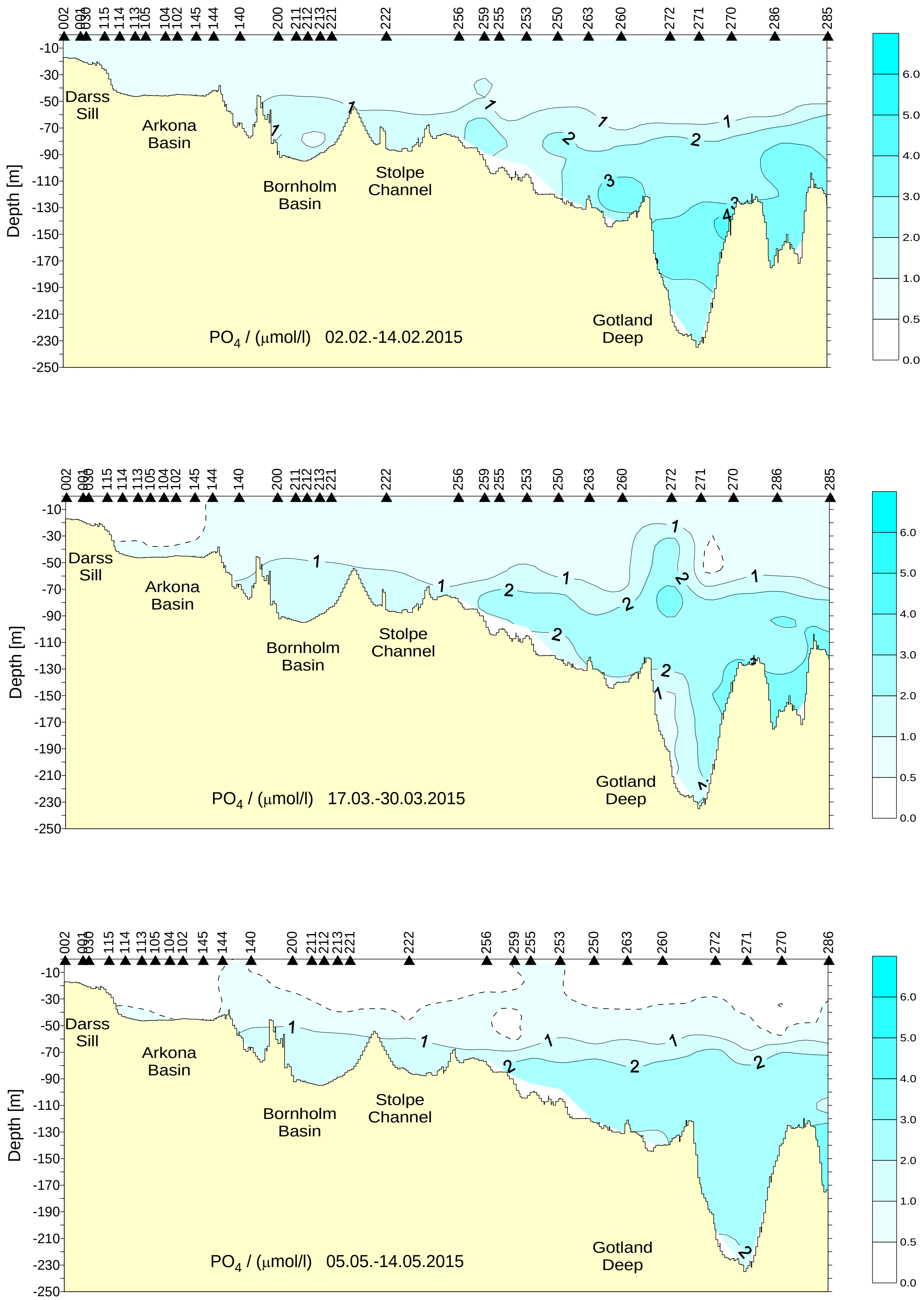


Fig. 40a: Vertical distribution of phosphate 2015 between Darss Sill and northern Gotland Basin

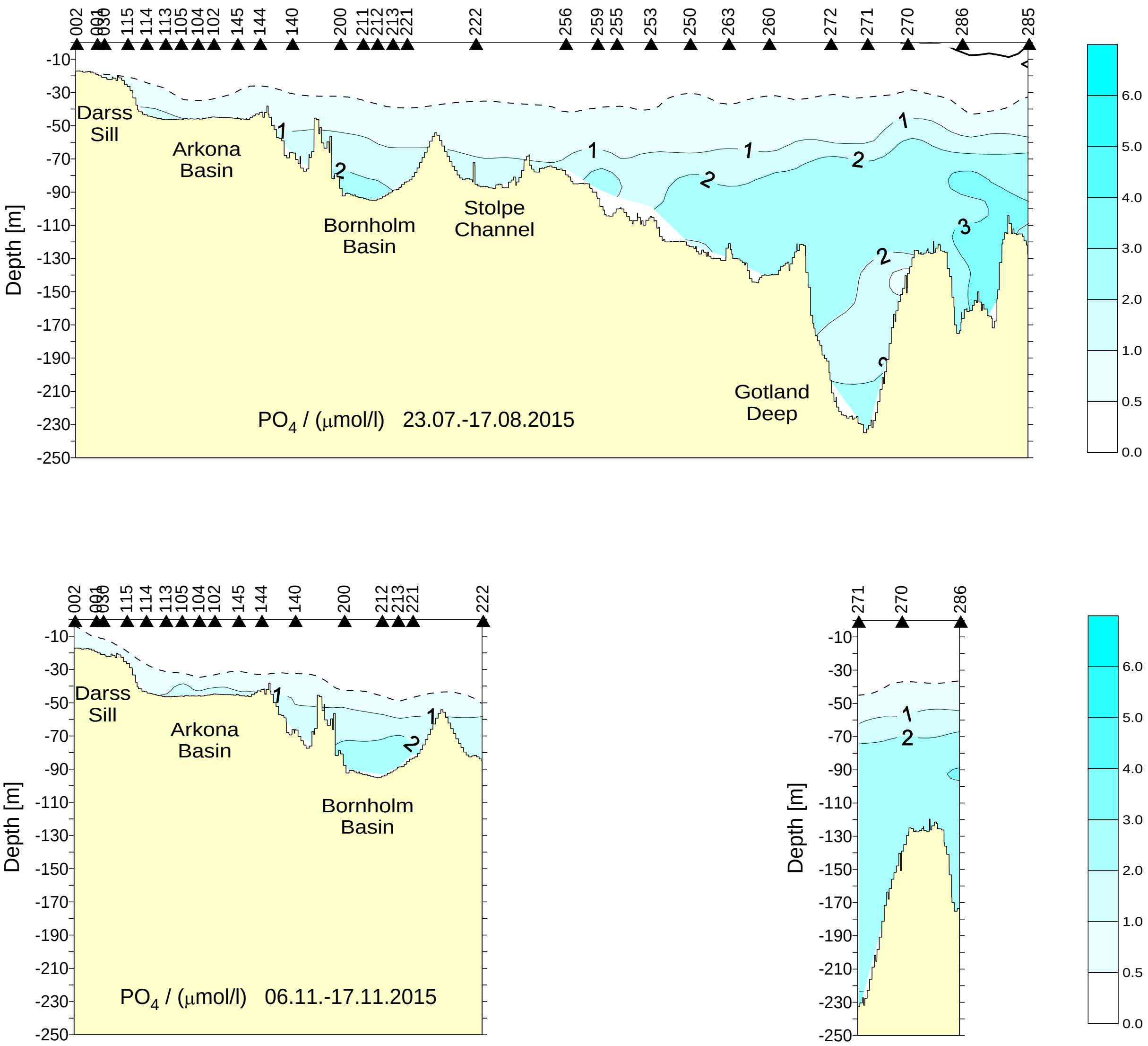


Fig. 40b: Vertical distribution of phosphate 2015 between Darss Sill and northern Gotland Basin

Table 9: Mean nutrient concentrations in the surface layer (0-10 m) in winter in the western and central Baltic Sea (Minima in bold)

Phosphate (µmol/l; Minima in bold

Station	Monat	2011	2012	2013	2014	2015
360 (Fehmarn Belt)	Feb.	0.58 ± 0.01	0.71 ± 0.01	0.72 ± 0.01	**0.57 ± 0.01**	0.64 ± 0.01
022 (Lübeck Bight)	Feb.		0.71 ± 0.01	0.85 ± 0.01	0.71 ± 0.04	0.63 ± 0.02
012 (Meckl. Bight) Bucht)	Feb.	**0.55 ± 0.00**	0.73 ± 0.02	0.85 ± 0.01	0.56 ± 0.00	0.60 ± 0.01
113 (Arkona Sea)	Feb.	**0.51 ± 0.01**	0.73 ± 0.00	0.63 ± 0.01	0.53 ± 0.00	0.56 ± 0.00
213 (Bornholm Deep)	Feb.	**0.54 ± 0.01**	0.66 ± 0.01	0.71 ± 0.0	0.70 ± 0.01	0.60 ± 0.00
271 (Gotland Deep)	Feb.	0.54 ± 0.01	0.64 ± 0.01	0.54 ± 0.02	**0.52 ± 0.01**	0.50 ± 0.02
286 (Fårö Deep)	Feb.		0.56 ± 0.00	**0.50 ± 0.01**	0.78 ± 0.01	0.60 ± 0.00
284 (Landsort Deep)	Feb.		0.63 ± 0.01	**0.56 ± 0.02**	0.84 ± 0.01	
245 (Karls Deep)	Feb.		0.80 ± 0.02	**0.60 ± 0.02**	0.85 ± 0.00	0.80 ± 0.00

* SMHI data

Nitrate (µmol/l; Minima in bold)

Station	Monat	2011	2012	2013	2014	2015
360 (Fehmarn Belt)	Feb.	5.9 ± 0.2	5.7 ± 0.1	**4.1 ± 0.0**	4.9 ± 0.2	7.5 ± 0.1
022 (Lübeck Bight)	Feb.		**6.2 ± 0.2**	6.7 ± 0.1	6.6 ± 0.1	9.3 ± 0.2
012 (Meckl. Bight) Bucht)	Feb.	4.8 ± 0.0	**3.8 ± 0.2**	5.8 ± 0.0	4.5 ± 0.1	5.5 ± 0.0
113 (Arkona Sea)	Feb.	**2.6 ± 0.0**	2.9 ± 0.0	3.2 ± 0.0	5.2 ± 0.2	3.7 ± 0.0
213 (Bornholm Deep)	Feb.	3.7 ± 0.0	**2.6 ± 0.0**	3.0 ± 0.0	4.0 ± 0.1	3.3 ± 0.2
271 (Gotland Deep)	Feb.	3.2 ± 0,0	**2.6 ± 0.2**	2.9 ± 0.0	3.9 ± 0.0	3.1 ± 0.0
286 (Fårö Deep)	Feb.		3.3 ± 0.0	**3.0 ± 0.0**	4.5 ± 0.1	3.4 ± 0.0
284 (Landsort Deep)	Feb.		4.6 ± 0.1	4.4 ± 0.0	**3,8 ± 0,3**	
245 (Karls Deep)	Feb.		4.0 ± 0.1	3.8 ± 0.1	3.5 ± 0.2	**3.2 ± 0.0**

Table 10: Annual means and standard deviations for phosphate, nitrate and ammonium in the deep water of the central Baltic Sea: IOW and SMHI data (n = 15 – 14)

Phosphate (µmol/l; Maximal in bold)

Station	Tiefe/m	2011	2012	2013	2014	2015
213 (Bornholm Deep)	80	**2.66 ± 1.39**	1.81 ± 0.85	1.62 ± 0.35	1.49 ± 0.31	1.57 ± 0.44
271 (Gotland Deep)	200	5.66 ± 0.28	5.87 ± 0.16	**6.32 ± 0.92**	4.50 ± 1.54	2.16 ± 0.29
286 (Fårö Deep)	150	4.34 ± 0.61	4.45 ± 0.23	**4.77 ± 0.58**	4.60 ± 0.67	3.26 ± 0.23
284 (Landsort Deep)	400	3.67 ± 0.45	**3.92 ± 0.25**	3.89 ± 0.21	3.85 ± 0.35	3.57 ± 0.26
245 (Karls Deep)	100	**4.22 ± 0.33**	3.47 ± 0.47	3.91 ± 0.53	3.99 ± 0.51	3.92 ± 0.19

Nitrate (µmol/l; Minima in bold)

Station	Tiefe/m	2011	2012	2013	2014	2015
213 (Bornholm Deep)	80	**4.6 ± 2.8**	7.9 ± 3.1	6.4 ± 1.9	8.24 ± 1.83	11.12 ± 2.48
271 (Gotland Deep)	200	**0.0 ± 0.0**	**0.0 ± 0.0**	**0.0 ± 00**	**0.0 ± 00**	7.53 ± 3.31
286 (Fårö Deep)	150	**0.0 ± 0.0**	**0.0 ± 0.0**	**0.0 ± 0.0**	**0.0 ± 00**	**0.0 ± 00**
284 (Landsort Deep)	400	**0.0 ± 0.0**	**0.0 ± 0.0**	**0.0 ± 0.0**	**0.0 ± 00**	**0.0 ± 00**
245 (Karls Deep)	100	**0.0 ± 0.0**	1.51 ± 2.08	01. ± 0.2	**0.0 ± 00**	**0.0 ± 00**

Ammonium (µmol/l; Maxima in bold)

Station	Tiefe/m	2011	2012	2013	2014	2015
213 (Bornholm Deep)	80	**2.1 + 3.4**	0.1 ± 1.9	01. ± 0.1	0.1 ± 0.2	0.2 ± 0.1
271 (Gotland Deep)	200	20.2 + 2.8	**26.2 ± 2.8**	22.1 ± 8.7	18.4 ± 10.9	1.6 ± 3.7
286 (Fårö Deep)	150	9.0 ± 1.4	12.2 ± 1.5	12.6 ± 3.0	**12.8 + 3.6**	7.2 ± 2.1
284 (Landsort Deep)	400	6.3 ± 1.7	**8.5 ± 1.6**	7.2 ± 2.3	7.9 ± 1.7	6.5 ± 1.1
245 (Karls Deep)	100	**9.7 ± 3.5**	4.4 ± 2.9	6.5 ± 3.1	7.7 ± 2.1	7.7 ± 1.2

In the basins of the central Baltic Sea, nutrient distribution is primarily influenced by the occurrence or absence of strong barotropic and/or baroclinic inflows. Figures 39 and 40 also illustrate nutrient conditions in the deep water there. It should be noted that under anoxic conditions, ammonium represents the end product of the mineralisation of organic matter, and no nitrate can be formed (Table 10).

The Bornholm Basin is the westernmost of the deep basins, and barotropic and baroclinic inflows are often able to ventilate its deep water, as evidenced by long-term developments since 2001 (cf. chapter 6.3). The inflow events in autumn 2013 and in February and March 2014 produced already favourable oxygen conditions. The MBI of December 2014 improved the oxygen situation even more, at least in the first half of 2015 (cf. chapter 6.3). Nutrients reacted accordingly (Figure 41). Phosphate concentrations ‹2 µmol/l were present in the deep water because dissolved phosphate is precipitated under oxic conditions. On the other hand, oxygen permits the nitrification of ammonium to nitrate. Throughout the whole year, ammonium concentrations of 0.1 ± 0.2 µmol/l (Table 10) are in the range of the detection limit. Nitrate concentrations were in the beginning of 2015 of around 7 – 8 µmol/l and reached values › 14 µmol/l in autumn.

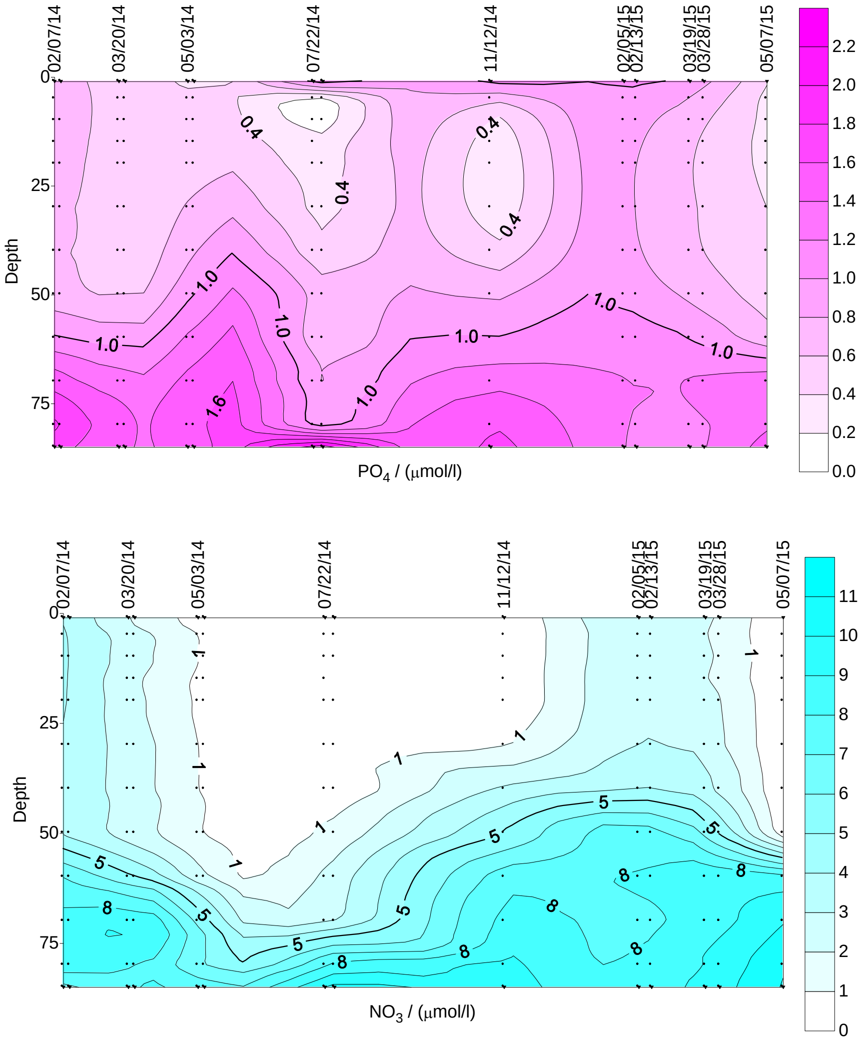
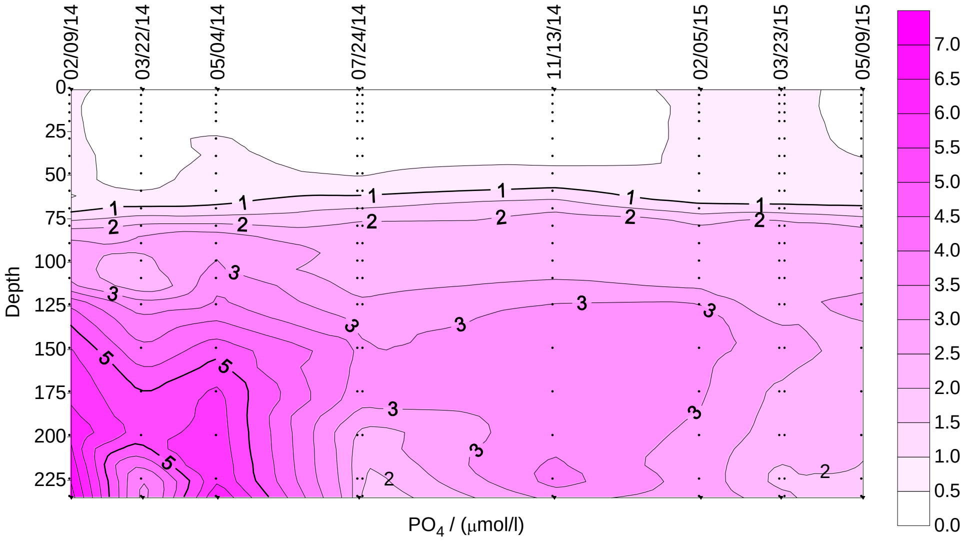


Fig. 41: Development of phosphate and nitrate in the Bornholm Deep between February 2014 and July 2015

Already the inflow events in autumn 2013 and in February and March 2014 influenced the nutrient situation in the deep water of the eastern Gotland Basin. Due to their repeated –if even briefly- ventilation a decline of phosphate concentrations was caused in 2014 and allowed the formation of nitrate for a short period of time (Figure 42). Thus, the MBI of December 2014 met a situation which is not typical for the end of long stagnation periods. Normally, phosphate values between 5 and 6 µmol/l are measured as can be seen in February and March 2014. In 2015, phosphate values ranged around 2 µmol/l. Also ammonium was already partly oxidized. In the first half of 2014 they ranged around 35 µmol/l, comparable to the end of the previous stagnation period in 2002. In the beginning of 2015, before the MBI of December 2014 arrived, only 12 µmol/l were measured. From March onwards when ventilation started ammonium concentrations ranged until the end of 2015 between 0.1 and 0.2 µmol/l near to the detection limit. Reverse reacted nitrate. Concentrations increased from zero in February to around 10 µmol/l in November 2015.



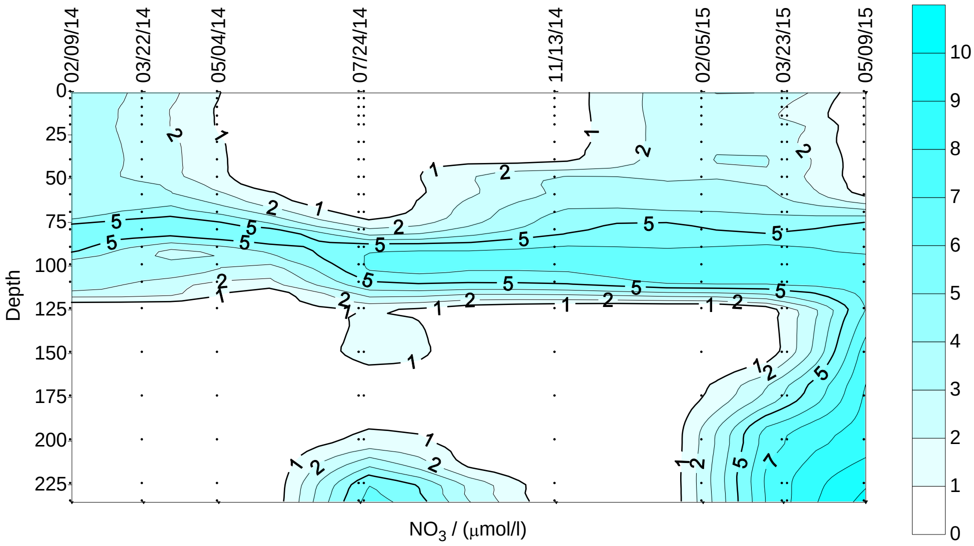


Fig. 42: Development of phosphate and nitrate in the Gotland Deep between February 2014 and July 2015

Surprisingly, the huge amount of highly saline, dense water was unable to ventilate the further north located Farö Deep. As described already in chapter 6.3 increasing salinity and temperature values as well as decreasing hydrogen sulphide concentrations may be an indicator that oxygenated water could penetrate to the Farö Deep, but be unable to turn the system completely to oxic conditions. This is reflected in the nutrient conditions. No nitrate could be measured, but ammonium concentrations decreased from around 9 – 10 µmol/l in the first half of 2015 to around 5 µmol/l and the end of the year. Also a slight decrease in phosphate concentrations can be seen in the course of the year. In the western Gotland Basin the data base in 2015 is relatively sparse. Thus no clear trends can be observed.

6.5 Dissolved Organic Carbon and Nitrogen

The dissolved organic matter (DOM) in the Baltic Sea is an important contributor within the carbon and nutrient cycles. The DOM correlate with the salinity of the water. Higher dissolved organic carbon (DOC) values at low salinities reflect the input from terrestrial sources. The high saline and DOM less water originate from the North Sea. As consequence the DOC in surface water of the Baltic Sea has higher concentration than the deep water at all stations. The concentration of dissolved organic nitrogen (DON) varies due to biogeochemical processes in the water column (NAUSCH et al., 2008b).
The dissolved nitrogen species: nitrate, nitrite, ammonium and DON are summarized as dissolved nitrogen (DN). The relation of DOC/DN (C/N ratio) has in general higher values in surface water (17-18) than bottom near water (9-11).

The inflow event in December 2014 and the biogeochemical effects of the high salinity and oxygen rich water on the water masses in the Bornholm and Gotland Basin was one main scientific interest in the year 2015. The replacement of the anoxic waters from the long stagnant period took place between February and May 2015. In Table 1 the key physical and chemical parameters are listed. The inflow water (see table 1, AB/0113, Febr. 2015) was characterized by salinity › 20, T about 6°C and DOC concentrations of about 180-190 µmol/kg. In April 2015 first inflow water reached the deep Gotland basin. In May the increase of salinity in the GB and the oxygen concentration of 2 ml/L are clear indicators that the old water mass was replaced.

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

	MB 0012	MB	AB 0113	AB	BB 0213	BB	GB 0271	GB
	Febr.	May	Febr.	May	Febr.	May	Febr.	May
	24 m		46 m		88 m		236 m	
S	21,3	18,1	22,8	17,5	19,8	19,5	12,3	13,5
T	4,1	6,2	5,6	5,1	7,1	7,0	6,7	6,9
O_2	7,5	5,5	5,9	4,1	5,3	2,4	0	2,0
DOC	194	232	185	228	208	204	258	256
DN	21	17,8	19,5	14,4	20,8	24,4	22,3	25,2
C/N	9,4	13	9,5	15,8	10	8,4	11,5	10,1

The DOC and DN changes at station MB, AB, BB and GB between February and November 2015 are shown in Figures 43-46.

In the Mecklenburg Bight no influence of the inflow water from December 2014 could be monitored in February 2015 (Fig. 43). The increase in DOC during the year is due to the biological production during spring and summer time.

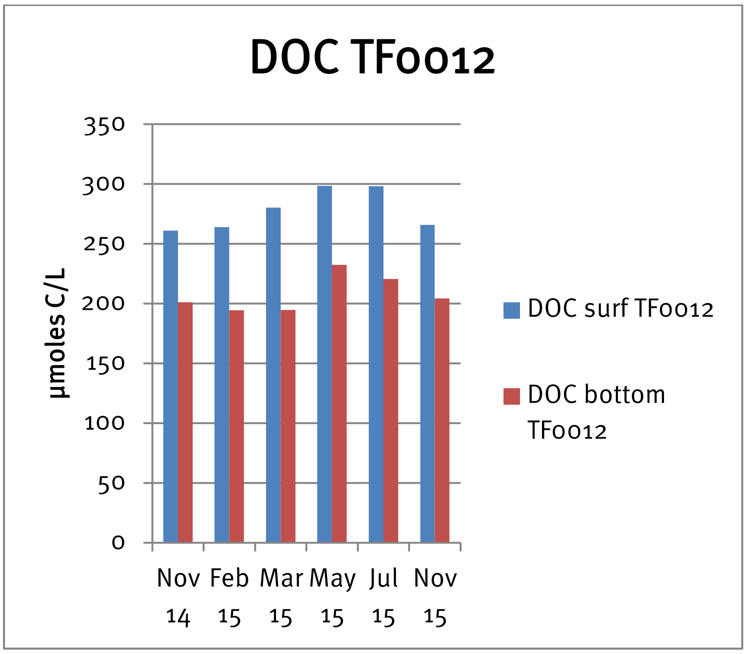


Fig. 43: Surface (2m) and bottom (24m) dissolved organic carbon (µmol/l) at Station TF0012 in the Mecklenburg Bight

The lowest DOC concentration was observed at the station Arkona Basin (TF 0113) in February 2015 (Fig. 44a), a clear signal from the inflow water. The DN (Fig. 44b) was not noticeable changed. During the year the DOC and DN values were at an average for this region.

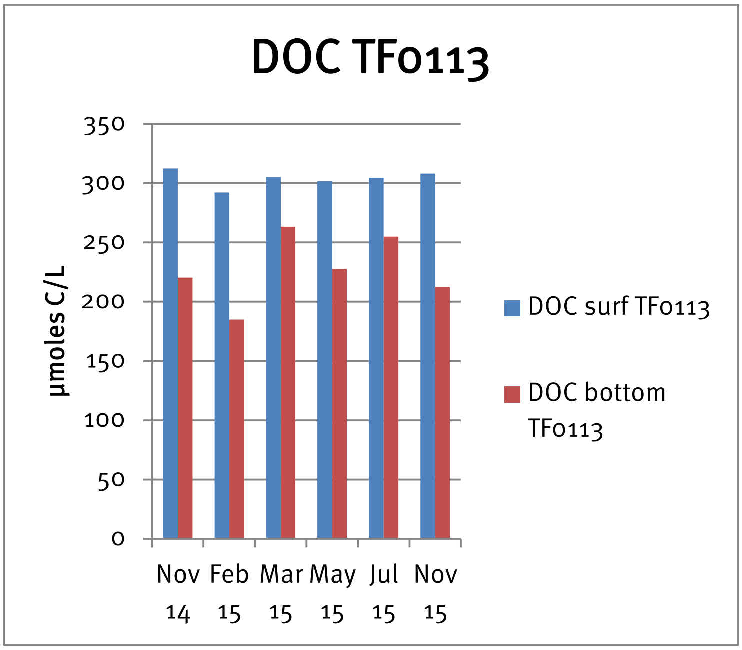


Fig. 44a: Surface (2m) and bottom (46 m) dissolved organic carbon (µmol/l) at Station TF0113 in the Arkona Basin

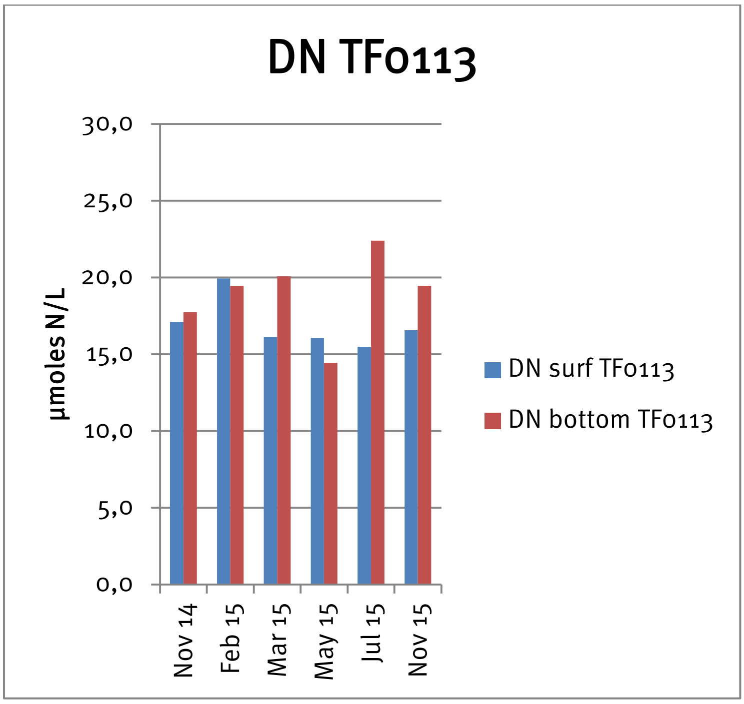


Fig. 44b: Surface (2m) and bottom (46 m) dissolved nitrogen (µmol/l) at Station TF0113 in the Arkona Basin

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 DN concentration all over the entire year, little variations are related to biological processes. The deep DOC concentration decreased from February to May and stayed stable for the rest of 2015. No more water exchange occurs. Either the DN values changed not significant.

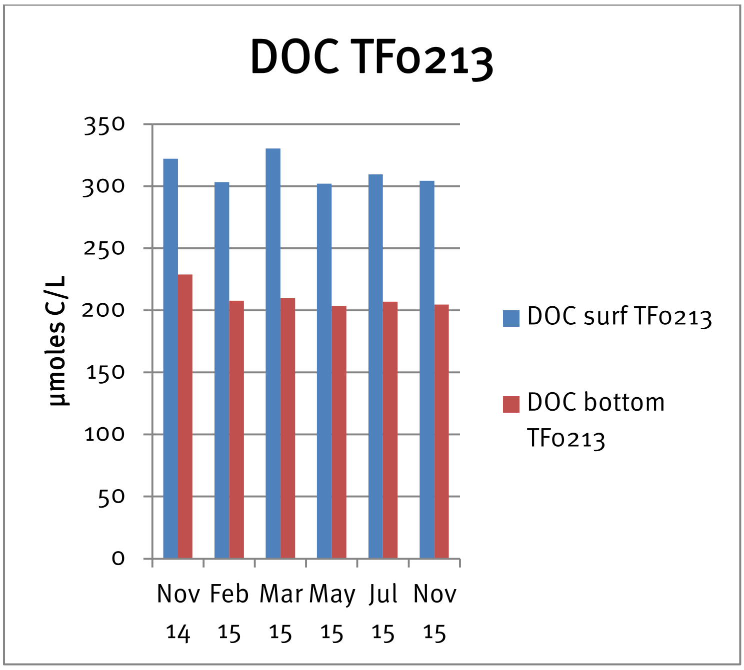


Fig. 45a: Surface (2m) and bottom (88 m) dissolved organic carbon (µmol/l) at Station TF0213 in the Bornholm Basin

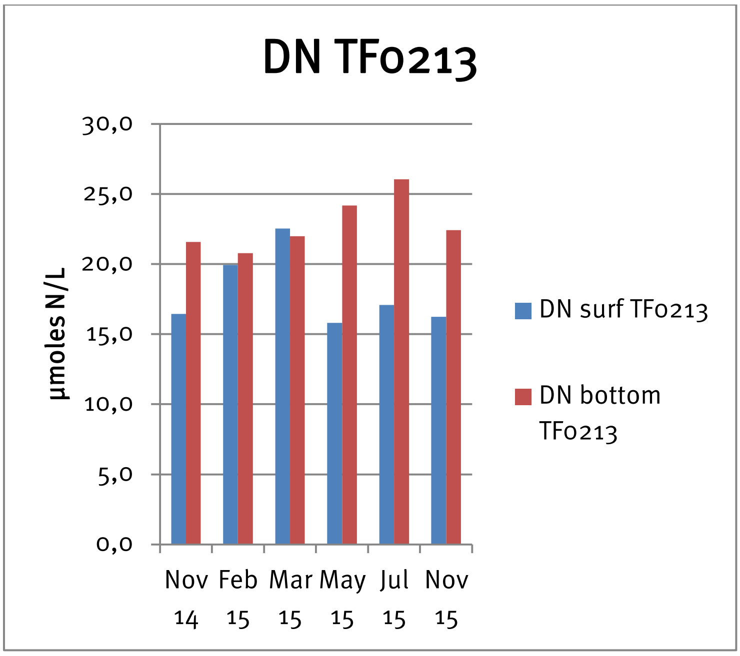


Fig. 45b: Surface (2m) and bottom (88 m) dissolved nitrogen (µmol/l) at Station TF0213 in the Bornholm Basin

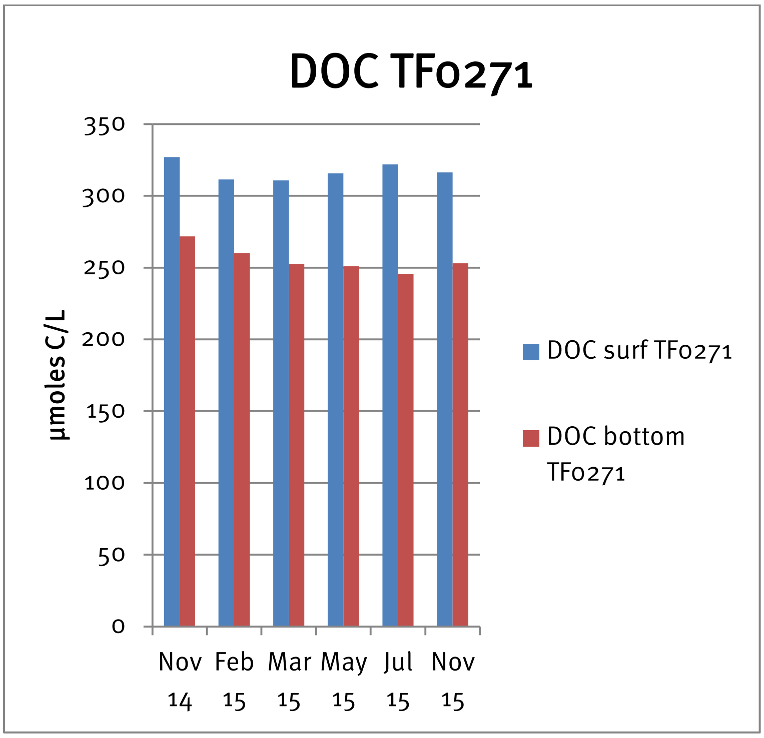


Fig. 46a: Surface (2m) and bottom (236 m) dissolved organic carbon (µmol/l) at Station TF0271 in the eastern Gotland Basin

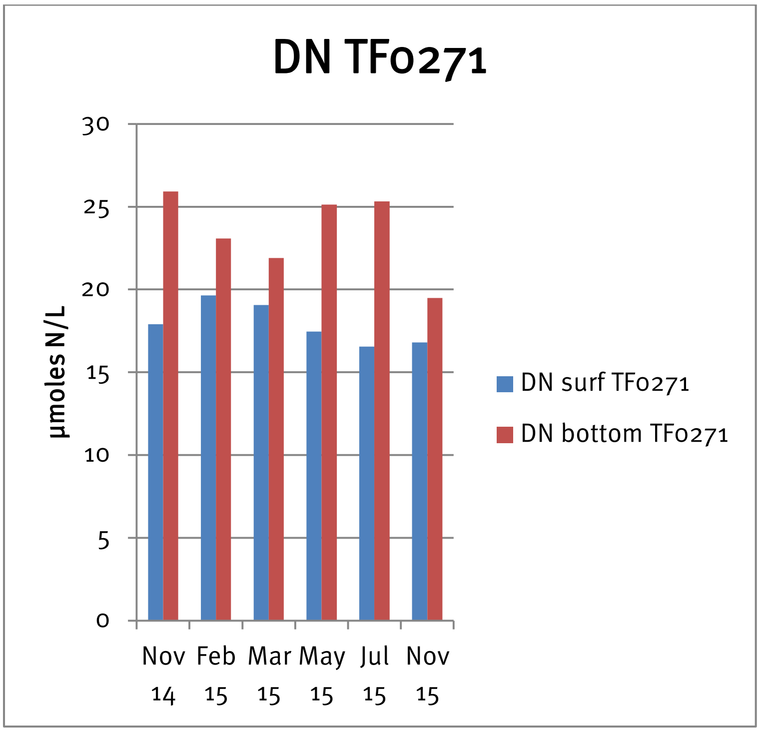


Fig. 46b: Surface (2m) and bottom (236 m) dissolved nitrogen (µmol/l) at Station TF0271 in the eastern Gotland Basin

Summary

For the southern Baltic Sea area, the cold sum of 19.8 Kd at Warnemünde station amounted to a very warm winter in 2014/15. This value plots far below the long-term average of 103.6 Kd in comparative data from 1948 onwards and ranks as 7th warmest winter in this time series. The months December to March were all far too warm and November and April showed balanced values compared with the average. January 2015 was exceptional warm with a cold sum of 0 Kd. With a warm sum of 182.3 Kd, recorded at Warnemünde, the summer 2015 is ranked in the upper midrange over the past 68 years on 21st position and far below the previous year of 236.9 Kd on 10th place. The 2015 value exceeds the long-term average of 151.3 Kd, but is within the standard deviation, meaning that the year can be classed as an ordinary one.

With respect to sea surface temperature, the year 2015 was after 2014 the second warmest since 1990 and approximately 0.9 K above average for the period 1990-2015 and 0.3 K colder than 2014. Except for the summer month June-August, all other months contributed to this annual mean. SST anomalies of up to +2 K characterized nearly the entire Baltic from January – May, due to one of the mildest winters in air-temperature since 1948. January – March and October belonged to the warmest months since 1990. In the Gotland Sea, March was the coldest month of the year, but in Arkona Sea and Bothnian Sea it was February. February and March were rather similar and both the coldest months since 1990.

Inflow events with estimated volumes between 141 and 270 km^3 occurred in the Baltic Sea on five occasions in 2015. In January, an inflow volume of 162 km^3 was calculated based on changes in sea level at Landsort Norra. After a phase of dominating outflow in February and March, a low stand of -30.9 cm MSL at 22nd March was registered. A next inflow phase of two pulses occurred up to 17th April, which brought again a volume of about 161 km^3 into the Baltic Sea. During the summertime the sea level variations were low and in August a next outflow period occurred. At the beginning of September a next smaller inflow of 141 km^3 was induced by a change from summery highs to dominating deep pressure systems. A next longer outflow period followed and the lowest sea level of the year was reached at 15th October (-37.6 cm MSL). Afterwards an intensified inflow phase of some smaller pulses and a next Major Baltic Inflow of moderate intensity dominated the end of the year. From November 1st to 19th a total volume of about 270 km^3 was transported, which contain about 76 km^3 of highly saline water (>17 g/kg) and a salt import of 1.5 Gt. In December a smaller pulse of 148 km^3 followed. In conclusion, intensified water exchange processes were recorded in the last two years and some inflow pulses were able to reach the bottom water of the central Baltic Sea fostering the large Major Baltic Inflow of December 2014.

The annual cycle of oxygen saturation in the surface water was again typical in 2015. Due to the dominance of oxygen-consuming processes and low productivity, the surface water in February in all sea areas was slightly undersaturated at 95 to 96 %. The winter 2014/15 was one of the warmest since 1948. Thus phytoplankton development started early. Thus, in March in all four investigated areas saturation was over 100 % whereby the spring bloom in the eastern Gotland Basin was at the beginning and reached its maximum as in the Bornholm Basin in May. In

general, no real high spring bloom could be observed. This can be either due to low productivity or we missed the peak due to low sampling frequency. The summer period 2015 is characterized by only slight oversaturation around 105 %. This is an indication no huge cyanobacteria blooms occurred. In the autumn, intensified degradation processes again led to undersaturation between 95 and 100 %.

Oxygen conditions in the deep water of the basins of the central Baltic Sea are primarily influenced by the occurrence or absence of strong inflows. The Bornholm Basin is the westernmost of the deep basins. Barotropic and baroclinic inflows are often able to ventilate its deep water. The situation in 2015 was coined by the Major Baltic Inflow (MBI) of December 2014 which was together with 1913 the third largest on record. The highly saline water transported huge amounts of well oxygenated water into the basin. Thus, the oxygen content increased in the 80 m horizon of the Bornholm Deep from mid December 2014 (0.31 ml/l) to 5.90 ml/l in the beginning of February 2015. During the further course of the year oxygen concentrations decreased due to mineralisation processes to 0.77 ml/l in the mid of November. The MBI of December 2014 proceeded further into the central basins. Already in March 2015 0.4 – 0.9 ml/l were measured below 170 m in the eastern Gotland Basin. Inflow events in autumn 2013, in February and March 2014 were able to advance into the eastern Gotland Basin whose deep water they oxygenated repeatedly - if briefly - for the first time since 2003. Thus, the concentrations of hydrogen sulphide measured in the eastern Gotland Basin towards the end of 2014 were relatively low. Thus, the MBI met relatively favourable conditions in the depth. In April 2015 oxygen concentrations up to 3 ml/l were measured. However, all the time an intermediate layer of different thickness remained below the halocline where quite low amounts of oxygen or even traces of hydrogen sulphide remained. It was quite astonishing that despite these "good" pre-conditions oxygen started rapidly to decrease. At 200 m in the Gotland Deep around 1 ml/l remained in the middle of November. An explanation of this rapid and unexpected decrease is still open. However, several inflow events at the turn of 2015/2016 were able to improve the situation again.

Nutrient conditions in the deep basins reflect the intensive inflow processes. In the Bornholm Basin, phosphate concentrations <2 µmol/l were present because dissolved phosphate is precipitated under oxic conditions. On the other hand, oxygen permits the nitrification of ammonium to nitrate. Throughout the whole year, ammonium concentrations of 0.1 ± 0.2 µmol/l are in the range of the detection limit. Nitrate concentrations were in the beginning of 2015 of around 7 – 8 µmol/l and reached values >14 µmol/l in autumn. The above mentioned inflow events in autumn 2013 and in February and March 2014 influenced the nutrient situation in the deep water of the eastern Gotland Basin. Due to their repeated –if even briefly- ventilation a decline of phosphate concentrations was caused in 2014 and allowed the formation of nitrate for a short period of time. Thus, the MBI of December 2014 met a situation which is not typical for the end of long stagnation periods. Normally, phosphate values between 5 and 6 µmol/l are measured as can be seen in February and March 2014. In 2015, phosphate values ranged around 2 µmol/l. Also ammonium was already partly oxidized. In the first half of 2014 they ranged around 35 µmol/, comparable to the end of the previous stagnation period in 2002. In the beginning of 2015, before the MBI of December 2014 arrived, only 12 µmol/l were measured. From March onwards when ventilation started ammonium concentrations ranged until the end of 2015 between 0.1 and 0.2 µmol/l near to the detection limit. Reverse reacted nitrate. Concentrations increased from zero in February to around 10 µmol/l in November 2015.

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