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Hydrographic-hydrochemical assessment of the Baltic Sea 2014

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Content

1. Introduction

This assessment of hydrographic and hydrochemical conditions in the Baltic Sea in 2014 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 2008Duties 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 2014 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 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). RV *Alkor* was deployed in February and March; RV *Elisabeth Mann Borgese* was deployed in May, July, and November. 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 overhaul, 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-May to mid-December 2014; it was taken out of service for a break over the winter of 2014/2015. 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). 2014 was assessed in relation to the mean values for 1990-2014 and extreme years.

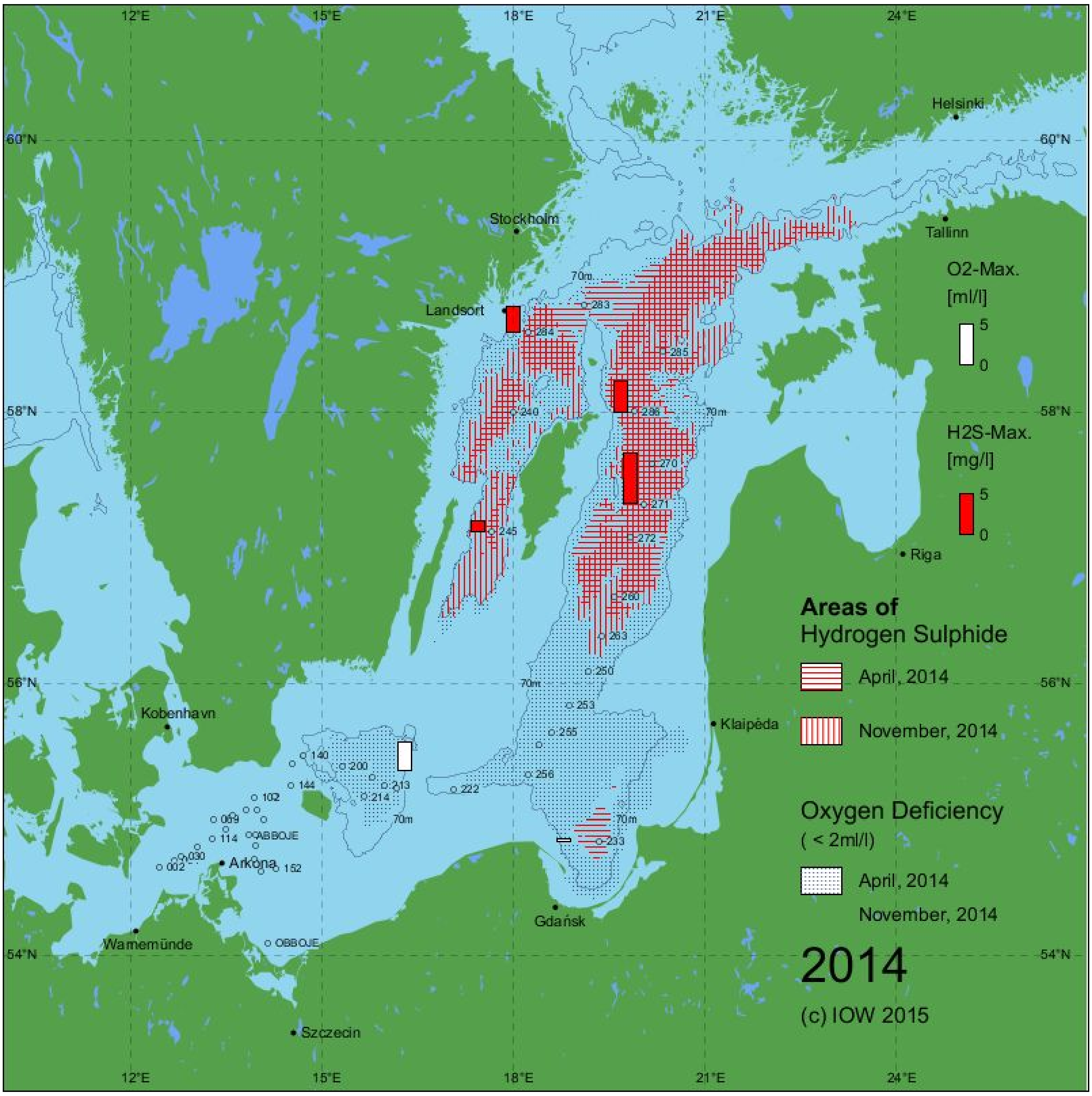


Fig. 1: Location of stations (■ MARNET- stations) and areas of oxygen deficiency and hydrogen sulphide in the near bottom layer of the Baltic Sea. Bars show the maximum oxygen and hydrogen sulphide concentrations of this layer in 2014; the figure contains additionally the 70 m -depth line

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, 2014), 2014 was the warmest year since the beginning of extensive weather records in 1881, both for Germany as a whole, and worldwide. The mean annual temperature of 10.3 °C was about 1.4 K higher than the average for 1981-2010. This new record value exceeds the previous peak years of 2000 and 2007 by 0.4 K. The year began with much too mild a winter: along Germany's Baltic coast, February, March and April each exceeded the thirty-year mean by >2 K. A warm temperature profile continued throughout the year. Along the coast, only June and August were exceptions: their values were marginally below the long-term average.

Across Germany, the amount of precipitation was 721 mm, 11 % below the average of 808 mm, and below 774 mm in 2013. In a regional comparison, however, Schleswig-Holstein (801 mm) and Mecklenburg-Vorpommern (603 mm) had an identical share of the average for 1981-2010 at 98 %. The driest months were March and November.

The average annual sum of 1,621 hours of sunshine exceeded by 2 % the long-term average of 1,588 hours. As in 2013, Arkona station came first with 2,031 hours, ahead of the district of Dahlem in south-west Berlin with 1,844 hours. December was the least sunny month: with an average of 22 hours, it was 42 % below the long-term average. In March, the sun shone 60 % longer than usual. The peak values belonged to the months of June and July: 232 and 229 hours respectively.

2.1 Ice Winter 2013/14

For the southern Baltic Sea area, the cold sum of 65.8 Kd at Warnemünde station amounted to a warm winter in 2013/14 (Table 2). This value falls well short of the long-term average of 104.5 Kd in comparative data from 1948 onwards. In comparison, Arkona station at 42.1 Kd (Table 3) is markedly lower, and even represents half the value of winter 2012/13. 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 a longish cold spell of 12 days of frost and 8 days of ice in the second half of January, only the occasional, brief cold spell was recorded in the wintertime (Table 1). Overall, only 8 days of frost and 20 days of ice were recorded at Warnemünde as against 24 and 86 days in the equally mild winter of 2012/13 (NAUSCH et al., 2013, 2014). The winter's warm temperature profile was also reflected in icing rates.

According to SCHMELZER & HOLFORT (2014), this ice season in the Baltic Sea is classified as weak to extremely weak. Given weather developments after January's cold spell, the maximum extent of ice was not reached until the first ten days of February: it had an area of some 95 000 km² and a very low volume of 15.7 km³. The maximum extent of ice corresponded to some 23 % 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 Gulf of Finland as well as the Gulf of Riga and other lagoons on the south coast of the Baltic Sea. The value of 95 000 km² is well below values in recent years: 179 000 km² in 2011/12, and 187 000 km² in 2012/13. By some 55 %, 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 170 000 km².

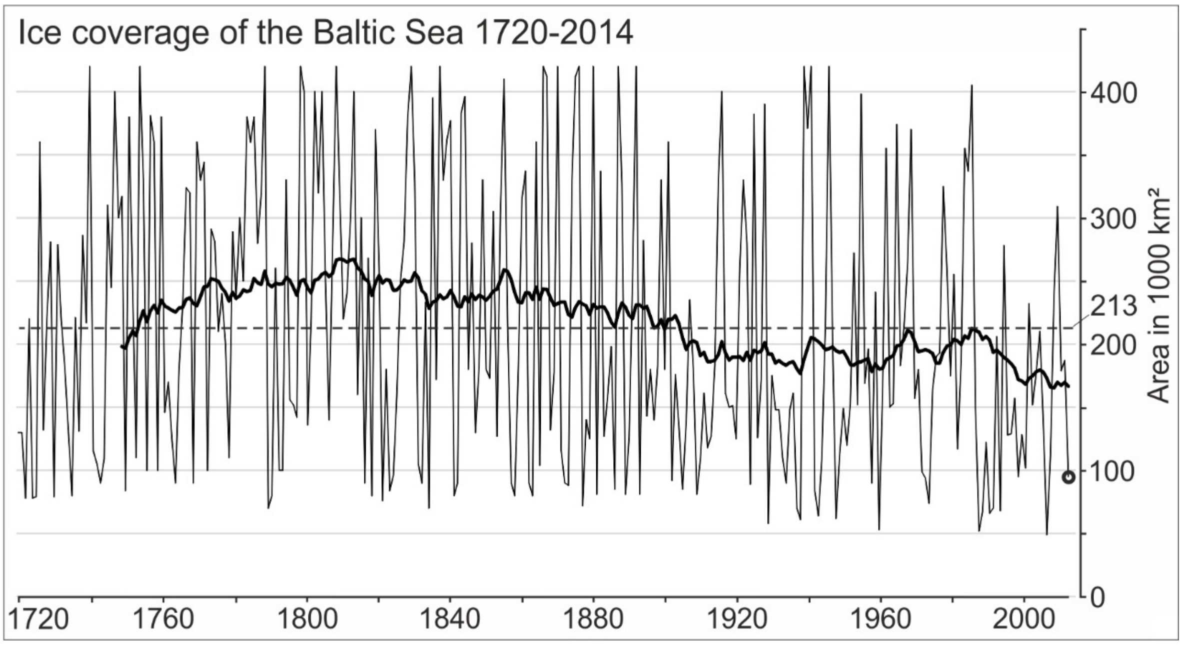


Fig. 2: Maximum ice covered area in 1000 km² of the Baltic Sea in the years 1720 to 2014 (from data of SCHMELZER et al., 2008, SCHMELZER & HOLFORT, 2014). The long-term average of 214 000 km² is shown as dashed line. The bold line is a running mean value over the past 30 years. The ice coverage in the winter 2013/2014 with 95 000 km² is encircled

Along Germany's Baltic Sea coast, local conditions were assessed as a weak ice winter on the basis of an accumulated areal ice volume of 0.37 m (SCHMELZER & HOLFORT, 2014). 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 0.37 m, the accumulated areal ice volume for winter 2013/14 is on a level with 2012/13 at 0.38 m, yet is markedly lower than in previous years: 1.12 m in 2011/12; 2.45 m in 2010/11; and 4.22 m in 2009/10. Moreover, small-scale variations in values occur depending on local coastal morphology and hydrodynamics. Thus during the two-week-long cold spell, the shallow waters of Mecklenburg-Vorpommern's bays froze, as did sections of the Pomeranian Bight, while Schleswig-Holstein's narrow coastal inlets remained ice-free except for a small area of Neustadt Bay and the mouths of the rivers Schlei and Trave.

In the winter of 2013/14, the accumulated areal ice volume for the coast of Mecklenburg-Vorpommern was 0.56 m, which is classified as a moderate ice winter; in Schleswig-Holstein, only 0.14 m was recorded (very weak ice winter). The number of recorded ice days was thus as follows: 16 at Landtief station in the Pomeranian Bight; 24 in Vierendehl Channel in the south of Rügen; 14 at Timmendorf (Wismar Bay); 12 at Lübeck (mouth of the river Trave); and 21 ice days at the mouth of the river Schlei. More open German sea areas all remained ice-free, according to the BSH maritime data portal and SCHMELZER & HOLFORT (2014).

2.2 Weather Developments in 2014

Over the course of 2014, pressure systems and air currents regularly changed direction between prevailing westerly to south-westerly directions, and easterly 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, 2014).

January started with a succession of Atlantic troughs that produced mild and stormy weather. Lows ('Christina' and 'Dagmar') moved north-west across northern Europe from 7-12. This brief phase of westerly winds with daily means of between 10-15 m/s and hourly maxima of 20.2 m/s caused the sea level at Landsort Norra to rise temporarily to 44.4 cm MSL (mean sea level). After 15, the influence of an anticyclone ('Benjamin') over Scandinavia strengthened, and during the rest of the month it extended across wide areas of Eastern Europe. By the end of the month, conditions changed to cold, winter weather with lowest values below -10°C. The easterly wind associated with it caused a strong outflow; at the end of the month, values of -43 cm MSL were recorded at Landsort Norra (Fig. 7a). The temperature profile for January revealed only a slight deviation of 0.2 K below the long-term average along Germany's Baltic Sea coast. Sunshine duration in most areas of Germany was below average. At Arkona station, for instance, only 49 % of the average duration was recorded (Table 1), just falling short of 2013's value of 53 %. The coast of Mecklenburg-Vorpommern recorded average amounts of precipitation (Arkona 100 %), while the hinterland was marginally too dry; in Schleswig-Holstein, values increased by around 7 %.

February began with a change in the weather driven by lows 'Nadja' and 'Okka' over the North Atlantic; they brought an influx of mild air masses from south-westerly to southerly directions. The mild conditions lasted throughout the month, with positive temperature anomalies of around 3.5 K along Germany's Baltic Sea coast, reduced precipitation at 70-80 % (Arkona station: 70 %), and a possibly record-breaking sunshine duration of more than half the usual value. At Arkona station, sunshine duration amounted to 155 %, putting February in first place in terms of standard deviation from the norm.

The steady south-westerly to westerly wind caused the water level at Landsort Norra to rise from a low of -46.6 cm MSL on 03 of the month to -3.6 cm MSL on 20, an increase of 43 cm. A volume of some 141 km³ of water thus entered the Baltic Sea before southerly to south-easterly winds set in on 27, leading to a slight outflow (Figures 7a, 5b).

In **March**, too, mild weather continued as high pressure dominated; it was interrupted only mid-month by a succession of lows ('Danli', 'Ev' and 'Feliz'). As they moved across northern Europe, persistent westerly to north-westerly winds set in from 15-20, with average daily speeds in excess of 10 m/s (Figure 5a); again they caused the sea level at Landsort Norra to rise from -35.7 cm MSL to 21.7 cm MSL (Figure 7a). The difference in sea level of 57.4 cm corresponded to an inflow volume of some 203 km³. In combination with the inflow events after October 2013, this had a ventilating effect as far as the basins of the central Baltic Sea (NAUMANN & NAUSCH 2015). Towards the end of the month, winds again veered easterly, and the sea level began to fall again. Overall, the temperature profile was clearly too warm. At the start of meteorological spring, widespread record temperatures were reached, for instance 18 °C in Rostock. Along Germany's Baltic Sea coast, monthly averages deviated by 2.6 K. In addition, across Germany it was much too dry, with amounts of precipitation only 40-50 % of the long-term average along the Baltic Sea coast. The average sunshine duration was 182 hours, 60 % higher than the long-term average of 114 hours.

April saw the warm and largely dry weather continue. Temperatures along Germany's Baltic Sea coast were some 2 K above the long-term average. Amounts of precipitation varied greatly from area to area: in Schleswig-Holstein, it was more than 60 % too wet; in Rostock, it was 26 % too dry; at Arkona station, it was 13 % too wet; and in Ueckermünde on the Polish border, it was about 41 % too wet. An average of 168 hours of sunshine across

Germany corresponded exactly to the long-term average. At Arkona station, it was about 10 % too sunny. Throughout the month, differences in atmospheric pressure above Europa were relatively small, and with Central Europe under the influence of high pressure, no lengthy periods of wind able to influence the sea level of the Baltic were recorded. The sea level at Landsort Norra fluctuated between -20 cm MSL and 10 cm MSL.

In the first half of **May**, the weather was largely influenced by areas of low pressure above the North Atlantic. Lows ('Vicky' and 'Xena') brought cool and moist air masses to Central Europe where weather developments were next controlled by highs ('Steffen', 'This' and 'Urs').

Across Germany, the month was too cool; only along the coasts was it slightly too warm (0.4 K along Germany's Baltic Sea coast). Nationwide, amounts of precipitation were above average, but did vary greatly from region to region. In a swathe stretching NW to SE from the North Sea coast to Bavaria, it was much too wet, with peak values of 112 % above the long-term average. Along the coast of Mecklenburg-Vorpommern, in contrast, it was too dry (Rostock -24 %, Arkona -42 %, Ückermünde -2 %). The sun shone mainly in the second half of the month for 180 hours, or 12 % below average (-8 % at Arkona). Winds were mainly weak (<10 m/s), except during a brief phase of easterly winds from 27-28 with high daily means of 15.1 m/s and 17.7 m/s. The level of the Baltic Sea fluctuated only slightly between 0 and -25 cm MSL.

June turned out to be very changeable. A heatwave over Whitsun (Pentecost) was accompanied on 11 by thunderstorms with downpours, severe hail and gale-force winds that caused major damage across Germany. A north-westerly flow of air then set in, bringing cool but mostly dry weather. Across the British Isles, a stable high ('Xerxes') together with a succession of lows ('Frederike', 'Gisela' and 'Hildegunde') over Scandinavia and the Arctic Ocean produced a lengthy phase of north-westerly to westerly winds at a constant 5-6 Beaufort from 18-24. The south-east component of the wind (positive north-westwards) exceeded daily means of >5 m/s, which at Landsort Norra led to a rise in sea level of around 30 cm (Figures 7b, 7a). As is usual in the summer, the rest of the month was characterised by weak to moderate winds. The temperature of 16.1 °C was about 0.4 K higher than the long-term average for 1981-2010; along the Baltic Sea coast, it was about 0.6 K above average. Overall, June was too dry with 52 mm of precipitation. Southern Germany in particular experienced a lack of rainfall, while along the Baltic Sea coast it varied from place to place: -56 % in Schleswig, 13 % too wet in Rostock and -17 % in Arkona. At 232 hours, sunshine duration was about 15 % higher than the average of 202 hours.

Again in **July**, conditions alternated between dry and sunny weather, with areas of high pressure ('Zeus' and 'Bertram') above Scandinavia and Eastern Europe, and brief periods of low pressure. Interrupted briefly by westerly winds (Figure 5b), persistent north-easterly to easterly winds developed, causing the sea level at Landsort Norra to fall gradually by some 25 cm to the level seen in early June (Figure 7a). With above-average levels of sunshine, July was too warm and too wet. Along the German Baltic Sea coast, temperatures were on average 2.4 K too warm. As in June, rainfall varied greatly from place to place: from -56 % at Arkona station, to -48 % in Schleswig; values in and around Ueckermünde were stable, while slightly positive values around 9 % were recorded in Rostock. At 229 hours, sunshine duration was only 4 % above the long-term average, while Arkona recorded 122 %.

At the beginning of **August**, an area of high pressure ('Susanne') extending from the British Isles to Scandinavia and Central Europe caused severe thunderstorms in the north on 3. A persistent area of low pressure then became established; its centre moved from the British Isles to southern Scandinavia. From 9 to the end of the month, it and areas of high pressure above the Mediterranean produced a phase of south-westerly winds (Figure 5b) that led to low tides in the western Baltic Sea and a rise of 47.8 cm in the sea level of the central Baltic (corresponding to a volume of 164 km³). Inflowing water masses from the Kattegat were relatively small at only 25 km³, as the curve of the accumulated inflow via the Öresund clearly illustrates (SMHI, 2015b). Thus it was mainly water masses from the south-west of the Baltic Sea that were forced into its central areas.

The summery temperatures that prevailed at the start of the month fell sharply; sunshine was of limited duration, and in many places rainfall increased significantly. Along Germany's Baltic Sea coast, temperatures were about 0.7 K below average. At Arkona station, for instance, rainfall amounted to 134 mm, which represents an extreme value of 220 % of the long-term average; sunshine duration was stable at 241 hours. Across Germany as a whole, sunshine duration was about 14 % below average at 176 hours.

September was characterised by constant change between areas of high and low pressure over Central Europe. After areas of high pressure ('Helmut', 'Ingemar' and 'Josef') slipped away to Eastern Europe, their influence there was long-lasting. Equalizing low-pressure areas above the North Atlantic and Scandinavia produced largely easterly winds throughout the month. When a low-pressure area ('Irina') moved across the region from 25, the westerly component again became more important (Figure 5b). The combined effects of a high-pressure area ('Ingemar') over Scandinavia and a low-pressure area ('Elisabeth') over the Bay of Biscay produced the sole phase of stronger, easterly winds with daily average speeds of 11.6 m/s and 11.3 m/s (Figure 5a). As a result, the water level of the Baltic Sea fell significantly from 27.5 cm MSL to -20 cm MSL by the end of the month. Across Germany, the average temperature of 14.9 °C was 1.4 K above the long-term average; 52 mm of rainfall was about 22 % below the average of 67 mm; at 136 hours, sunshine duration was also 8 % below the long-term average. In the south-west of the Baltic Sea area, temperatures were about 1.8 K above average; in its western section, it was about 39 % too dry, while rainfall of 67 mm at Arkona meant it was about 20 % too wet there. In terms of sunshine duration, 204 hours (119 %) was recorded at Arkona; nationwide, Ueckermünde came first with 198 hours of sunshine (126 %).

In **October**, a succession of low-pressure areas moving in from the North Atlantic crossed Scandinavia ('Joanna', 'Katrin', 'Margit', 'Noa', ex-hurricane 'Gonzalo'), and interacted with high-pressure areas over south-east and eastern Europe. This pressure system resulted in a sustained flow of mild air, mainly from south-westerly to south-easterly directions, that produced an average temperature of 11.9 °C, 2.7 K above average for 1981-2010 (only October in 2001 and 2006 was warmer). Typical autumn storms were not recorded; Landsort Norra gauge fluctuated between 0 and -20 cm MSL. At 63 mm, precipitation equalled the average value; at 100 hours, sunshine duration was 6 % below average. Stations along the Baltic Sea coast recorded monthly temperatures that on average were 2.7 K too warm. Again there were regional variations in rainfall: in Schleswig-Holstein, values were slightly negative; Arkona was too dry at 45 mm (-15 %); Ueckermünde recorded a positive rainfall amount of 71 mm (182 %).

In **November**, mild air masses from southerly directions continued to dominate thanks to extensive and persistent areas of high pressure ('Quinn' and 'Robin') over Eastern and South-Eastern Europe. From 12, easterly winds predominated, interrupted only briefly by westerly to north-westerly winds from 24-25. In November, no daily mean wind speed exceeded 10 m/s, so typical autumn storms still failed to materialise. The sea level at Landsort Norra fell quickly, and reached the year's record low of -52.7 cm MSL on 3 December. November started with record temperatures across Germany: with an average temperature of 2.1 K (6.5 °C), the average for the month was far exceeded. With 29 mm of rainfall, conditions were clearly much too dry, and were 56 % below the thirty-year mean of 66 mm. The average sunshine duration was calculated to be 60 hours, higher than the average of 54 hours. Along the coast, too, the positive temperature anomaly matched the average value for Germany as a whole. Arkona recorded only 17 mm of rainfall, 35 % of what is usual in November. The sunshine duration there was 49 hours, 9 % below average for 1981-2010.

At the beginning of **December**, an area of high pressure ('Robin') still dominated Eastern Europe; it gave way to highs ('Stefan' and 'Thue') moving from Southern Europe to north-east Europe where they remained until the end of the month. Coming from the North Atlantic, a succession of deep depressions moved in across Scandinavia over three weeks (6-26): 'Yasmina' and 'Zoe' were the first, followed by 'Alexandra' with a central pressure of 955 hPa (Figure 3). By the end of the month, they were followed by lows 'Doris', 'Engel', 'Freia' and 'Hiltrud'.

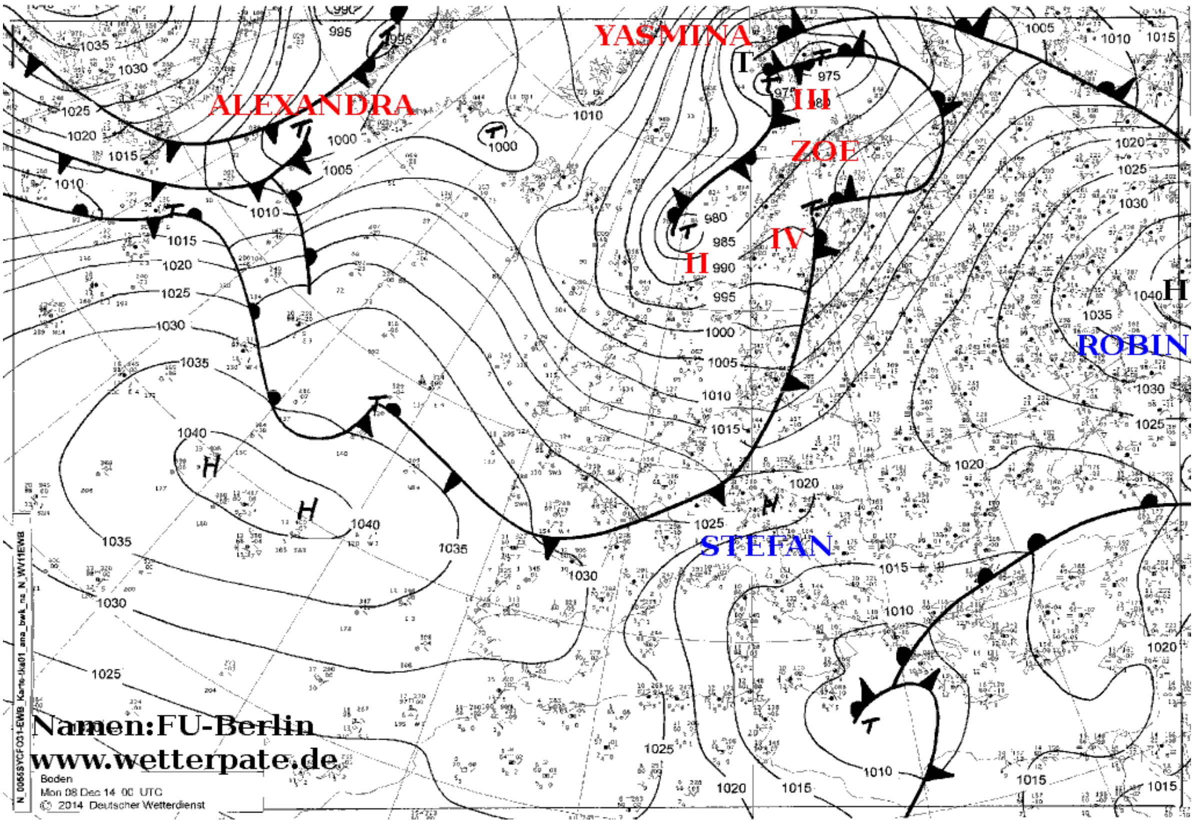


Fig. 3: Weather chart of 8 December 2014 with a storm front over the North Atlantic (FU-Berlin, 2014)

This exceptionally long phase of westerlies produced a massive inflow of saline water into the Baltic Sea (Figures 5a, 5b). On 24, Landsort Norra recorded the year's highest sea level of 48.6 cm MSL, representing a difference of more than one metre compared with the beginning of the month. On this basis, an inflow volume of 358 km^3 containing some 198 km^3 of saline water was calculated, which is sufficient to ventilate the deep basins of the central Baltic Sea (Mohrholz et al., 2015). Overall, the last month of the year was also too mild. With an average temperature of 2.7 °C, it was 1.5 K too high. Along the coast, the month had started with freezing days, and during the phase of westerly winds had experienced peak temperatures in excess of 10 °C, and after Christmas had come to a close with cold temperatures again. Mean monthly temperatures along the coast were on average 1.3 K too high. The amount of precipitation across Germany was calculated at 76 mm, only just exceeding the average of 72 mm. Rainfall of 87 mm in the north of Rügen was twice as high as usual, however. Sunny spells being the exception, the average sunshine duration was 22 hours, which corresponded to a reduction of 42 % compared with the thirty-year mean of 39 hours. Arkona station recorded 25 hours of sunshine.

2.3 Summary of Some of the Year's Significant Parameters

An annual sum of 387 139 J/m² of **solar radiation** was recorded at Gdynia. Lying in seventeenth 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 373 595 J/m², on a level with 2012. The sunniest months were May, June and July. At 65 193 J/m², July comes tenth 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 4376 J/m² in December, lying in twenty-sixth place on a level with the long-term average of 4354 J/m².

With a **warm sum** of 236.9 Kd (Table 2), recorded at Warnemünde, 2014 again comes in tenth place over the past 67 years, forcing 2013's value of 230.4 Kd into eleventh place. The 2014 value far exceeds the long-term average of 150 Kd, and exceeds the standard deviation, meaning that the year can again be classed as a particularly warm one, even if average monthly temperatures in June and August were slightly below the long-term average, and April and October were balanced. In comparison, May, July and September present warm sums that were twice as high; they were exceptionally warm months that come eighth, fourth, and sixth respectively in the time series since 1948.

With a **cold sum** of 65.8 Kd in Warnemünde, the winter of 2013/14 is the twenty-seventh warmest winter in the long-term data series, and is positioned in the upper mid range. Only January at 65.8 Kd was cooler than the long-term mean of 39.1 Kd; the other winter months were all too warm with a cold sum of 0 Kd. Along the German Baltic Sea coast, February was some 3.5 K too warm, as was March by some 2.5 K, followed by April at 2 K.

Table 1: Monthly averaged weather data at Arkona station (Rügen island, 42 m MSL) from DWD (2014). *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 (2015). 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	**1.1**	0.1	**90**	49	100	**12**	**8**	4764
Feb	3.6	2.5	89	**155**	70	5	-	13863
Mar	5.5	**2.6**	86	142	58	1	-	28984
Apr	7.6	1.6	86	110	113	-	-	48397
May	11.5	1.1	83	93	58	-	-	53449
Jun	15.2	1.0	79	121	83	-	-	59769
Jul	**19.2**	2.1	82	122	44	-	-	**65193**
Aug	17.3	**0.0**	77	100	**220**	-	-	48882
Sep	15.7	1.6	84	119	120	-	-	37048
Oct	12.5	2.5	89	71	85	-	-	16661
Nov	7.9	2.4	**90**	91	35	2	-	5753
Dec	3	0.7	**90**	66	202	10	1	**4376**

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 1948–2014 are given

Month	CS 2013/14	Mean 1948-2014	Month	HS 2014	Mean 1948-2014
Nov	0	2.6 ± 6.3	Apr	0	1.1 ± 2.5
Dec	0	22.2 ± 28.3	May	14.4	5.4 ± 6.7
Jan	65.8	39.1 ± 39.7	Jun	18.8	23.2 ± 14.7
Feb	0	31.9 ± 38.1	Jul	117.7	56.4 ± 35.9
Mar	0	8.6 ± 12.1	Aug	59.4	52.2 ± 32.1
Apr	0	0 ± 0.2	Sep	24.5	11.3 ± 12.0
			Oct	2.1	0.4 ± 1.1
Σ 2013/2014	65.8	104.5 ± 79.5	Σ 2014	236.9	150 ± 68.7

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

Month	CS 2013/14	Month	HS 2014
Nov	0	Apr	0
Dec	0	May	2.2
Jan	42.1	Jun	7
Feb	0	Jul	100
Mar	0	Aug	57.9
Apr	0	Sep	15
		Oct	0
Σ 2013/2014	42.1	Σ 2014	182.1

Figures 4 to 6 illustrate the **wind conditions** at Arkona throughout 2014. 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 2014 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 2014 curve (33 600 km eastwards, 44 000 km northwards) deviates considerably from the curve for the climatic mean (52 000 km eastwards, 25 000 km northwards). This can be attributed to the frequent phases of easterly winds that alternated with phases of westerly winds throughout the year (Figure 5b), and which in a long-term comparison show higher annual means. According to the wind-rose diagram (Figure 6), easterly winds account for about 46 % of the annual sum; prevailing westerly to south-westerly winds account for a further 40 %. The mean wind speed of 6.7 m/s (Figure 5a) just falls short of the long-term average of 7.1 m/s (HAGEN & FEISTEL, 2008). If the east component of the wind (positive westwards) of, on average, 1.1 m/s (Figure 5b) is compared with the climatic mean of 1.7 m/s (HAGEN & FEISTEL, 2008), however, the intensified phases of easterly winds become clear. With an average speed of 1.39 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, the curve for 2014 - especially from April to October - shows strong wind vector compensation compared with the average for 1951-2002. The trend towards prevailing SW winds that began in 1981 and continues today (HAGEN & FEISTEL, 2008) is more evident only in February, August, October and December.

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).

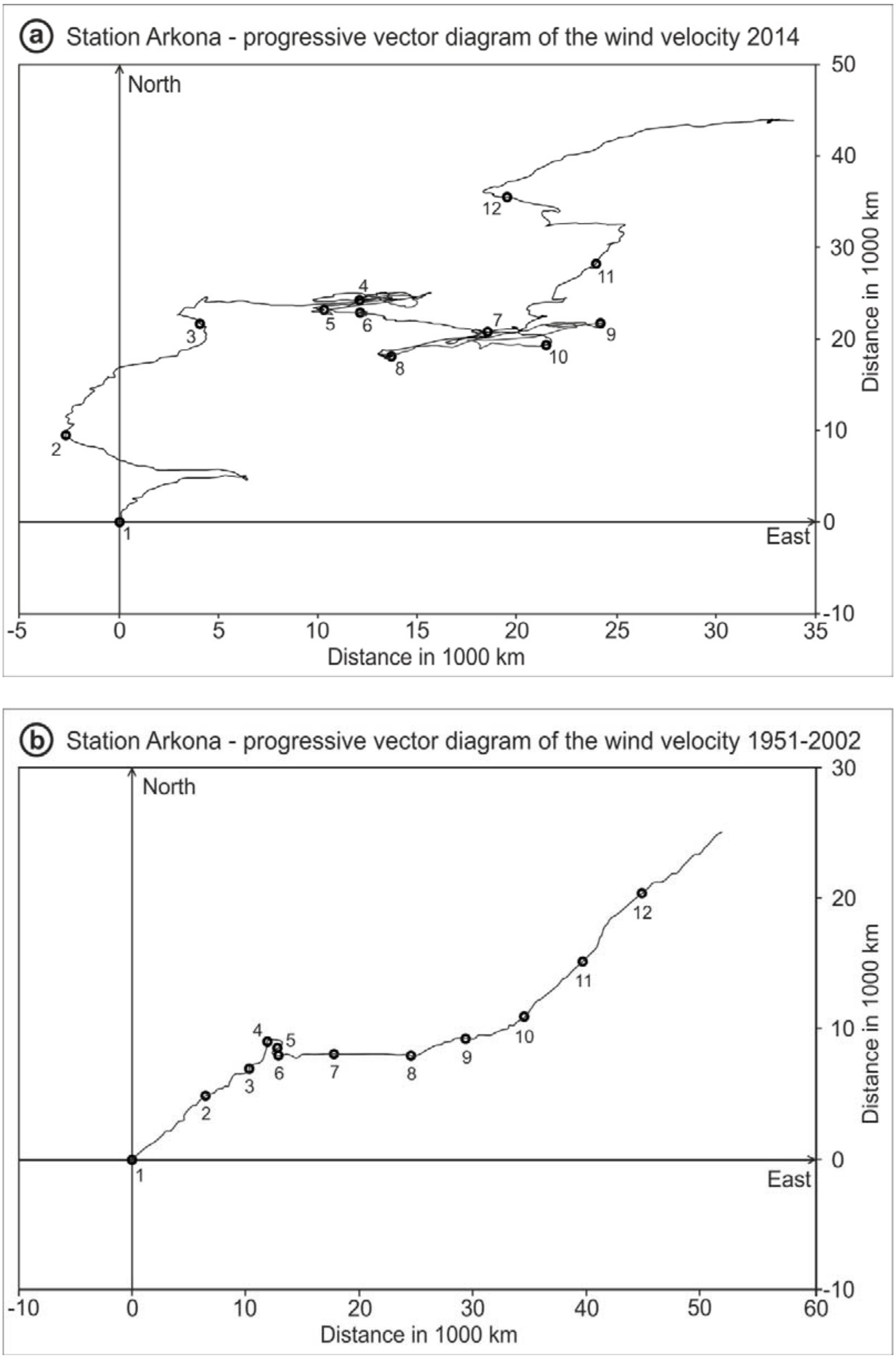


Fig. 4: Progressive vector diagram of the wind velocity at the weather station Arkona, distance in 1000 km, positive in northerly and easterly directions. The first day of each month is encircled. a) the year 2014 (from data of DWD, 2015) b) long-term average

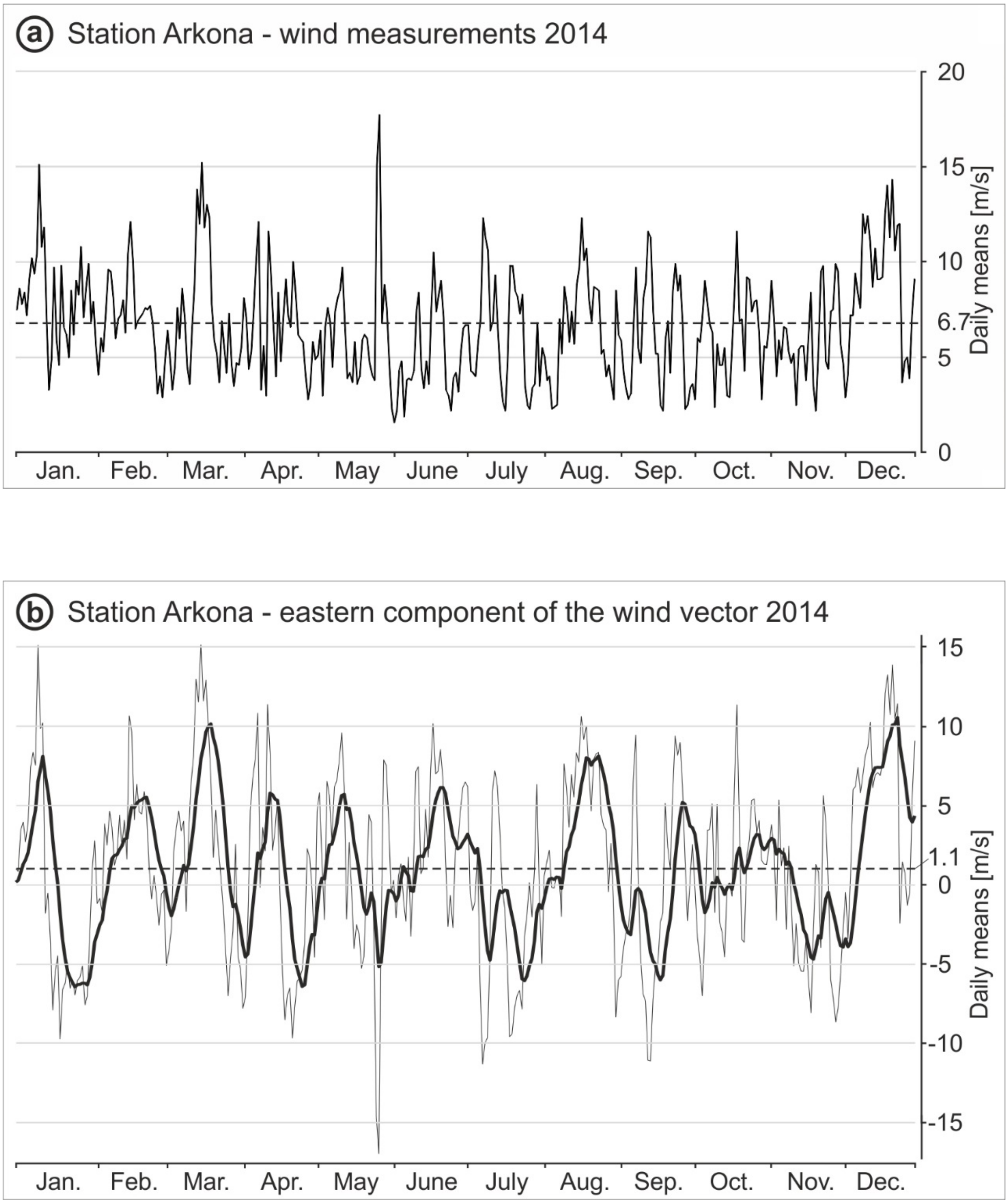


Fig. 5: Wind measurements at the weather station Arkona (from data of DWD, 2015). a) Daily means of wind speed, in m/s, the dashed line is the annual average of 6.7 m/s. b) Daily means of the eastern component (westerly wind positive), the dashed line is the annual average of 1.1 m/s. The line in bold is filtered with a 10-days exponential memory

Wind development in the course of the year reveals rather an unusual distribution of gale-force events, 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). What is particularly striking is the greatest daily average of 17.7 m/s, with gusts up to 25.4 m/s, from easterly to north-easterly directions on 28 May. Normally such events occur in the winter months between October and March. The annual mean wind speed of 6.7 m/s is slightly lower than 2013's 7.0 m/s, 2012's 7.1 m/s, and 2011's 7.3 m/s (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 late evening of 9th January; in 2013, this value was exceeded on seven days (NAUSCH et al., 2014). From 9-11 January, a deep depression ('Dagmar') swept across the Baltic Sea from the west, reaching a top speed of 21.2 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 not occur, in contrast to 2013 (NAUSCH et al., 2014).

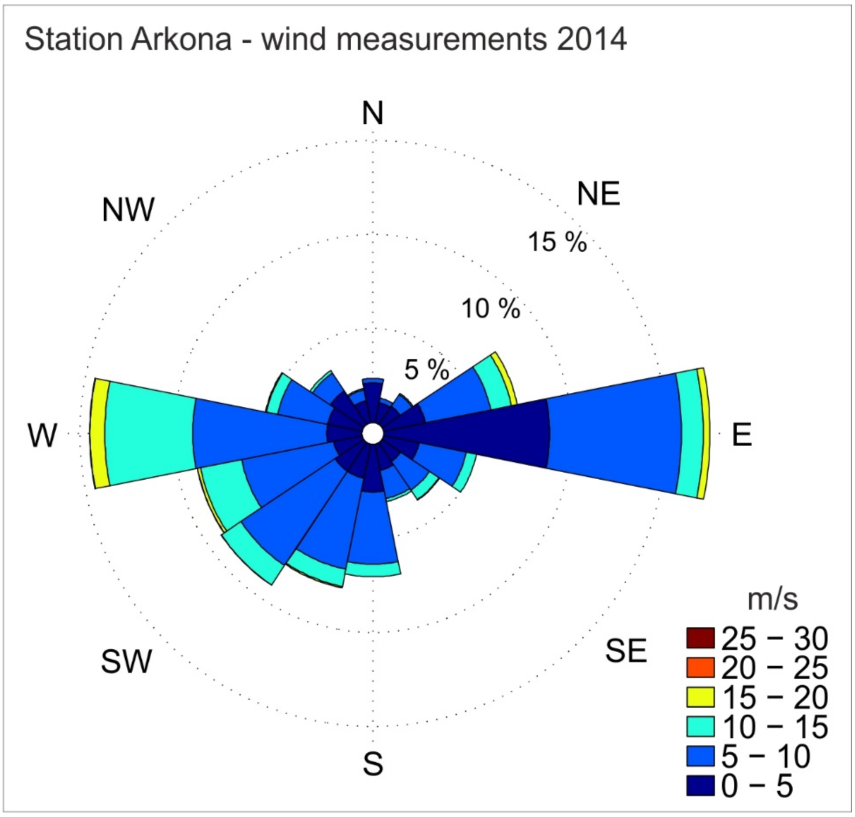


Fig. 6: Wind measurements at the weather station Arkona (from data of DWD, 2015) as windrose plot. Distribution of wind direction and strength based on hourly means of the year 2014

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 (LN) in 2005 revealed a correlation coefficient of 98.88 % and a linear regression relation L + 500 cm = 0.99815 □ LN + 0.898 cm with a root mean square deviation (rms) of 3.0 cm and a maximum of 26 cm.

In the course of 2014, the Baltic Sea experienced four inflow phases with volumes estimated between 141 km³ and 358 km³. Rapid increases in sea level that are usually only caused by an inflow of North Sea water through the Sund 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:

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

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 10 January, the gauge at Landsort Norra recorded a high water mark of 44.4 cm MSL (Figure 7a) as a result of gale-force winds in November and December 2013. A persistent easterly wind then produced a strong outflow, and the sea level fell to a low of -46.6 cm MSL on 3 February. An inflow phase began, and over 17 days the sea level rose by 43 cm to -3.6 cm MSL (20 February). With the empirical approximation formula:

$$\frac{\Delta V}{\mathrm{km}^3} = 3.8 \times \frac{\Delta L}{\mathrm{cm}} - 1.3 \times \frac{\Delta t}{\mathrm{d}}$$

(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 3 to 20 February thus yields a volume of 141 km³. After a brief outflow, and with the gauge registering -35.7 cm MSL, the next phase began on 8 March and lasted until 19 March when sea level rose to 21.7 cm MSL. Based on this height difference of 57.4 cm and 11.5 days duration, an estimated volume of some 203 km³ is calculated. In combination with the earlier effects of persistent westerlies from late October to early November as well as of hurricane 'Xaver' in December 2013, both these events produced a complex interaction that resulted in water spilling over Stolpe Channel in late April / early

May. These water masses reached the Gotland Deep in late May and oxygenated its deep water for the first time since 2003 (Nausch & Naumann, 2015). Towards the end of March, the sea level fell again to values around -20 cm MSL, and until mid-August fluctuated between -25 cm MSL and 15 cm MSL as easterly and westerly winds alternated (Figure 5b). The sea level rose over a lengthy third phase from 13 to 27 August, and the water volume increased by 164 km³ over a period of 13.5 days as a result of two weeks of south-westerly winds. At Landsort Norra, the sea level rose by 47.8 cm from -20.3 cm MSL to 27.5 cm MSL. In terms of ventilation of the deep basins, effects were confined to the Arkona and Bornholm Basins. Measurements by Rak (2015, in press) at the beginning of October showed increased temperatures in the deep water of the Bornholm Basin that are attributable to the inflow of warmer water during the summer. Measurements indicated only low oxygen concentrations, however. Then at the beginning of September the sea level fell again, and fluctuated between -20 cm MSL and 16 cm MSL until the end of October. Persistent easterly winds in November caused a strong outflow: at Landsort Norra the sea fell to its lowest level of the year, -52.7 cm MSL on 3 December. A strong south-westerly set in at the beginning of December; initially it forced water masses out of the southern Baltic towards the north-east, and produced low water levels in the western Baltic. After 13 December, the wind veered westerly, and large amounts of saline water from the North Sea were forced into the Baltic. Over 21 days (3 to 24 December), the sea level at Landsort Norra rose by 101.3 cm, which gives a total volume of 358 km³. The highest sea level of the year was recorded on 24 December at 48.6 cm MSL. According to calculations by Mohrholz et al. (2015), this event represents the third-largest inflow of saline water since the beginning of the record in 1880.

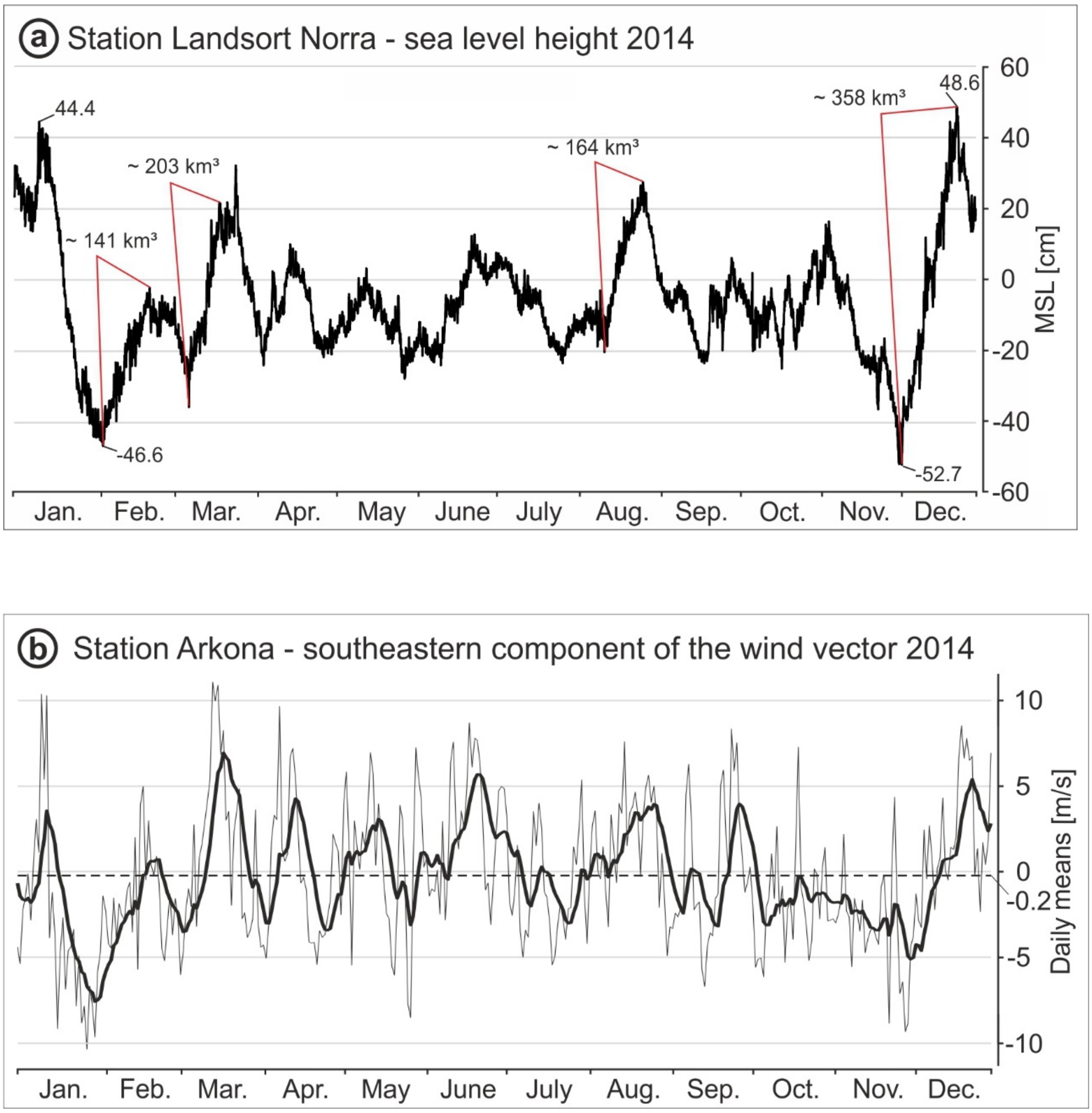


Fig. 7: a) Sea level at Landsort as a measure of the Baltic Sea fill factor (from data of SMHI, 2015). b) Strength of the southeastern component of the wind vector (northwesterly wind positive) at the weather station Arkona (from data of DWD, 2015). The bold curve appeared by filtering with an exponential 10-days memory

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

Shipyard maintenance and technical issues in recent years meant that Darss Sill monitoring station (DS) had been supplying only incomplete series of measurements. In 2014, however, complete and continuous records of temperature, salinity and oxygen concentrations again became available. As usual, in addition to the automatic oxygen readings taken on the 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) and the measurement curves were corrected accordingly.

Complete readings by the acoustic Doppler current profile (ADCP) at DS are available for 2014 except for a brief data gap from 18 October to 3 November that was due to hardware failure.

3.1 Statistical Evaluation

Statistical evaluation of data from DS confirms that 2014 was an unusually warm and record-setting year: average annual water temperatures at all sampled depths in part clearly exceeded all previous average temperatures observed there (Table 4, Figure 8). The previous peak value of 9.99 °C for the average temperature of the surface layer from 2007 was exceeded by the spectacular value of 0.6 K, making 2014 by far the warmest year in the entire recording period.

Similarly, the annual amplitude, here determined by Fourier analysis, lay in the upper range of the reference period, but despite the high summer temperatures described below (Table 5), it failed to reach record values because water temperatures at the end of the year were still relatively warm, and because the duration of maximum summer temperatures was relatively short. Overall this caused the annual amplitude to flatten off somewhat, which is also reflected in the standard deviations of temperature that are essentially determined by it (Table 4, Figure 8). Maximum values since the beginning of the record were not exceeded here either.

The strong inflow activity in 2014 is seen most obviously in the value for average surface salinity that clearly exceeded all previously observed average values – in contrast to the readings from near-bottom sensors (Table 4, Figure 9). Even the standard deviation of surface-layer salinity, itself a measure of fluctuations in salinity levels, only just fell short of the record value in 1993. The distinct signatures of the surface-layer inflows in 2014, most especially of the extreme event in December, are due to the exceptionally high inflow volumes that affected the entire water column at Darss Sill (see discussion below).

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

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

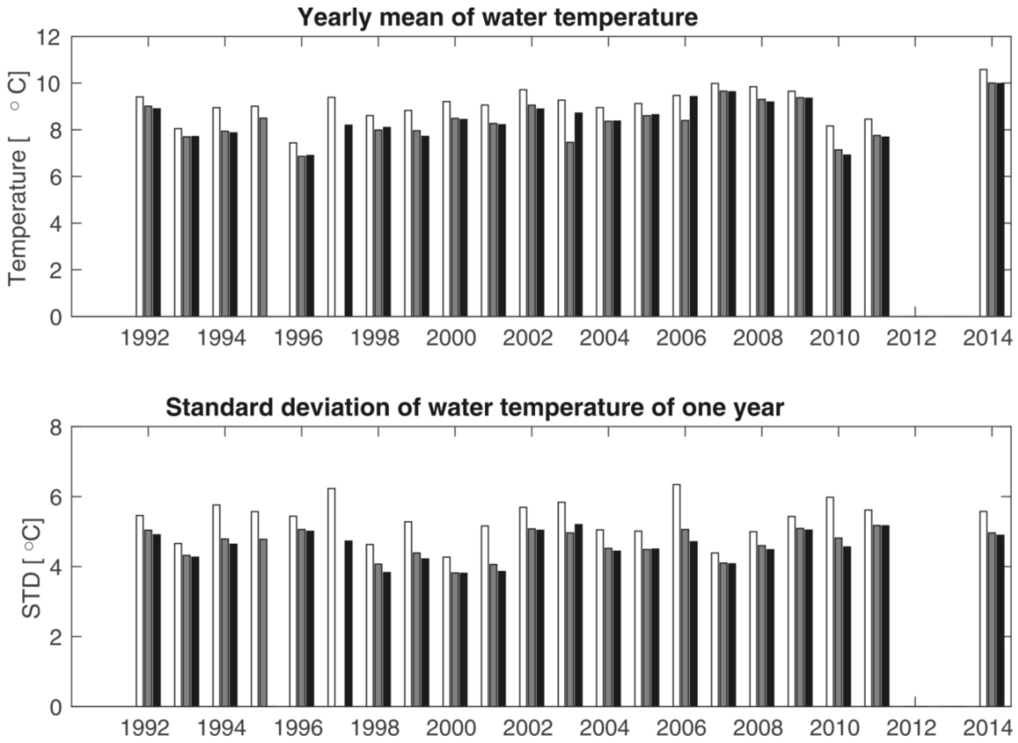


Fig. 8: Mean and standard deviation of water temperature taken over one year in the surface layer (7 m, white bars) and the bottom layer (17 m, grey bars and 19, black bars) at the Darss Sill

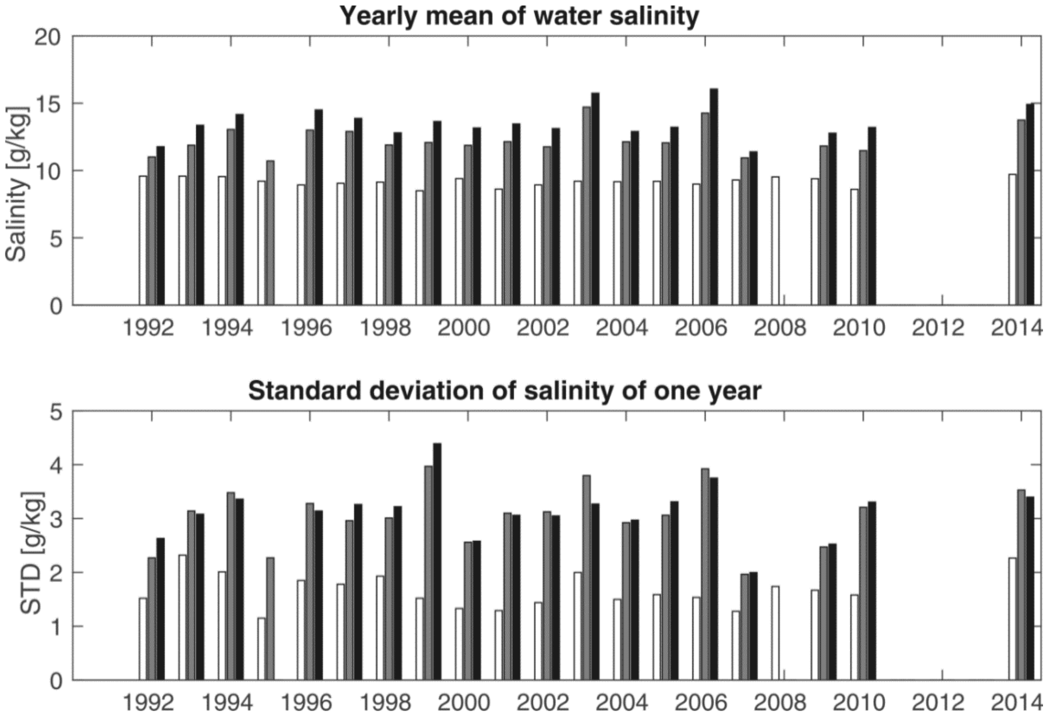


Fig. 9: Mean and standard deviation of salinity taken over one year in the surface layer (7 m, white bars) and the bottom layer (17 m, grey bars and 19, black bars) at the Darss Sill

3.2 Warming Phase with Inflows in February and March

Figure 10 shows the development of water temperature and salinity in 2014 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, and were plotted as a 'progressive vector diagram' (pseudo-trajectory). This integrated presentation format filters short-term fluctuations from current measurements, and allows long-term phenomena such as inflow and outflow events to be recognised more easily. According to this definition, the current velocity corresponds to the slope of the curves shown in Figure 11, positive slopes reflecting inflow events. Note that the integrated velocities shown in Figure 11 contain an unknown shift parameter because of the roughly two-week-long data gap after 18 October (described above), from which point on they are not directly comparable with readings from previous years.

As already touched on in chapter 2, January was characterised by pronounced easterlies. They were reflected in the current measurements at Darss Sill in a consistently strong and rapid outflow throughout the water column over a three-week period from 13 January to 2 February (Figure 11). Outflow velocities of up to 0.4 m/s and a rapid fall in the sea level at Landsort Norra were observed; its gauge fell to the second-lowest level of the year (Figure 7a).

The water column was thoroughly mixed, and was characterised by the almost consistent salinity levels found in the western Baltic Sea (8-9 g/kg). As a result of strong heat loss to the atmosphere during this phase (chapter 2), the water temperature fell steadily, and in the first few days of February reached around 2.2 °C, its minimum value in 2014.

When easterly winds moderated, the first strong inflow phase of the year began as of 3 February. It was observed at Darss Sill until 13 February, first as a continuous velocity signal, and then as a weak, fluctuating one. Analysis of gauge data from Landsort Norra yielded an inflow volume of some 140 km^3 during this event; bottom salinity levels at Darss Sill rose to more than 16 g/kg (Figure 10). From 2 March easterly winds caused a brief outflow phase (Figure 11) that led to a moderate fall in the sea level (Figure 7a).

With winds veering westerly, an inflow phase set in again on 8 March. By 15 March it had reached its height with unusually high inflow speeds in excess of 0.7 m/s; it began to decline slowly after 19 March (Figure 11). Gauge data (Figure 7a) indicate an inflow volume of some 200 km^3 – or the second-largest inflow of 2014 (chapter 2). On 22 March, salinity levels in the surface layer reached maximum values of around 17 g/kg; bottom salinity levels even exceeded 18 g/kg (Figure 10). This phase coincided with the start of the spring bloom that is clearly identifiable in the measurements of greatly supersaturated oxygen levels in the surface layer at Darss Sill (Figure 12).

Neither of these two inflow events in spring 2014 fulfilled the criteria of a Major Baltic Inflow. Surprisingly, however, IOW observations identified a clear signature from these inflows in the bottom water of the central Baltic Sea: from July, ventilation of the bottom water in the eastern Gotland Basin was observed for a short time in a near-bottom layer some 30-40 m thick. It was accompanied by a reduction in phosphate remobilization and an increase in nitrate levels. It is assumed that lateral intrusions caused partial oxidation of hydrogen sulphide, even in water layers nearer the surface. This ought to be considered when interpreting the effects of the Major Baltic Inflow in December 2014, as described below.

The second inflow of the spring was ended by a strong outflow phase from 23 March to 8 April. Thereafter, during the summer months until August, no stronger inflows of saline water were observed. Two smallish combined inflow events in June were noteworthy around this time (Figure 11). The warm water they imported from the Kattegat led to sudden warming of the near-bottom layers (Figure 10) and to a recovery of oxygen concentrations in the bottom water that at the beginning of the month had fallen below 60 % saturation (Figure 12). The highest surface-layer temperature of the year was 21.5 °C, observed on 8 August. The maximum temperature of the bottom water of 17.2 °C was reached only at the end of the month because of the delay due to lateral advection. As a result of the high temperatures of the bottom water during the summer (Figure 10) and the absence of further inflows, bottom oxygen concentrations in July and August occasionally fell below 40 % saturation (Figure 12).

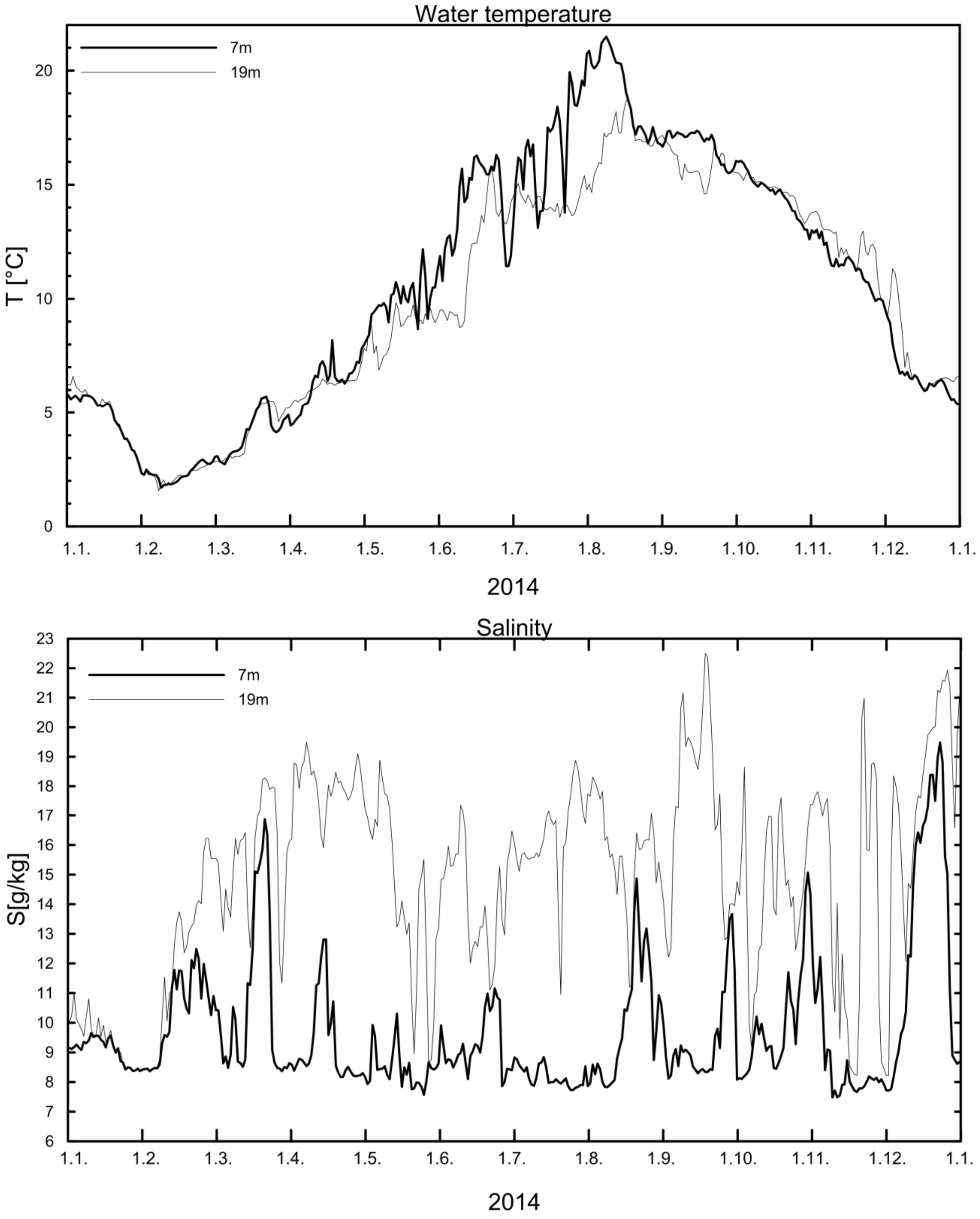


Fig. 10: Water temperature (above) and salinity (below) measured in the surface layer and the near bottom layer at Darss Sill in 2014

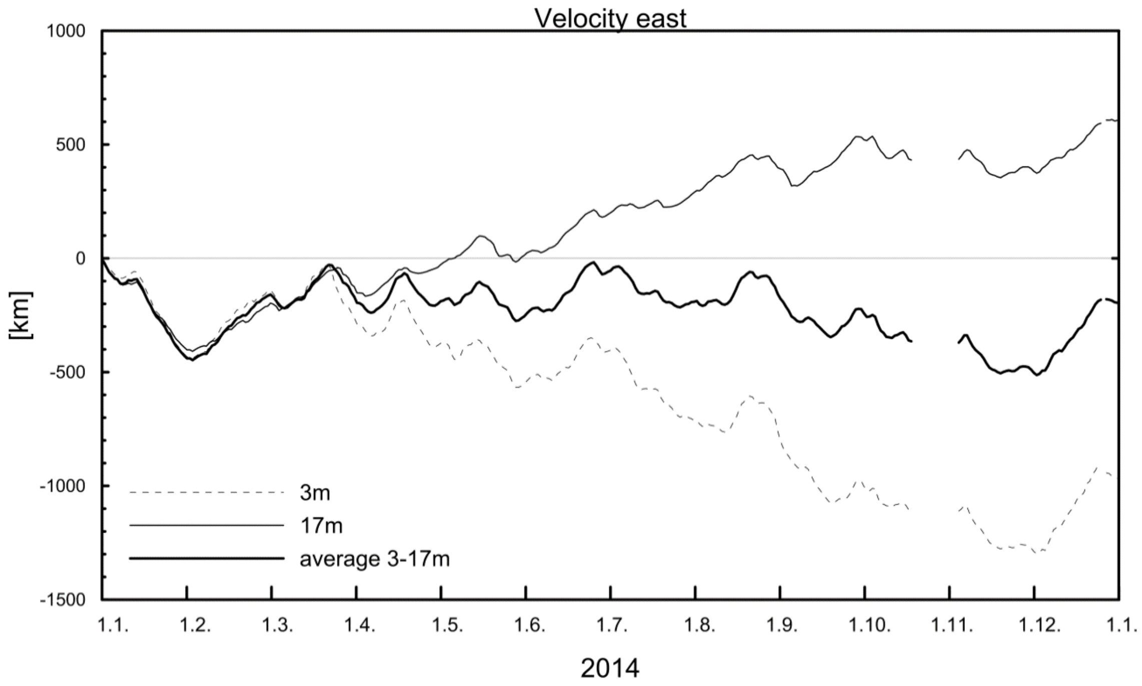


Fig 11: East component of the progressive vector diagrams of the current in 3 m depth (solid line), the vertical averaged current (thick line) and the current in 17 m depth (dashed line) at the Darss Sill in 2014

3.3 Cooling Phase due to the Major Baltic Inflow in December

With easterlies strengthening, a strong inflow began on 12 August and lasted until 21 August; it coincided with the start of the autumn cooling phase. During this event, oxygen saturation in the bottom water recovered suddenly after 16 August from below 40 % to over 95 %. Salinity levels in excess of 15 g/kg were observed in the surface layer. Interestingly, Landsort Norra gauge recorded a steady increase in sea level until 27 August (Figure 7a), almost a week after the inflow across Darss Sill had subsided.

SMHI current data show that the increase in sea level during the last week of August cannot (as was initially suspected) be explained by inflow through the Öresund (http://www.smhi.se/hfa_coord/BOOS/Oresund.html). It can be assumed to have been a transient phenomenon, probably caused by a wind surge that was not directly linked to the water masses entering the western Baltic Sea. Their estimated inflow volume of 164 km^3 (as calculated in chapter 2 and formally the third largest of the year) is presumably overestimated in effect. While the distinct signature of this inflow was observed in the Bornholm Basin (RAK, in press), none was observed in the bottom water of the central Baltic Sea.

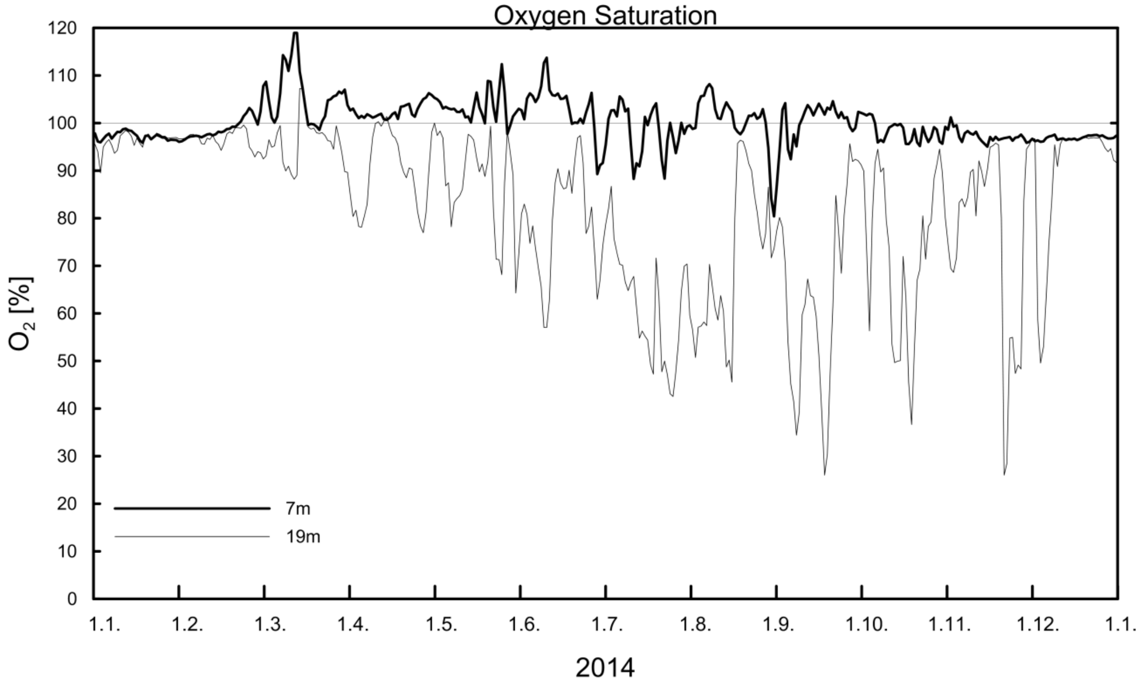


Abb. 12: Oxygen saturation measured in the surface and bottom layer at the Darss Sill in 2014

After a period of strong outflow (speeds of 0.85 m/s were observed in the surface layer on 31 August), the sea level at Landsort Norra levelled off around neutral values in the first week of September (Figure 7a). On 5 September, currents in the bottom layer veered east (signifying inflow), while an outflow continued in the near-surface layers (Figure 11). This trend towards near-bottom baroclinic inflow (i.e. one driven by differences in density), and near-surface barotropic outflow, with barely any changes in sea level, lasted for much of September, as the spread of the pseudo-trajectories in the bottom and surface layers in Figure 11 clearly shows. On 19 September, the highest salinity levels of the year were observed in the bottom water: 23 g/kg (Figure 10). Only now did bottom oxygen concentrations begin to recover slowly (Figure 12), having fallen below 25 % saturation, their lowest value of the year. In the last week of September, the tendency towards baroclinic inflow was intensified by a short but powerful barotropic inflow that by the end of the month led to oxygen saturation levels of around 90 % in the bottom water.

October was characterised by limited water exchange across the sills and by sea level stagnating at neutral values. The preparatory phase for one of the largest inflow events ever observed then began on 7 November when a month(ish)-long outflow phase driven by persistent easterly winds got underway. It was briefly interrupted a number of times, but overall it led to the lowest sea levels of the year (Figure 7a). On 2 December, with winds still easterly but moderating, the current at Darss Sill changed direction, and a long and uninterrupted salt-water inflow began (Figure 11). Initially driven by differences in sea level, and later by strong and persistent westerly winds, this process led at Landsort Norra to a rise in sea level of about 1 m, corresponding to an inflow volume of some 360 km^3 (Figure 7a).

As chapter 2 explains, this event was the third-largest inflow ever recorded, and was the largest since 1951. During it, the water column at Darss Sill remained slightly stratified, with salinity levels on 26 December reaching peak values of 22.2 g/kg on the seafloor, and 15.5 g/kg in the surface layer (Figure 10). As oxygen concentrations remained near saturation levels throughout the water column, a vast amount of imported oxygen can be assumed (Figure 12). According to the latest estimates and observations at the time of going to press, this event will be of crucial significance for the development of the properties of the deep water in the central Baltic Sea in the years to come.

4. Observations at the Buoy “Arkona Basin”

The dynamics of saline bottom currents in the Arkona Basin was investigated some years ago by two projects, “QuantAS-Nat” and “QuantAS-Off” (Quantification of water mass transformation in the Arkona Sea), which were funded by Germany’s DFG and BMU. Among other findings, the results contain the first detailed turbulence and velocity profiles through density-driven bottom currents that were observed during some medium-strength inflow events in a channel north of Kriegers Flak (ARNEBORG et al., 2007; UMLAUF et al., 2007; SELLSCHOPP et al., 2006). In a detailed pilot study, BURCHARD et al. (2009) investigated the spreading paths of medium-strength inflow events 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 modelling data using data from the MARNET monitoring network as published in this series every year. Advanced theoretical investigations based on QuantAS data have revealed a surprisingly strong influence of Earth’s rotation on turbulent interference processes in dense bottom currents, and have led to the development of new theoretical models for such currents (UMLAUF & ARNEBORG, 2009a, b, UMLAUF et al., 2010).

The Arkona Basin monitoring station is located almost 20 sea miles north-east of Arkona in 46 m of water. As it did in 2013, the monitoring station in 2014 again provided complete series of measurements of temperature, salinity, and oxygen concentrations (as described in chapter 3, oxygen concentrations were corrected using occasional, direct measurements of oxygen using the Winkler method). Figure 13 shows the time series of water temperature and salinity at depths of 7 m and 40 m; corresponding oxygen concentrations, plotted here as saturation values, are shown in Figure 14.

The annual cycle of surface-layer temperature in Figure 13 shows that the lowest temperature of the year of 2.4 °C (daily mean) was recorded on 7 February. This value clearly exceeds 2013’s minimum value of 0.9 °C that was reached only on 23 March following an unusually late cold spell. In contrast, near-surface temperatures in 2014 showed a rising trend as early as mid-February. As a result of inflow activity, bottom-layer temperatures followed with a delay of about three weeks (see chapter 3). The warming phase strengthened in March; towards its end, the highest daily mean of the year was reached in the surface layer on 8 August. At 22 °C, it was about 1 °C above the previous year's already high value, thus further emphasizing the exceptional character of 2014.

The autumn cooling phase began immediately after this maximum temperature; even at the end of August, surface-layer temperatures were already only just above 17 °C. After further steady cooling in the autumn months that followed, towards the end of the year the surface layer temperature was still 6.3 °C, a value that was 1-2 °C above that observed at the end of the two previous years. In the second half of the year, temperatures in the bottom layer followed the cooling trend with a delay, falling abruptly due to the succession of cold, salt-water inflows (chapter 3). What is really striking here is the drop in temperature of more than 5 °C in the bottom layer as a result of December's Major Baltic Inflow.

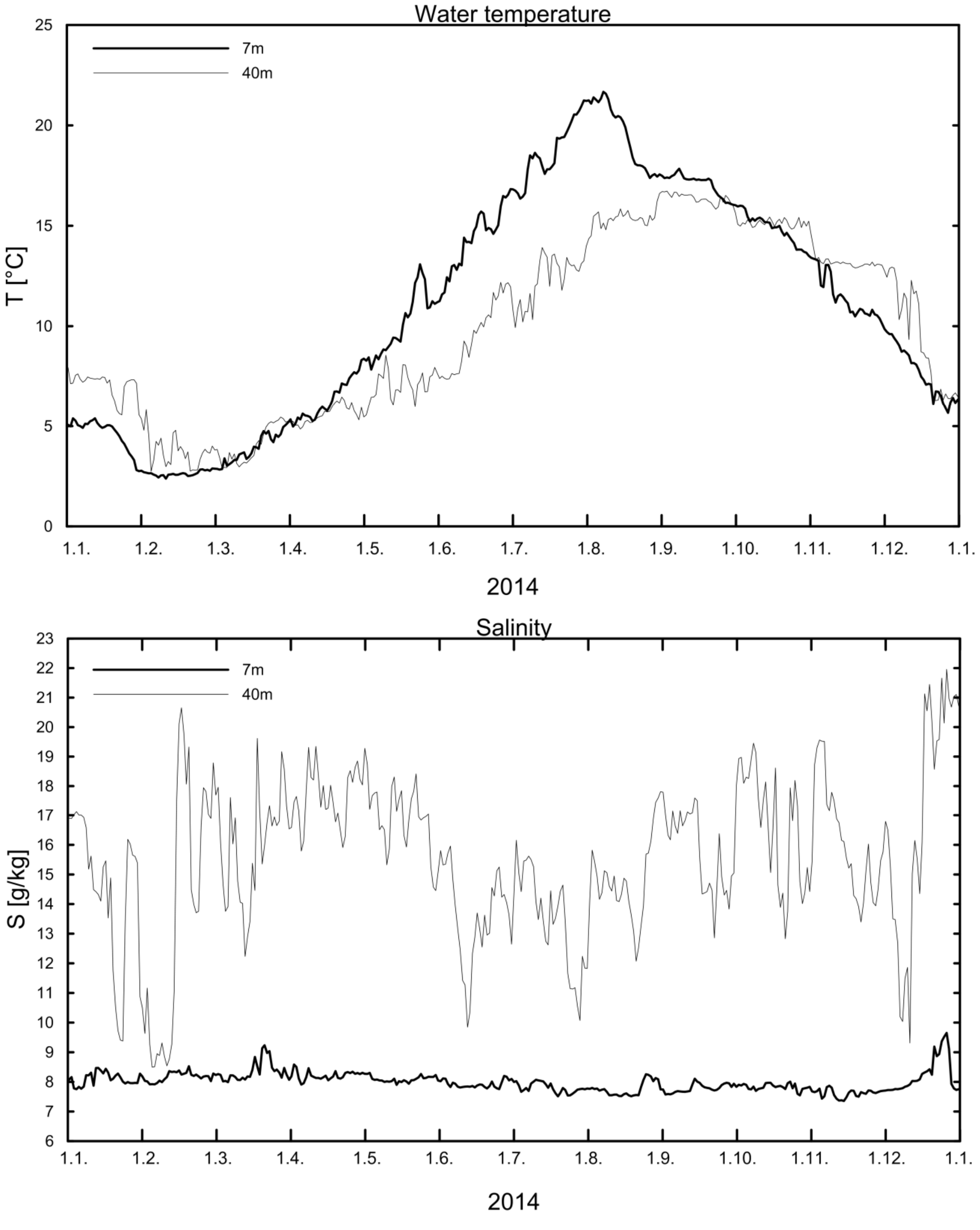


Fig. 13: Water temperature (above) and salinity (below) measured in the surface layer and near bottom layer at the station AB in the Arkona Basin in 2014

As with the surface temperatures, oxygen concentrations in the surface layer (Figure 14) also showed a distinct seasonal signal. As early as the end of February, a month earlier than in 2013, saturation values exceeded 100 % for the first time, and thus indicated greatly increased rates of photosynthesis and primary production at the onset of the spring bloom. The year's highest oxygen concentrations were reached on 13 March when, after a few days of really calm and very sunny weather, values of up to 115 % oxygen saturation were observed in the surface layer. As a result of strengthening winds and falling temperatures in the surface layer, oxygen saturation levels began to fall after 11 August, coinciding with the start of the autumn cooling phase (described above), and finally dipped below 100 % again. They fluctuated around saturation levels until the beginning of November, and in the last two months of the year fell back again slightly to reach typical winter concentrations of around 95 % of the saturation limit.

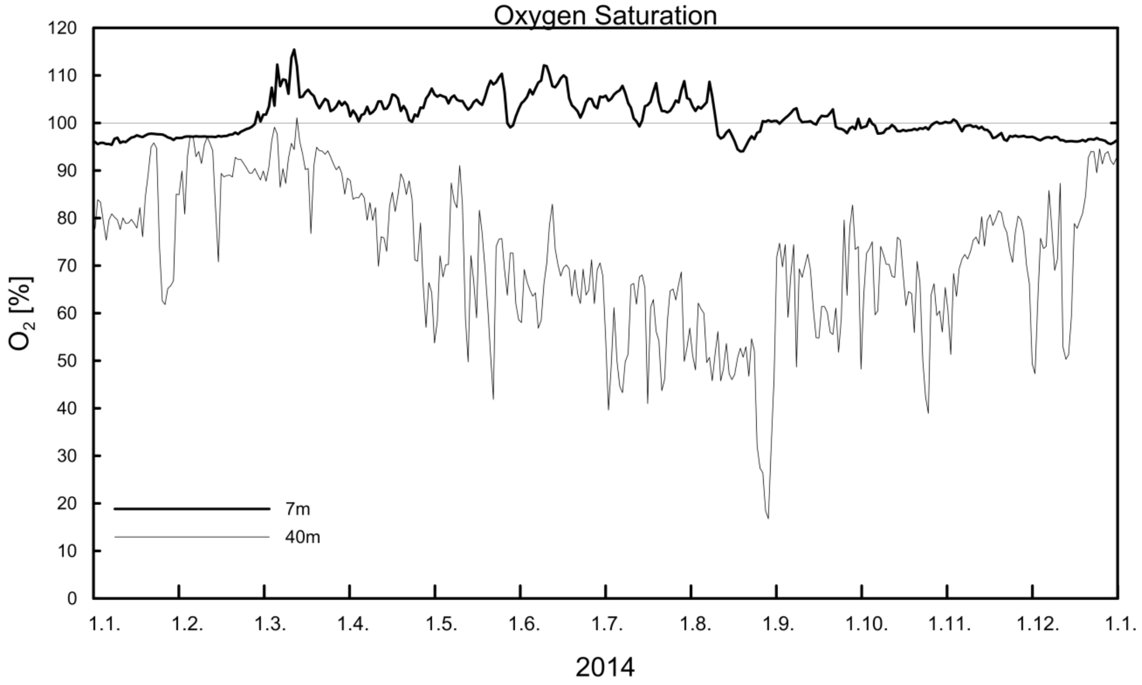


Fig. 14: Oxygen saturation measured in the surface and bottom layer at the station AB in the Arkona Basin in 2014

The signature of the two moderate inflows in February and March (see chapter 3) was clearly identifiable in the bottom water where salinity levels after week 2 in February increased within a few days to over 20 g/kg (Figure 13). The data from other sensors at depths of 40 m, 33 m and 25 m (not shown here) indicate that these inflows into the Arkona Basin formed a saline pool of bottom water that may have been 15-20 m thick. Oxygen concentrations in the bottom water were high at the time, but began to fall steadily after mid-March given the lack of subsequent inflows, and because of the preceding spring bloom in the surface layer.

As a result of a weak but steady inflow trend, bottom oxygen concentrations did not fall below 40 % saturation until the last week of August. Interestingly, the lowest oxygen concentrations of the year (below 17% saturation) were observed on 29 August (Figure 14), i.e. at a point when the water masses from the August inflow (chapter 3) began to reach the Arkona Basin. Figure 13 shows that salinity levels in the deep water indicate an inflow of salt water as early as 23 August, while oxygen concentrations were falling sharply at the same time. This suggests that the first pulse of the August inflow introduced almost anoxic water masses, presumably because of consumption processes in the Danish Straits. In the course of this inflow event, increasingly oxygen-rich water masses began to enter the Arkona Basin, and allowed its bottom oxygen concentrations to recover permanently. The largely baroclinic inflow in September (described above) continued this trend, although the pool of salty bottom water in the Arkona Basin never exceeded 10 m in thickness.

Until the start of the outflow phase (chapter 3) that prepared the way for the large December inflow, oxygen concentrations in the bottom layer fluctuated between 60-70 % saturation. In the course of this outflow phase, the water in the Arkona Basin was gradually replaced by water flowing in from the Bornholm Basin. As Figures 13 and 14 show, this was expressed in a fall in salinity and a slight increase in oxygen concentrations. At the end of the outflow phase, bottom salinity at a depth of 40 m measured only 10-11 g/kg. Only the sensor nearest the seabed at a depth of 43 m (not shown in Figure 13) continued to indicate residual saline bottom water with salinity levels over 14 g/kg.

The signal of the Major Baltic Inflow (see chapters 2 and 3) that began at Darss Sill on 2 December reached the bottom water below the monitoring station in the Arkona Basin on 11 December. With the aid of the five deepest sensors, of which only the one at 40 m depth is shown in Figure 13, it is possible to track in detail how the inflowing salt water filled the Arkona Basin. Salinity levels at depths of 43 m, 40 m and 33 m passed the 20 g/kg mark on 13, 17 and 26 December respectively. All in all this indicates a layer of highly saline water at least 10 m thick. The greatest bottom salinities had a daily mean of just under 23 g/kg, and although such a high salinity was not recorded at depths of 25 m and 16 m, a marked increase in salinity occurred there too: they surpassed 15 g/kg on 21 and 22 December respectively. Even in the surface layer, salinity levels increased from 7.5-8 g/kg before the inflow to 9-9.5 g/kg at its conclusion.

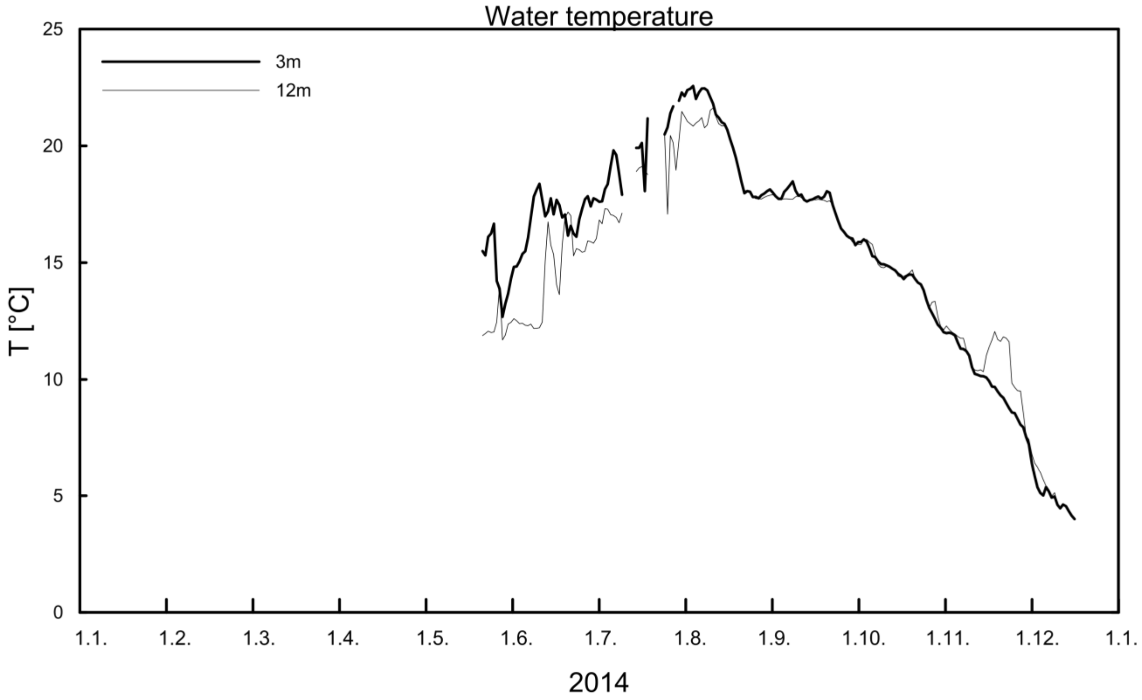
As of 26 December, salinity levels at a depth of 16 m began to fall again as a result of the discharge through the Bornholm Channel; they reached the standard value of 7.5 g/kg before the end of the year. The deeper sensors (25 m and below) were then still recording salinity levels of more than 18 g/kg, even if on a downward trend. Besides its high levels of salinity, the outflowing water was largely characterised by oxygen concentrations above 90 % saturation and comparatively low temperatures of 6-6.5 °C. This should prove useful in the year to come when tracking the progress of these water masses as they flow out of more easterly basins.

5. Observations at the Buoy "Oder Bank"

The distribution of water masses and circulation in the Pomeranian Bight have been investigated as part of the TRUMP project (*TR*ansport und *UM*satzprozesse in der *P*ommerschen Bucht) (v. BODUNGEN et al., 1995; TRUMP, 1998), and have been described by SIEGEL et al. (1996), MOHRHOLZ (1998) and LASS, MOHRHOLZ & SEIFERT (2001). With winds from the west, well-mixed water is observed in the Pomeranian Bight (a small amount of surface water from the Arkona Basin is admixed to it. With winds from the east, 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 are an important influence on primary production and the oxygen balance in the Pomeranian Bight.

The Oder Bank monitoring station (OB) is located almost 5 nautical miles nord-east of Koserow/Usedom in 15 m of water; it measures temperature, salinity and oxygen at depths of 3 m and 12 m. Following the gradual conversion of the oxygen sensors at all monitoring stations, continuous oxygen measurements have been taken at OB since 2010 using new optodes by Aanderaa. During servicing, the measurements are calibrated with comparative measurements obtained using the Winkler method. The monitoring station was removed to its winter quarters on 18 December 2013. After its winter break, it did not go back into operation until 22 May 2014. From then it provided continuous data series for all parameters until 16 December when it was again brought in to avoid damage from floating ice.

Temperatures and salinity levels at OB are plotted in Figure 15; associated oxygen readings are plotted in Figure 16. The temperature time series are noteworthy especially for the high temperatures in the surface layer in 2014; at midsummer during July and August, they came close to those of 2013, which had already been an exceptionally warm year. At the start of August, in hot summer weather with low wind speeds, the surface layer temperature stagnated for more than ten days above 22 °C, a value that in average years is not reached even for a short time. The highest daily mean of 22.5 °C was recorded on 8 August; hourly means in the afternoon of 6 August even exceeded 23 °C. The maximum values of record-breaking 2010 and of the exceptionally warm 2013 were thus narrowly exceeded.



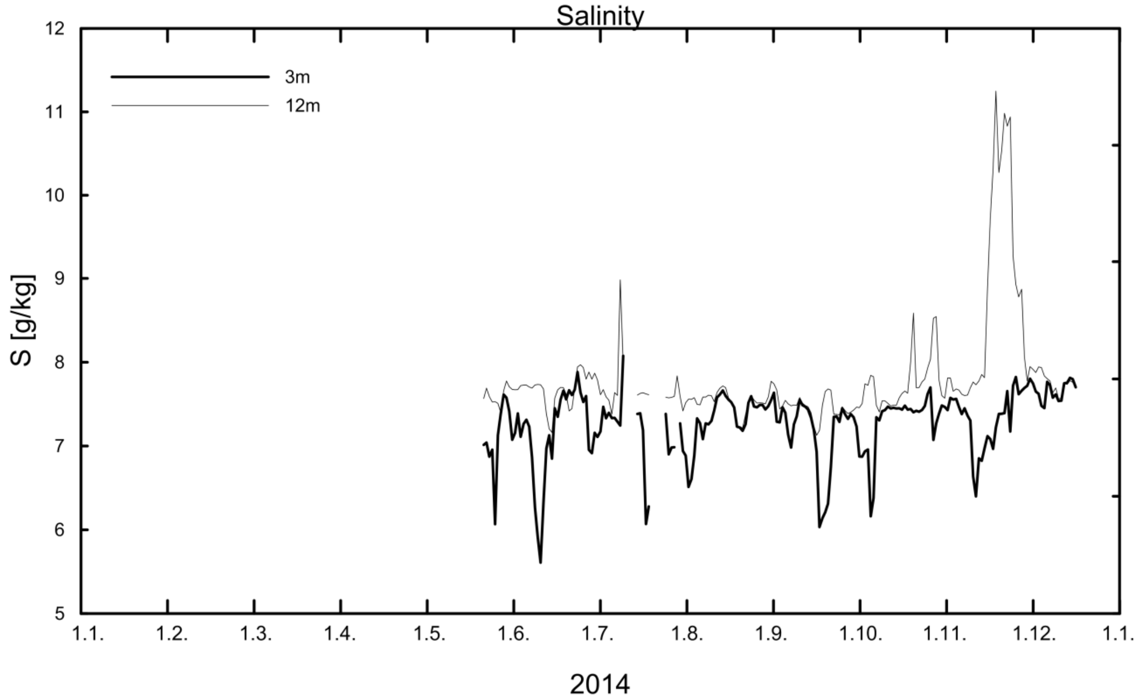


Fig. 15: Water temperature (above) and salinity (below) measured in the surface layer and near bottom layer at the station OB in the Pomeranian Bight in 2014

A significant dynamic reason for the strong warming in the surface layer of Oder Bay lies in the suppression of vertical mixing caused by the stratification of less saline (i.e. less dense) mixed water from Oder Lagoon. During the summer months, such stratification events generally correlate very well with short phases of distinct temperature stratification and high temperatures in the surface layer. In 2007 and 2010, similar, widespread stratification events also led to a sharp drop in near-bottom oxygen concentrations.

Distinct events of this type were observed in 2014 in June, August, September and October. On 11 June, for instance, salinity in the surface layer - typically fluctuating slightly around a mean value of about 7.5 g/kg - fell to 5.6 g/kg as a result of stratification of water from Oder Lagoon; simultaneously, the surface-layer temperature rose to 18.4 °C (Figure 15). Freshening winds with speeds up to 10 m/s produced mixing that brought this event to an end over the days that followed. At the beginning of August, a similar but weaker event prepared the physical environment that allowed the record temperatures to develop in the surface layer (described above). During a phase of autumnal stratification of lagoon water on 17 September and 5 October, surface-layer salinities also fell sharply in each case to around 6 g/kg. With the solar and atmospheric heat supply already greatly reduced, no significant increase in surface-layer temperatures was observed (Figure 15).

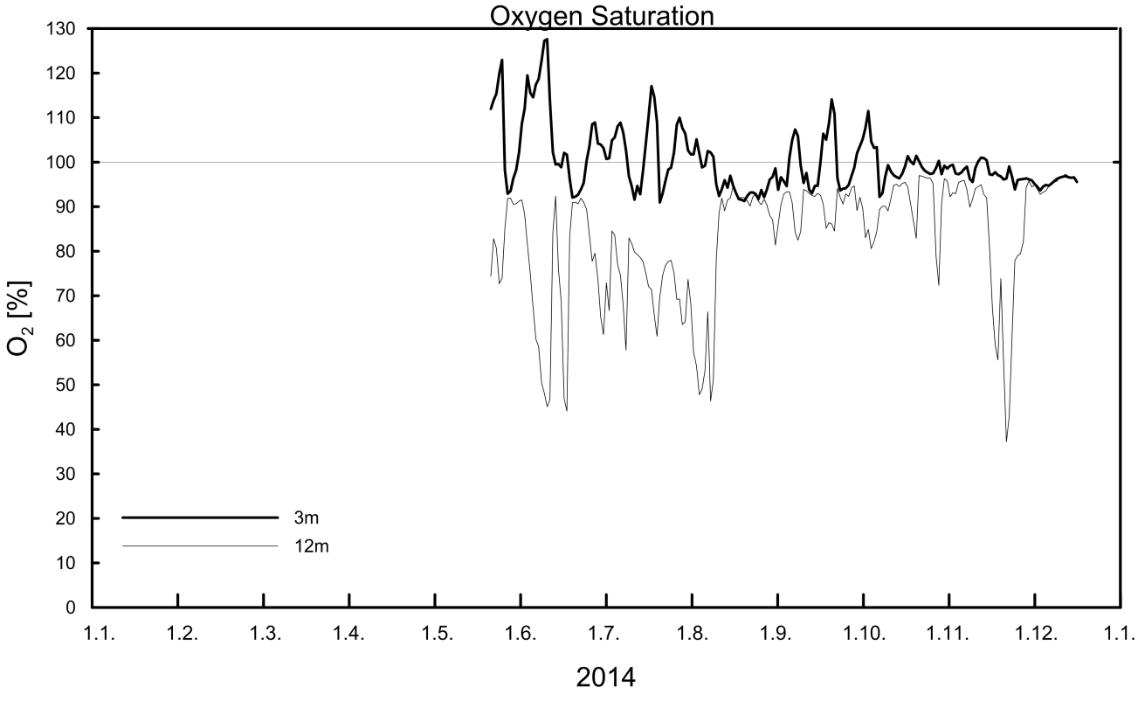


Fig. 16: Oxygen saturation measured in the surface and bottom layer at the station OB in the Pomeranian Bight in 2014

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 as the bottom layer is cut off from direct atmospheric ventilation. This effect on the oxygen balance of the Pomeranian Bight is illustrated in Figure 16; it plots oxygen concentrations at depths of 3 m and 12 m. During all stratification events, a distinct negative correlation emerged between increasing oxygen saturation in the surface layer and a decrease in the near-bottom layer. In the case of the summer events in June and early August described above, bottom oxygen concentrations each fell to about 45 % of saturation; in the case of the autumnal events, consumption rates were already too low to lead to a marked reduction. All in all, the low oxygen concentrations observed in previous summer months - far less the anoxic conditions of record-breaking 2010 (NAUSCH et al. 2011a) - were not reached, however.

It seems likely that the increase in primary production of biomass in the Oder Lagoon - due to the lateral transport of lagoon water to OB - led to the supersaturated oxygen concentrations that were observed in the surface-layer during all these events (Figure 16). In addition, lagoon water exports high nutrient concentrations from the lagoon. At OB, this resulted locally in increased production, which in turn may explain the increased oxygen concentrations in the surface layer. The correlation between these events and the decrease in oxygen in the near-bottom layer indicates increased oxygen consumption through the decay of sinking biomass. In view of the high water temperatures that were observed, the associated microbial processes occurred at an accelerated rate.

Remarkably, the lowest oxygen concentrations of the year - at 37 % saturation - were observed on 21 November, at a time when bottom oxygen concentrations are typically found near the saturation limit due to autumnal mixing processes, low water temperatures, and reduced consumption rates as a result of minimal primary production (Figure 16). At the same time, temperature and salinity levels in the bottom layer rose sharply (Figure 15): salinity levels reached 11 g/kg, a value that is very rarely observed in the shallow Oder Bank.

This rare phenomenon is explained by the fact that November was characterised by an outflow trend driven by easterly winds. Even in the days before the event, strong easterly winds were observed across the Arkona Basin, which suggests the following physical explanation: according to Ekman's classic theory, as a result of the Earth's rotation, a northerly direction of transport occurs in the surface layer when winds are easterly. In the area of the southern directed coast of the Arkona Basin, this Ekman Transport is directed away from the coast, and suggests that compensational upwelling of water masses from deeper layers occurs. Such coastal upwelling led in this case to the near-bottom transport of salty, warm and oxygen-deficient water masses from intermediate depths in the Arkona Basin into the area of OB.

Further oxygen consumption in this bottom layer - isolated from direct atmospheric aeration because of strong density stratification - probably contributed to the low oxygen concentrations that were observed. When easterly winds moderated, this saline bottom layer sank again due to its high density, and thus disappeared from the range of the monitoring sensors at OB (Figures 15 and 16).

6. Hydrographic and Hydrochemical Conditions

6.1 Water Temperature

6.1.1 The Sea Surface Temperature of the Baltic in 2014 derived from Satellite Data

The development of Sea Surface Temperature (SST) in the Baltic was followed with the aid of US NOAA satellite data and European MetOp weather satellites; 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 Sea Surface Temperature (SST) in the Baltic is summarised in NAUSCH et al. 2014 and in HELCOM Environment Fact Sheets (SIEGEL & GERTH, 2014). Reflections on the long-term development of SST since 1990 are presented in SIEGEL et al. (1999, 2006, 2009) and SIEGEL & GERTH (2010). The warm and cold sums of air temperature at Warnemünde (Table 2) as well as data from MARNET stations (BSH/IOW) and the in-house monitoring network of Mecklenburg-Vorpommern’s Agriculture and Environment Agency (StALU) were consulted as part of the interpretive process.

2014 was the warmest year since 1990 and thus was around 1.2 K above average for the period 1990-2014; it was 0.4 K higher than 2008, formerly the warmest year. Except for February and June, all other months contributed, especially July and August in the north of the Baltic Sea. The western Baltic Sea exceeded long-term mean values by +1 to +3 K in every month except February.
After a mild start to the year, a cold spell starting around 20 January produced strong cooling until the beginning of February. Nevertheless, the monthly average for January exceeded the long-term means for 1990-2014 by +2 K; January was the second-warmest January in the western Baltic since 2007. February lay in the range of long-term means, and in the Arkona Sea and Gulf of Bothnia was the coldest month of the year. February 4 was the coldest day in the entire Baltic Sea, and 6 February was the day of maximum ice cover. As usual, March developed into the coldest month of the year in the Gotland Sea. From March to May throughout the Baltic Sea, and even from March to December in its western section, anomalies of +1 to +3 K were recorded. June was the only month with negative anomalies of -1 to -2 K throughout the basins of the central and northern Baltic Sea. July was the warmest month only in the Mecklenburg Bight; otherwise it was August. The warmest day was 28 July with temperatures of 21-25 °C. The atypically stable temperature distribution throughout the Baltic Sea in July and August led to large anomalies of up to +5 K in its northern section in July. July 2014 was the warmest month since 1990. With anomalies of up to +3 K, October and November were the warmest in the western Baltic Sea.

The cold and warm sums of the air temperature at Warnemünde (Table 2, Chapter 2) shed light on the severity of the winter and the course of the summer. With a cold sum of 66 Kd the winter of 2013/14 was one of the warmest since 1948. The month of January accounts for this cold sum: it was considerably colder than the January long-term average of 39.1 Kd. The other winter months were too warm by +2 to +3.5 K. The warm sum for the summer of 2014 (236.9 Kd) was only slightly higher than the value for 2013 (230.4 Kd), but far exceeded the long-term mean (150 Kd). The months of May and June to October exceeded the long-term means; at 117.7 K · d (56.4 Kd) July in particular contributed to the warm sum.

The overall trend of SST is discussed with reference to monthly means. Figure 17 shows the anomalies of monthly means for 2014 for the entire Baltic Sea.

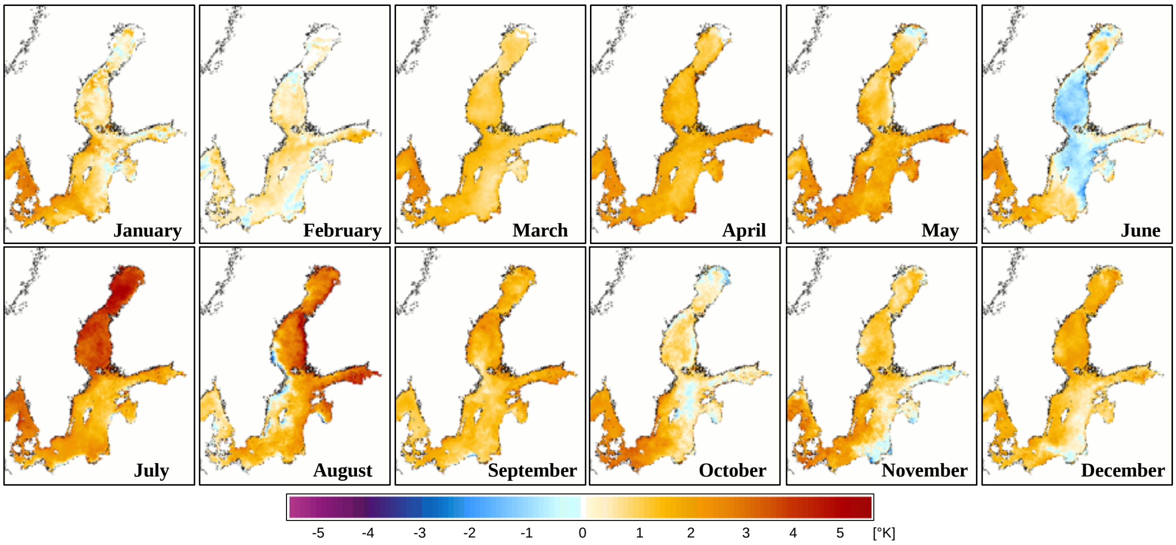


Fig. 17: SST- Anomalies of the monthly mean temperature of the Baltic Sea in 2014 referring to the long-term means 1990-2014

The seasonal development of mean monthly 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 1990-2014. A detailed description of the temperature development is given on the basis of daily means of SST (which are not presented here).

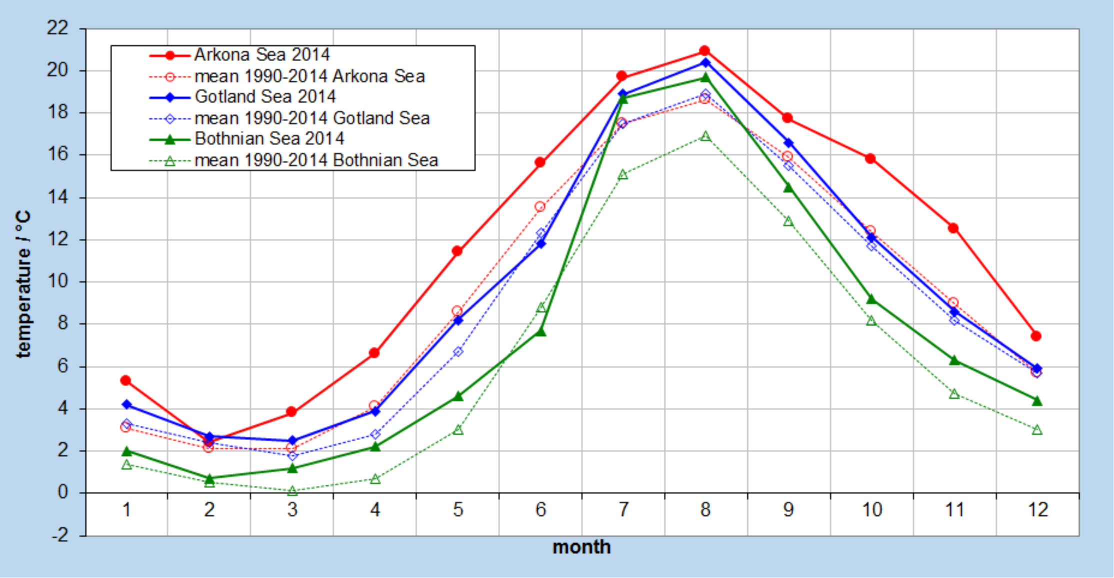


Fig. 18: Seasonal course of sea surface temperature in the central Arkona-, Gotland- and Bothnian Sea in 2014 in comparison to the mean values of the last 25 years (1990-2014)

After the comparatively mild first half of January in the western Baltic Sea with SSTs around 5 °C, a cold spell started about 20 January (see cold sums of air temperature). By the beginning of February, it produced strong cooling to around -0.5 °C in the Pomeranian Bight; 1-2 °C in the Mecklenburg Bight; and 2-3 °C in the Arkona Sea on 4 February (Figure 19). That day was also the coldest day in German coastal waters and the entire Baltic Sea. February 6 is recorded as the day of maximum ice cover throughout the Baltic (SCHMELZER & HOLFORT, 2014). Despite this cooling, the monthly means for January reveal anomalies of +2 K. In the past twenty-five years, January 2014 was thus the second-warmest January in the western Baltic after January 2007. The temperatures reached in early February were largely sustained until the end of the month, meaning February was in the range of long-term means, and was the coldest month of the year in the Arkona Sea and in the Bothnian Sea. Thereafter wind-driven mixing produced slight cooling in the Arkona Sea, shallower areas warmed slightly, and the ice retreated.

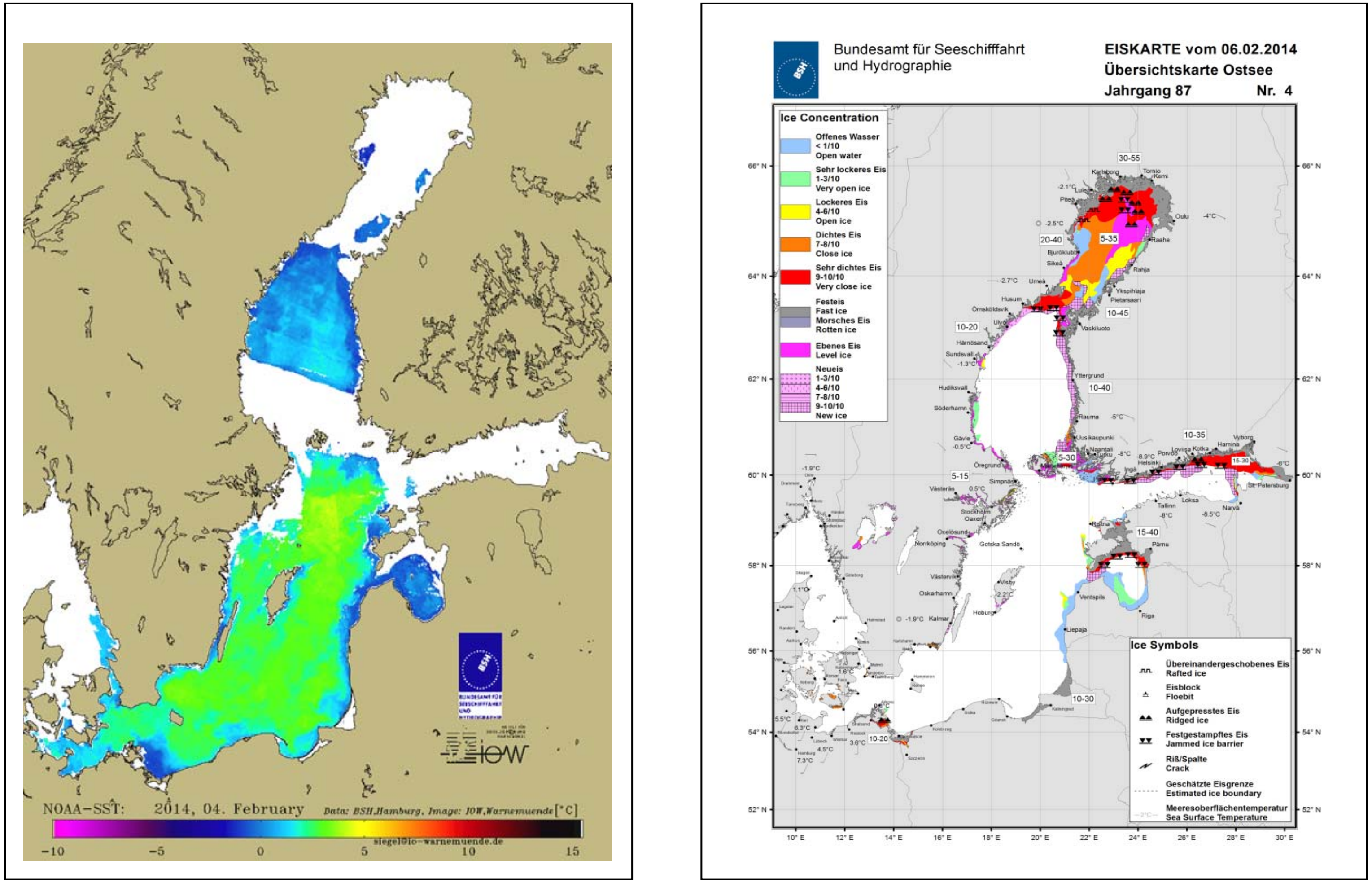


Fig. 19: SST of the Baltic Sea on 4 February (coldest day) and maximum ice coverage of the year 2014 on 6 February

Slight warming began in mid-February; by the end of the month, it had produced temperatures of 2-3 °C. March was characterised by a steady increase with short periods of stagnation. By the end of the month, temperatures had reached 4-5 °C throughout the western Baltic; 3-5 °C in the central Baltic as far as the Gotland Sea; and 0.5-2 °C in the Gulf of Bothnia and the Gulf of Finland. From March to May, the entire Baltic Sea area recorded anomalies of +1 to +3 K. As usual the Gotland See was coldest in March. In the western Baltic, similar anomalies were sustained over the whole year, and exceeded +2 K in October and November. Warming continued in April without the strong, wind-driven mixing that in previous years had often caused strong fluctuations in SSTs. In the shallow areas of the Mecklenburg Bight, the Pomeranian Bight, and the Bay of Gdańsk, 10 °C had been reached by the end of the month. In central areas of the western Baltic, SST was 7-8 °C; in the central Baltic it was 5-7 °C. In the northern Baltic, 2-4 °C was already being recorded - considerably warmer than the same time a year earlier. By mid-May, the western Baltic had warmed only slowly to 9-12 °C. There was no more ice in the northern Baltic where the SST was 2-5 °C. Rapid warming occurred after 20 May. By 26 May, the following values had been reached: 14-17 °C in the western Baltic; 12-15 °C in the central Baltic; 10-12 °C in the northern Gotland Sea; and 5-8 °C in the Gulf of Bothnia. Thereafter wind-driven mixing produced the first serious cooling of 2014, in some cases exceeding 1-2 K. At +2 K to +3 K, May was especially warm; after May 2008, it was the second-warmest May in the last twenty-five years.

Strong fluctuations were recorded in anomalies in the northern Baltic Sea. In May and especially in June, the typical increase of up to 8 K from north to south was very pronounced (Figure 18). This is also shown by SST distribution along the transect through the central basins of the Baltic Sea in June 2014 (Figure 20).

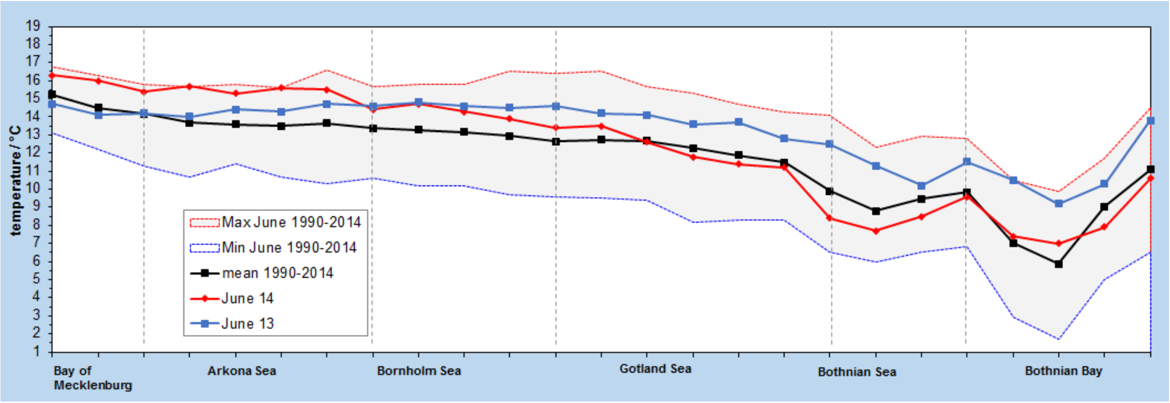


Fig. 20: Temperature distribution along the transect through the central basins of the Baltic Sea in June 2014 in comparison to the previous year, the long-term mean value of 1990-2014 and the variation range

SST is shown in relation to the long-term average for 1990-2014, the previous year, and the range of variation. June was very changeable: phases of high pressure that produced warming were repeatedly interrupted by troughs of low pressure bringing wind and high cloud cover. The water thus warmed only negligibly in June; mean monthly temperatures were relatively low (Figure 20), and negative anomalies occurred in the central and northern Baltic Sea. While the monthly average for SST in the Arkona Sea was as high as 16 °C (an anomaly of +2 K), in the Gotland Sea it was 12°C (-0.5 K), and in the Bothnian Sea it was only 7.5°C (-1.5 K). The next major warming phase occurred at the beginning of July: on 06, SST increased to 17-20°C in the western Baltic, to 15-18 °C in the Gotland Sea, and to 12-16 °C in the Gulf of Bothnia. In the days that followed, the northern Baltic Sea experienced particularly strong warming. On 9 July, a fairly even temperature of 16-20 °C was widespread throughout the Baltic Sea. Following wind-driven mixing from 12-15, these temperatures were again reached on 16 July. Thereafter SST increased sharply during a phase of weak winds. After 22 July, the northern Baltic Sea was warmer than its central and western sections.

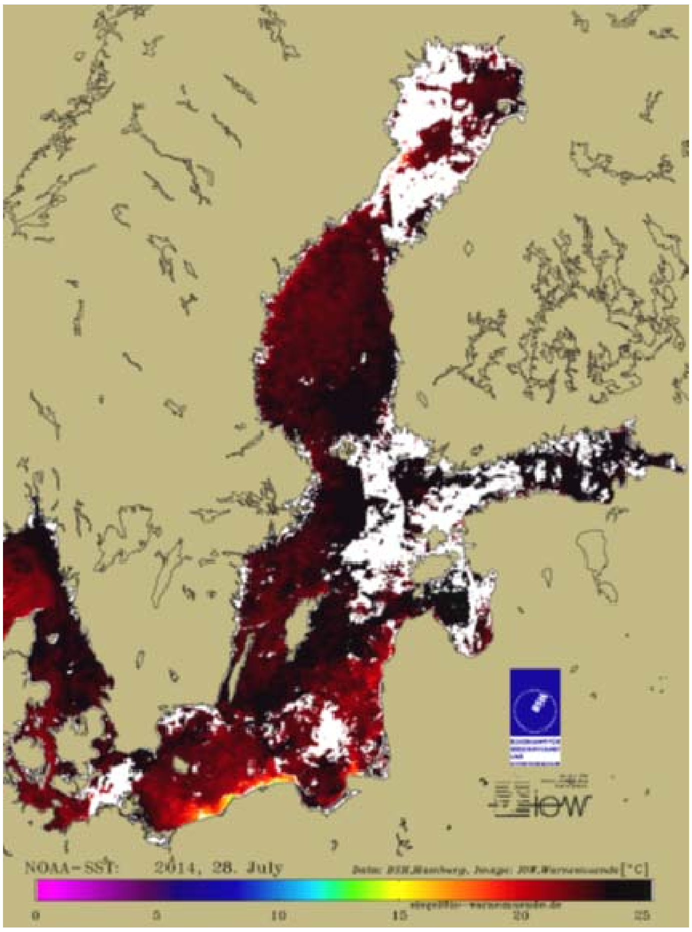


Fig. 21: SST of the Baltic Sea on 28 July, the warmest day of year 2014

Easterly winds and upwelling along the German and Polish coast prevented strong warming in the southern and western Baltic Sea. After 25 July, SSTs in the northern Baltic lay between 23-25 °C. A weakening of upwelling caused 28 July to develop into the warmest day in the western Baltic Sea, with temperatures of 21-24 °C (Figure 21). Thereafter easterly winds in the south and westerly winds in the north intensified upwelling activity both in the southern Baltic Sea and the Gulf of Bothnia, and caused SST to fall below 19 °C in upwelling regions and below 23 °C in wide areas of the central Baltic Sea. In July and August, no differences existed between north and south – in contrast to every other month. The entire Baltic Sea experienced similar mean monthly temperatures of 19-21 °C. The annual cycle of SST in the three central basins in Figure 18 illustrates this point well. Monthly averages are very close. Figure 22 shows the temperature distribution in July 2014 along the transect through the central basins of the Baltic Sea in relation to the long-term average for 1990-2014, the previous year, and the range of variation. The figure very clearly illustrates the slight differences in temperature along the transect (red curve). In the north, in the Bothnian Sea and Bothnian Bay, the mean values for July 2014 determined the upper limit of the range of variation throughout the period of investigation.

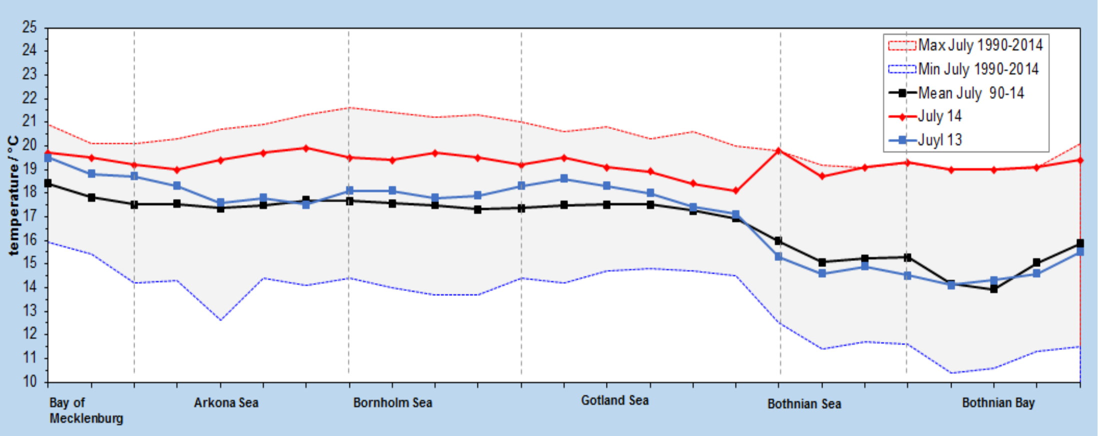


Fig. 22: Temperature distribution along the transect through the central basins of the Baltic Sea in July 2014 in comparison to the previous year, the long-term mean value of 1990-2014 and the variation range

This resulted in extreme anomalies in the northern Baltic Sea of up to +5 K. July 2014 was by far the warmest year in the northern Baltic in the past twenty-five years. The temperatures at the end of July continued until about 9 August when a first cooling phase began. The passage of troughs of low pressure in the second half of August produced further cooling with the result that at the end of the month, SST fell to 17-18 °C in the western and southern Baltic Sea, and to 13-17 °C in the central and northern Baltic Sea. August developed into the warmest month of the year in these three selected areas. Besides August 2002, it was also the warmest month in the period of observation. Subsequent SSTs were largely characterised by positive anomalies in the monthly averages. It was only in the eastern Gotland Sea that monthly averages lay in the range of the long-term averages. The temperatures at the end of August continued until 10 September. By 20 September, temperatures in the southern Baltic Sea were stagnating around

17 °C before the passage of low-pressure areas again produced wind-driven mixing. By the end of the month, SST fell to around 15-16 °C in the southern and western Baltic, to 13-15 °C in the central Baltic, and - noticeably - to 8-13 °C in the northern Baltic. From 3-6 October, brief warming in the western Baltic raised temperatures to 15-17 °C; compared with 2013, this represents a difference of more than +2 K. The next cloudy phase began; by the end of the month, SSTs had fallen steadily to 12-14 °C in the western Baltic, 9-13 °C in the central Baltic, and to 3-8°C in the northern Baltic Sea.

SST anomalies in October and November were particularly pronounced in the western Baltic (Figure 23). They were the highest of the past twenty-five years, as impressively shown by the transect of monthly averages for October through the central basins of the Baltic Sea (Figure 23). The monthly averages determine the range of variation during the period of investigation. These temperatures were preserved until around 11 November when areas of low pressure with high cloud cover moved across the region. By the end of the month, the central Baltic Sea and the shallow areas of the western Baltic in particular had cooled to 7-8 °C. The temperature of the Arkona Sea and the Bornholm Sea was still around 10°C; in the lagoons and in the north of the Bothnian Bay, it was only 1-4 °C. After 2 December, SSTs fell, especially in the shallow areas of the western Baltic. SSTs of 5-7 °C lasted until about 20 December before falling to 1 °C in the northern Baltic Sea, and to 6 °C in the southern Baltic Sea towards the end of the year.

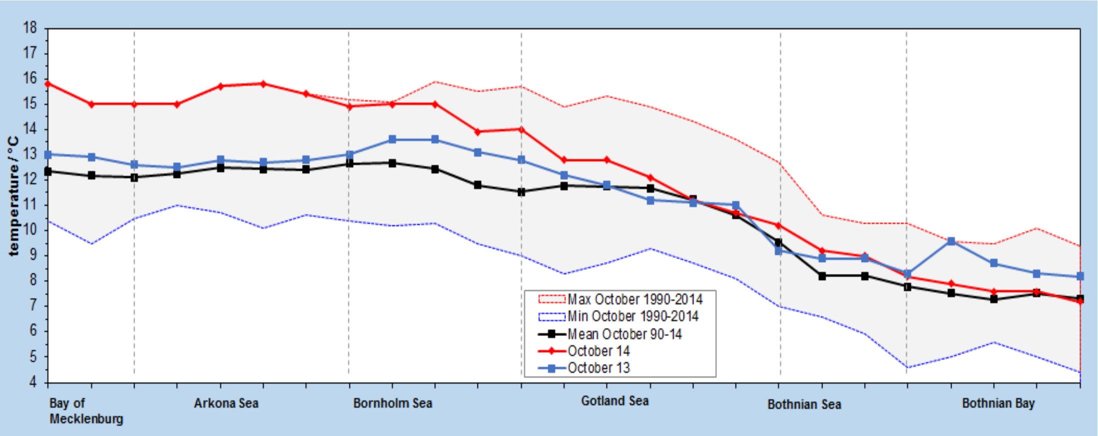


Fig. 23: Temperature distribution along the transect through the central basins of the Baltic Sea in October 2014 in comparison to the previous year, the long-term mean value of 1990-2014 and the variation range

Overall, 2014 was the warmest year of the past twenty-five years. In the western Baltic, monthly average anomalies were +1 to +3 K above long-term averages, except for February. In October and November, anomalies even partially exceeded +3 K, which makes them the warmest months in the past twenty-five years. Across the basins of the central and northern Baltic Sea, only June recorded distinct, negative anomalies of -1 to -2 K. July and August in particular contributed to making 2014 the warmest year in the northern Baltic. Unusually uniform temperature distributions across the entire Baltic Sea produced anomalies in July of up to +5 °C in the northern Baltic Sea. The average annual temperature throughout the Baltic Sea was 1.2 K higher than the long-term average, and 0.4 K higher than 2008, previously the warmest year on record.

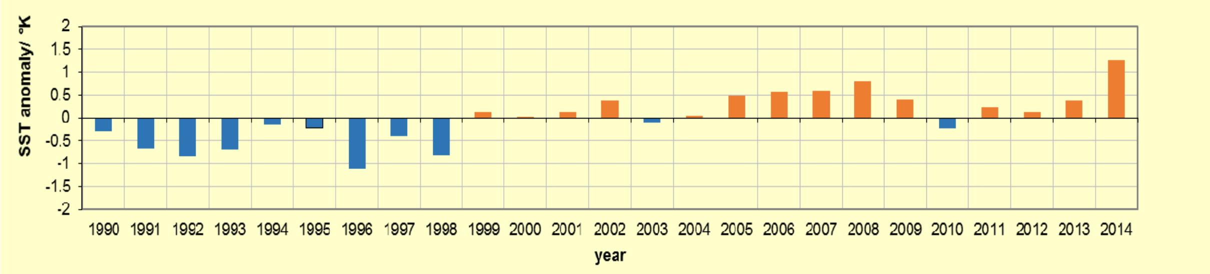


Fig. 24: Anomalies of the annual mean temperature of the whole Baltic Sea during the last 25 years (1990-2014)

6.1.2 Vertical Distribution of Water Temperature

The routine monitoring cruises undertaken by IOW provide the basic data for its assessments of the hydrographic conditions in the western and central Baltic Sea. In 2014, monitoring cruises were undertaken in February, March, May, July and November. Figure 25 shows snapshots of the vertical temperature distribution obtained on each cruise. For its assessments of the hydrographic conditions in the central Baltic Sea, the IOW additionally makes use of data collected monthly by Sweden's SMHI from central stations in each of the Baltic Sea basins. Other data were collected in the eastern Gotland Basin by means of two long-term hydrographic moorings that monitor the hydrographic conditions in its deep water. The results of these measurements are given in Figures 26 and 29.

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

In the course of 2014, a rare Major Baltic Inflow (MBI) was observed. This event occurred in December 2014, and transported into the Baltic around 198 km^3 of saline water carrying 4 Gt of salt (Mohrholz et al., 2015). The influence of this MBI only became effective in January 2015, however, and is therefore not covered by this report. Before December 2014, inflow activity was characterised by a series of small barotropic inflows, as in previous years (cf. chapters 2 and 3). In contrast to previous years, a portion of these inflows reached the deep water of the Baltic's central basins, and caused ecologically significant changes there even before the MBI of 2014.

In the central Baltic, the development of the vertical temperature distribution above the halocline is mainly influenced by the annual cycle of atmospheric temperature (cf. chapter 2). With the winter of 2013/2014 unusually mild, only January showed a temperature around the climatic mean. At the beginning of January 2014, temperatures in part clearly exceeded the long-term means (cf. chapter 2). A severe cold spell from mid-January caused the surface water to cool slightly. This effect was short-lived on account of the air temperatures in February and March, however. Surface temperatures throughout the year remained well above the long-term average, the inflow events of 2014 having a significant influence on the vertical temperature distribution in the central Baltic Sea.

Temperature distribution at the beginning of February 2014 revealed a very heterogeneous picture of seasonal cooling in the surface layer. As a result of the cold spell at the end of January, surface temperatures fell in the shallow areas of the western Baltic Sea, in part below 1 °C. The lowest temperature of 0.2 °C was recorded in the Pomeranian Bight, above the Oder Bank. Surface temperatures in the adjacent Arkona Sea were still around 1.6 °C. This value was already well below the density maximum with the result that further cooling stabilized stratification. In the central Baltic, the deep convection associated with cooling largely homogenized the surface layer. The thermocline at station TF271 in the eastern Gotland Sea lies at a depth of 53 m. The vertical temperature gradient down to the halocline at a depth of 70 m is weak, however. At 2.7 °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. As a result of the minor inflow in November 2013, bottom temperatures in the central Arkona Sea were relatively high at up to 7.3 °C (station 102).

The highest temperatures in the entire Baltic were measured in the Bornholm Basin below the halocline, up to 9.0 °C. This warm body of water occupies the deepwater layer in the Bornholm Basin from a depth of 60 m to the seabed, and also stems largely from the inflow in November 2013 that transported around 90 km³ of saline water into the western Baltic Sea. Some of that water has already spilled over Stolpe Sill, and at a temperature of 8.2 °C now forms the warm bottom water in Stolpe Channel (Figure 25). This body of warm bottom water extends between the outlet of Stolpe Channel and the eastern Gotland Basin with bottom temperatures of up to 7.0 °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 February and March 2014, the surface temperature of the western and central Baltic Sea increased again between early February and mid-March, however. West of Darss Sill, some temperatures were already well in excess of 5 °C. The maximum temperature of 5.6 °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 3.7 °C in the Arkona Basin, 3.8 °C in the Bornholm Basin, and 2.8 °C in the eastern Gotland Basin. Seasonal warming had already begun. Surface temperatures clearly exceeded those of the density maximum. The minor inflows in mid-February and early March, which imported some 75 km³ of cold, saline water, changed conditions in the deep water of the western Baltic Sea by mid-March. The temperature of the bottom water in the Arkona Sea was noticeably lower, and was now only 4.5 °C. Much of this inflow had already reached the Bornholm Basin and lifted the body of warm water from the November 2013 inflow. At 6.3 °C, the temperature of the bottom water was thus as much as 2.7 K below the value observed in February.

The body of deep water at depths between 55 m and 80 m was still composed of the warm November inflow with temperatures up to 8.5 °C. The bodies of warm bottom water in Stolpe Channel and to the east of it had cooled markedly because of mixing with cold water in the overlying layer. A bottom layer of warm water some 10 m thick had flowed into the eastern Gotland Basin. With a temperature of 6.7 °C, it was 0.3-0.5 °C warmer than the old bottom water, which it lifted up. The 6°C isotherm rose from a depth of 172 m at the beginning of February to 158 m in March; in the same period, the 5 °C isotherm rose from a depth of 111 m to 103 m.

At the beginning of May, the surface water of Baltic warmed noticeably compared to values in March. Surface temperatures lay between 7.2 °C in the Arkona Basin, 7.7 °C in the Bornholm Basin, and 5.3 °C in the eastern Gotland Basin. Seasonal thermal stratification was gradually becoming more pronounced, and brought to an end direct interaction between the atmosphere and the layer of winter water (30-70 m). Compared to 2013, this intermediate layer was relatively warm in 2014. In the eastern Gotland Sea, the minimum temperature of winter intermediate water in May 2014 was 3.0 °C; it thus exceeded the previous year’s value by up to 1.2 K. Similar conditions were observed throughout the central Baltic. In contrast, no distinct winter water layer was observed in the Bornholm Basin where mainly the effects of the inflows in February and March 2014 were noticeable. Those cold-water inflows had entirely replaced the previous body of deep water. In the deep water below the halocline, the temperature was some 1-3 K lower than in February. The cold-water inflow spread eastwards, and the bottom temperature in Stolpe Channel continued to fall to around 6.3 °C. East of Stolpe Channel outlet, the spread of this cold water ceased to traceable through its temperature signal. As the 5 °C isotherm continued to rise from a depth of 103 m in March to 98 m at the beginning of May, another inflow of saline water into the deep layers of the eastern Gotland Basin was indicated, however (cf. Figure 25).

By the end of July 2014, typical summer thermal stratification had become established throughout the Baltic Sea. The seasonal thermocline lay at a depth of some 25 m, and separated the strongly warmed layer of surface water from the cold winter intermediate water. In the basins of the central Baltic Sea, minimum temperatures in the intermediate water were around 3.4 °C, making it on average 1.0 K warmer than in 2013. No distinct layer of winter water was identifiable in the Bornholm Basin even in July.

Surface temperatures in the western Baltic Sea were only slightly below 20 °C, but also partly above. At station TF213 in the Bornholm Basin, 19.43°C was recorded on 22 July. Surface temperatures were relatively high in the central Baltic Sea, too: 19.6 °C was recorded at station TF271 in the eastern Gotland Basin.

In July, the inflow of a mass of warm intermediate water with maximum temperatures around 12-13 °C was observed in the western Bornholm Sea. This mass of warm water was driven across Darss Sill by baroclinic inflows that were facilitated by the month's calm conditions. At 5.9 °C, the deep water in the central Bornholm Basin was relatively cold. Here the influence of the cold water from the minor inflows in February and March 2014 was still dominant. As a result of these inflows, the body of deep water in the eastern Gotland Basin continued to cool. Given the relatively low salinity of its deep water, the water masses of the minor inflows in February and March were able to reach the bottom layer of the eastern Gotland Basin. These inflows further raised the 5 °C isotherm from 97 m at the beginning of May to 92 m in mid-July 2014.

The temperature distribution in early November 2014 reveals autumnal erosion of the thermocline in the surface layer. The temperature in the surface layer, now extending to a depth of 35 m to 40 m, was still 12.3 °C in the Arkona Basin; towards the central Baltic Sea it fell to 9.7 °C (station TF271). As a result of the warm summer and mild autumn, the water temperature above the halocline clearly exceeded the previous year's values. All that remained of the winter intermediate water in the central Baltic was a thin layer some 10 m to 15 m thick with minimum temperatures of 3.8 °C. No layer of winter intermediate water was present in the Bornholm Basin.

Minor inflows in August and September 2014 influenced the thermal stratification of the western Baltic into which they imported 45 km³ of warm, saline water. As the inflow of warm, saline water on the seabed of the Arkona Basin was almost the same temperature as its still relatively warm surface layer, only a very slight vertical temperature gradient was observed in the Arkona Basin. In the Bornholm Basin, the inflow of warm water stratified in the halocline where it formed a 20-m-thick intermediate layer with temperatures above 10 °C. This inflowing body of water was insufficiently dense to replace the bottom water in the Bornholm Basin, however. The warm water that had flowed in over the summer began to drain away across Stolpe Sill in November. East of Stolpe Channel, a body of water with temperatures of more than 6 °C was observed on the sea floor. It formed a layer in the eastern Gotland Basin at depths between 150 m and 190 m. In central areas of the eastern Gotland Basin, this raised the 5°C isotherm another 5 m to a depth of 87 m between mid-July and early November (Figure 25). Since February 2014, therefore, the influx of salt water from several minor inflows raised the 5 °C isotherm in the eastern Gotland Basin by 24 m.

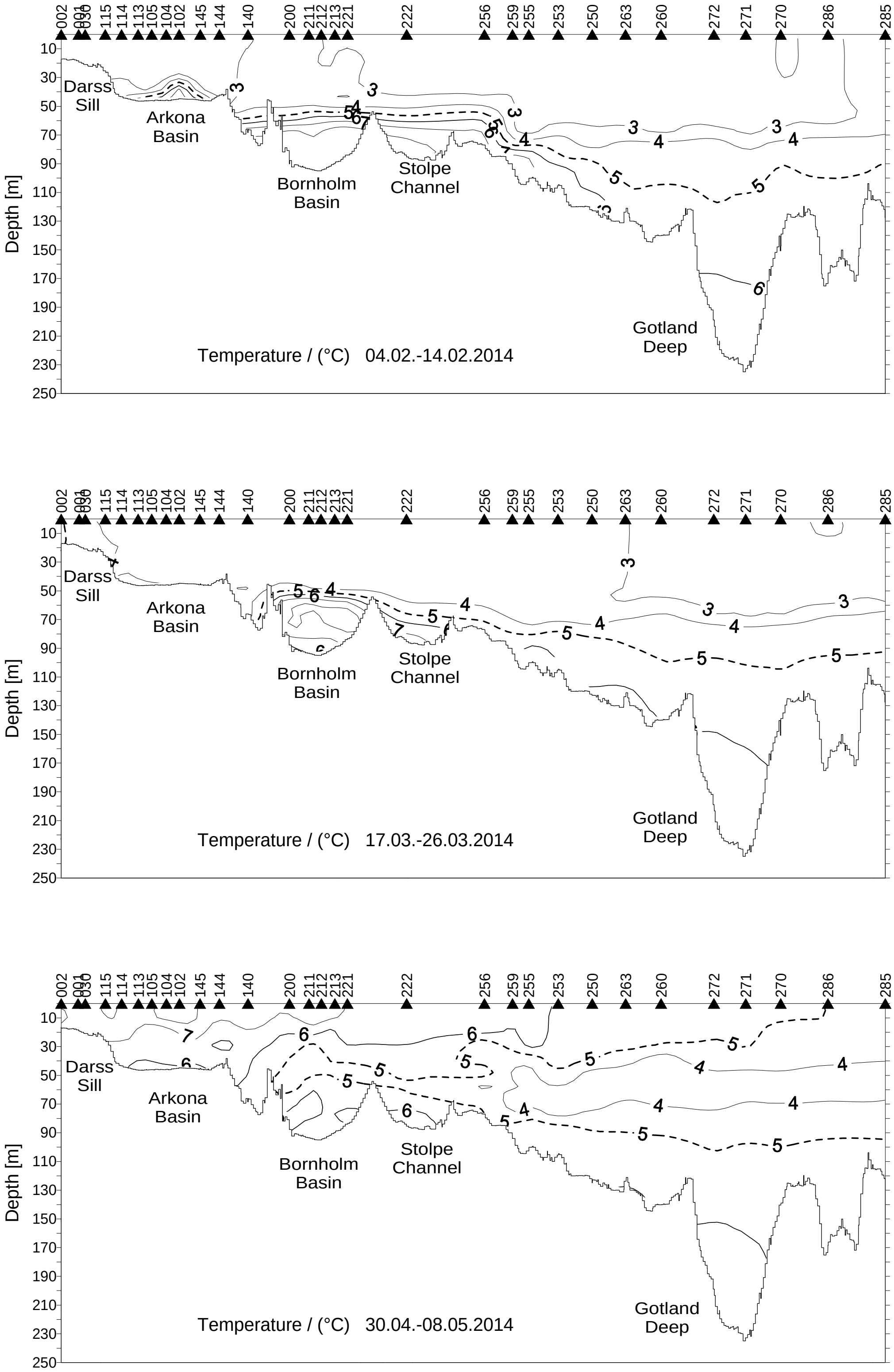


Fig. 25: Vertical water temperature distribution 2014 between Darss Sill and northern Gotland Basin

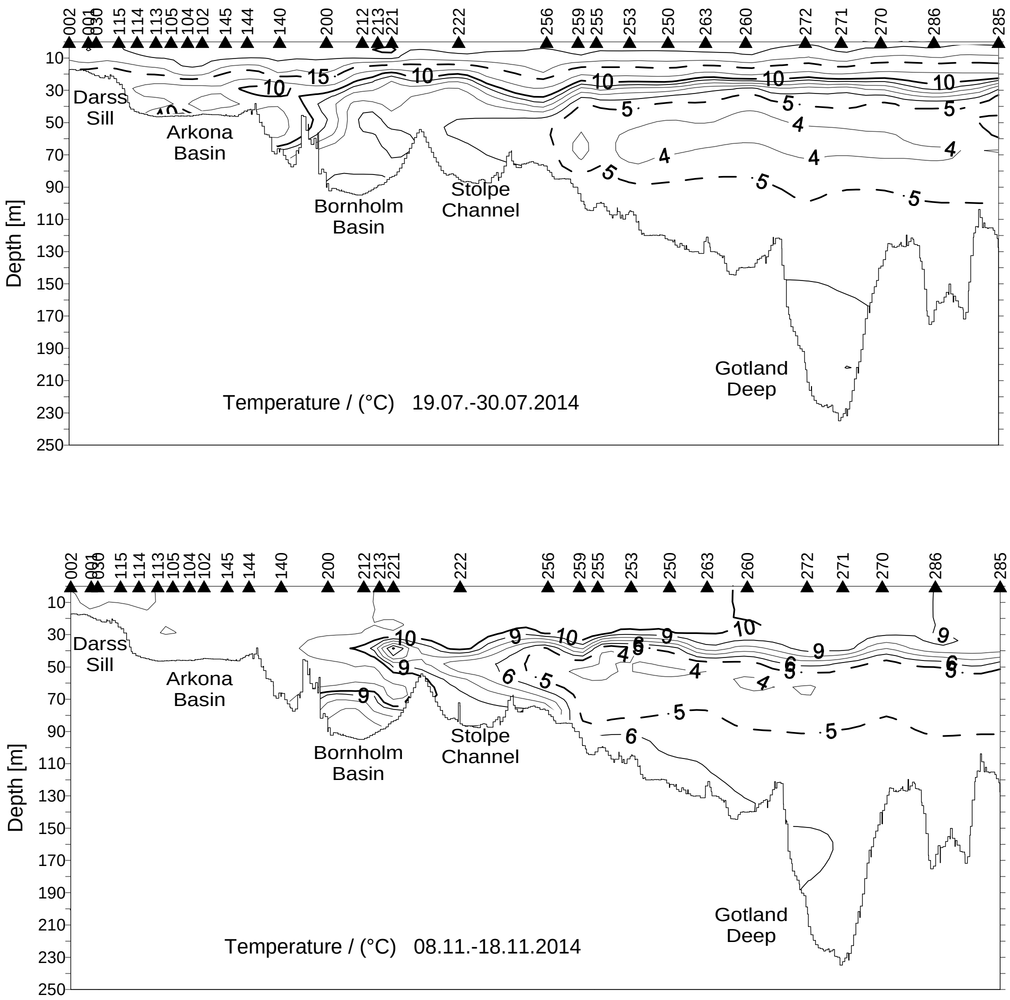


Fig. 25: Vertical water temperature distribution 2014 between Darss Sill and northern Gotland Basin

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 Nordost mooring - operational since 1998 and from where the well-known ‘Hagen Curve’ is derived - TF271 also collects salinity data. With the aid of its time series, the development of hydrographic conditions in the deep water of the Gotland Basin can be described 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 2014. Given the heterogeneous character of the inflowing bodies of water from various minor inflows, no general trend was identifiable for all five depths other than that the vertical temperature gradient fell steadily throughout the second half of the year.

At the beginning of March, the arrival of warm water from the inflow of November 2013 was detected as a positive temperature jump in the bottom water (Figure 26). This body of water was small in volume, and remained confined to the bottom layer. After May 2014 it became admixed with water from the February and March 2014 inflows that in the near-bottom layer caused inversion of the vertical temperature gradient.

Fluctuations on various timescales are superimposed on the overall trend of the temperature profile at the five measured depths. Short-term fluctuations of temperature can be caused by the transit of small-scale lenses of cold or warm water. Fluctuations are often correlated across the entire range of the deep water, and their amplitude decreases with depth.

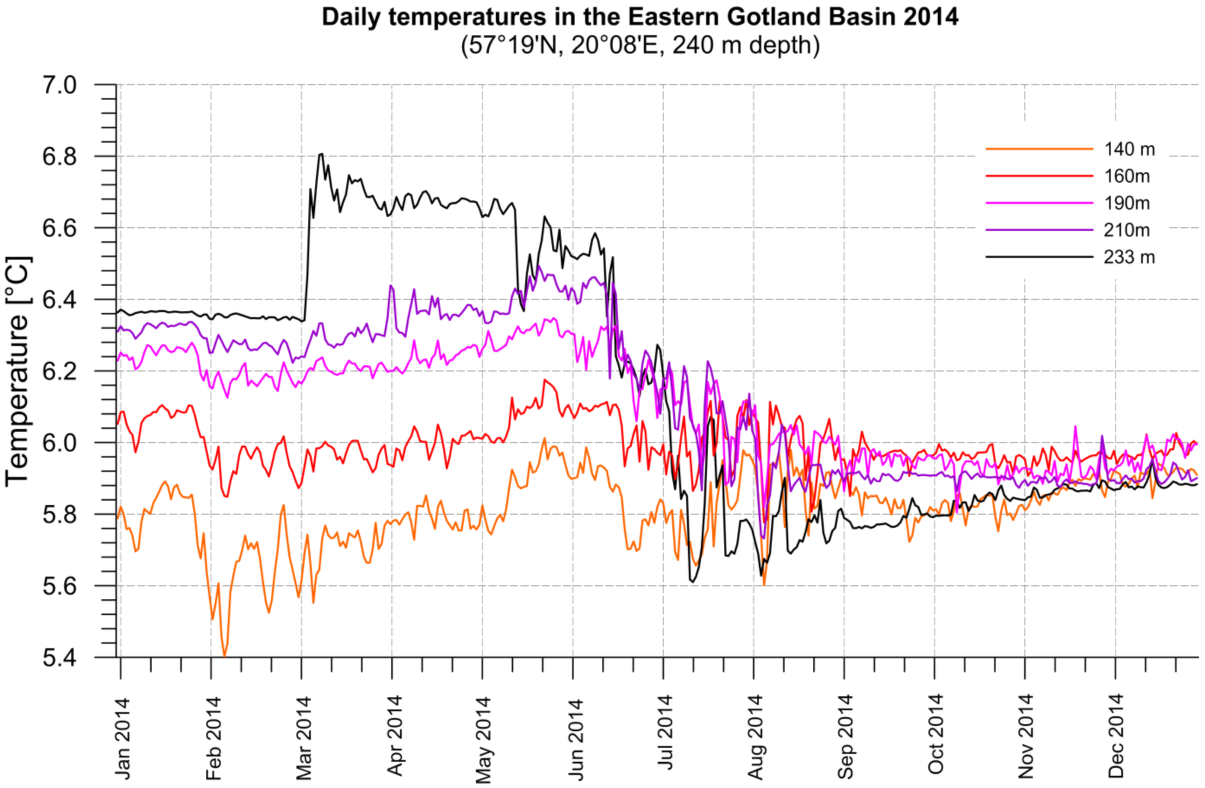


Fig. 26: Temporal development of deep water temperature in the Eastern Gotland Basin (station 271) from January to December 2014 (daily averages of original data with 10 min sampling interval)

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. In 2014 its deep-water temperatures were markedly lower than in 2013 due to the effects of the cold inflows in February and March 2014. The sole exception was the Bornholm Deep with an increase in its mean bottom temperature of around 1.5 °C compared to 2013. The standard deviations of temperature fluctuations in 2014 were within the usual range of variation. Here again the Bornholm Basin was an exception, as was the Gotland Deep in part. The stronger fluctuations observed there are attributable to increased inflow activity and the deep-water renewal associated with it.

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= 7-20)

Water temperature (° C; maximum in bold)

Station	Depth/ m	2010	2011	2012	2013	2014
213 (Bornholm Deep)	80	**8,29 ± 1,06**	6,48 ± 0,69	6,40 ± 0,40	5,55 ± 0,78	6,99 ± 1,29
271 (Gotland Deep)	200	**6,46 ± 0,07**	6,43 ± 0,00	6,42 ± 0,01	6,33 ± 0,03	6,11 ± 0,19
286 (Fårö Deep)	150	**6,74 ± 0,12**	6,42 + 0,07	6,14 ± 0,08	5,83 ± 0,05	5,69 ± 0,04
284 (Landsort Deep)	400	**6,09 ± 0,15**	5,95 ± 0,09	5,70 ± 0,06	5,46 ± 0,11	5,27 ± 0,06
245 (Karlsö Deep)	100	5,43 ± 0,10	**5,44 ± 0,07**	5,15 ± 0,12	5,22 ± 0,07	5,00 ± 0,04

Salinity (maximum in bold)

Station	Depth/ m	2010	2011	2012	2013	2014
213 (Bornholm Deep)	80	15,85 ± 0,33	14,68 ± 0,45	15,16 ± 0,49	15,16 ± 0,24	**16,06 ± 0,41**
271 (Gotland Deep)	200	**12,33 ± 0,03**	12,20 ± 0,03	12,13 ± 0,04	12,00 ± 0,04	12,06 ± 0,11
286 (Fårö Deep)	150	**11,77 ± 0,04**	11,69 ± 0,16	11,52 ± 0,06	11,28 ± 0,17	11,36 ± 0,08
284 (Landsort Deep)	400	**10,76 ± 0,03**	10,65 ± 0,02	10,50 ± 0,03	10,43 ± 0,05	10,37 ± 0,08
245 (Karlsö Deep)	100	**10,01 ± 0,17**	9,98 ± 0,11	9,61 ± 0,12	9,76 ± 0,18	9,58 ± 0,11

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

Station	Depth/ m	2010	2011	2012	2013	2014
213 (Bornholm Deep)	80	1,28 ± 0,88	**0,78 ± 0,83**	1,68 ± 1,45	1,62 ± 1,05	2,07 ± 1,47
271 (Gotland Deep)	200	-4,29 ±0,69	-3,98 ± 0,51	-4,81 ± 0,50	**-5,30± 0,83**	2,94 ± 2,38
286 (Fårö Deep)	150	-1,97 ± 0,34	-1,57 ± 0,30	-2,20± 0,38	-1,95 ± 1,46	**-2,35 ± 0,53**
284 (Landsort Deep)	400	-1,15 ± 0,26	-1,06 ± 0,31	**-1,24 ± 0,30**	-1,11±0,24	-1,02± 0,68
245 (Karlsö Deep)	100	**-1,49 ± 0,83**	-1,36 ± 0,58	-0,17 ± 0,44	-0,72 ± 0,73	-0,85±0,52

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 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 can they lead to slow, long-term changes in salinity. The salinity distributions shown in Figure 27 are mere 'snapshots' that cannot provide a complete picture of inflow activity. 2014 saw several minor inflows that 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 in the centre of the Arkona Basin, a 10 m to 15 m-thick salty bottom layer was observed that had built up as a result of the inflow in November 2013. Bottom salinity in the Arkona Basin at the time measured a maximum of 16. A large portion of the inflow had already drained into the Bornholm Basin where it formed the saline deep-water body. The old deep water had drained into Stolpe Channel and raised the 10 g/kg isohaline there. After a long period of stagnation, salinity in the deep water of the central Baltic Sea was relatively low at the beginning of 2014. On the seabed in the Gotland Deep, salinity measured only 12.04 g/kg in February 2014. The 12 g/kg isohaline lay at a depth of around 221 m.

By the end of March, the minor inflows at the end of February and the beginning of March 2014 had refilled the pool of saline water in the Arkona Sea. Bottom salinity rose to 21.3 g/kg. In the Stolpe Channel, the halocline again fell to its usual depth of around 70 m, and the bulk of old deep water from the Bornholm Basin drained towards the central Baltic Sea. In the Gotland Deep, this led to a slight increase in bottom salinity to 12.27 g/kg, and caused the 12 g/kg isohaline to rise 9 m to a depth of 212 m. At the beginning of May, the pool of saline water in the Arkona Basin continued to fill up. Mixing with the surrounding water caused bottom salinity to fall to 19.59 g/kg. The water from the inflows in February and March displaced the deep water from the Bornholm Basin. In the Gotland Basin, pulses of saline water continued to fill the basin's deeper stretches. Bottom salinity in the Gotland Deep was around 12.2 g/kg, both at the beginning of May and at the end of March. The 12 g/kg isohaline rose another 13 m to a depth of 199 m, however. This activity continued until July 2014. With bottom salinity remaining practically unchanged, the 12 g/kg isohaline rose another 19 m to a depth of 178 m.

At the beginning of November, salinity stratification in the western Baltic Sea was influenced by the minor summer inflows of August and September 2014. Bottom salinity in the Arkona Sea was 21.4 g/kg. These warm inflows were insufficiently dense to replace the deep water in the Bornholm Basin, however, and drained relatively quickly through the Bornholm Basin halocline towards Stolpe Channel. The inflow into the deep water of the eastern Gotland Basin had almost come to a standstill by this point. Between July and November 2014, the 12 g/kg isohaline barely changed, rising 3 m to a depth of 175 m.

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 not continued in the central Baltic. As a result of numerous small inflow events, salinity in the Gotland Deep and Fårö Deep rose slightly. At 16.06 g/kg, the highest mean bottom salinity levels in the past five years were observed in the Bornholm Deep. The Karlsö Deep and Landsort Deep were exceptions: bottom salinity there continued to fall slightly due to a period of stagnation that began in 2004 and still persists. The minor inflows that have been observed in the meantime have not reached the deep water of the Karlsö Deep and Landsort Deep.

Figure 28 shows the temporal development of salinity in the deep water of the eastern Gotland Sea in 2014, based on data from the hydrographic moorings described above. At all depth levels below 140 m, a positive trend for salinity emerges in the course of the year. What is striking is the increase in bottom salinity at the beginning of March as a result of the arrival of the November 2013 inflow. 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. Over the course of the year, the vertical salinity gradient decreased negligibly.

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 2013, surface layer salinities in the central Baltic rose slightly in 2014. Standard deviations of surface salinity are roughly on a level with those in 2013, and thus are in the usual range.

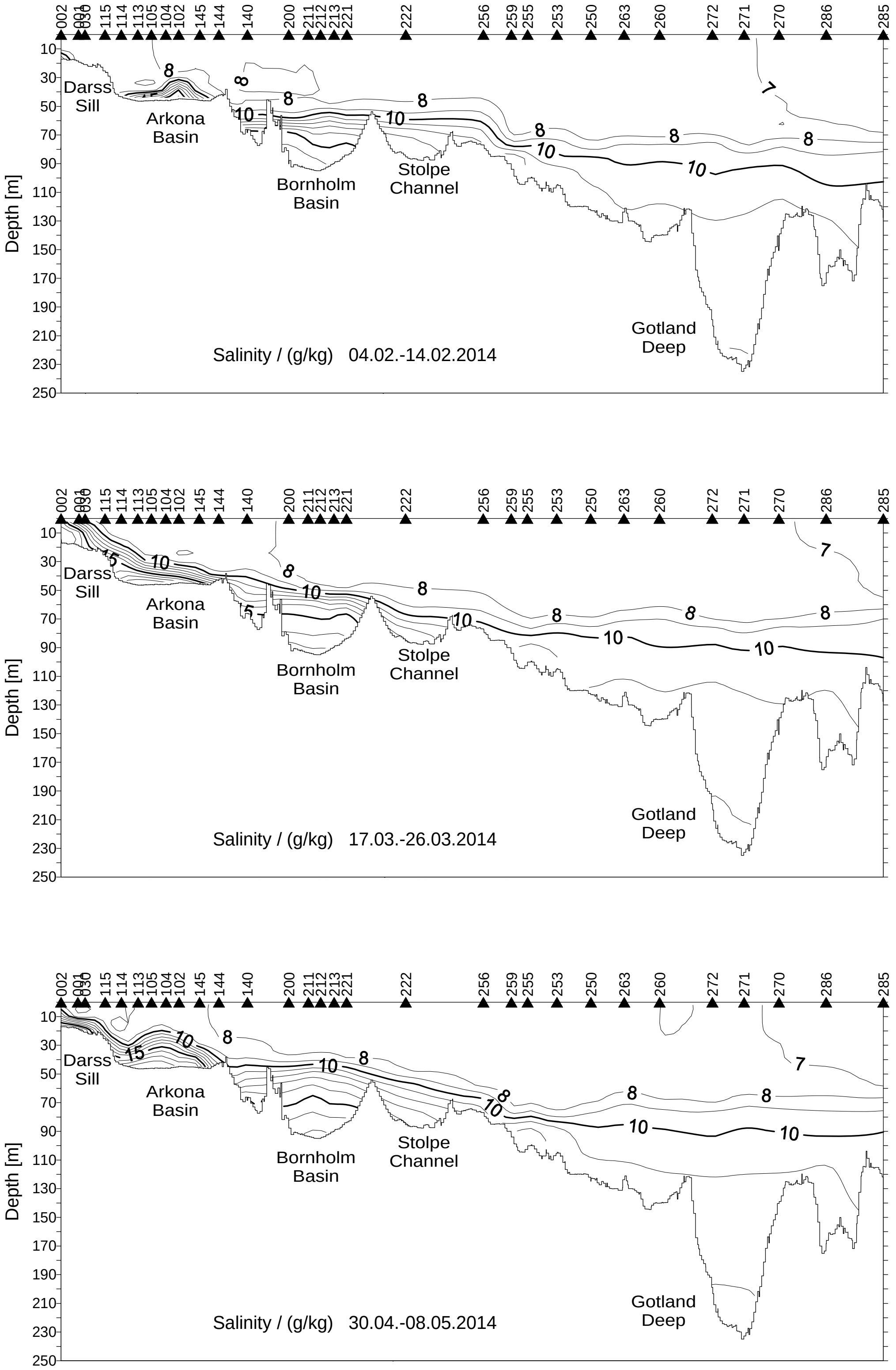


Fig. 27: Vertical salinity distribution 2014 between Darss Sill and northern Gotland Basin

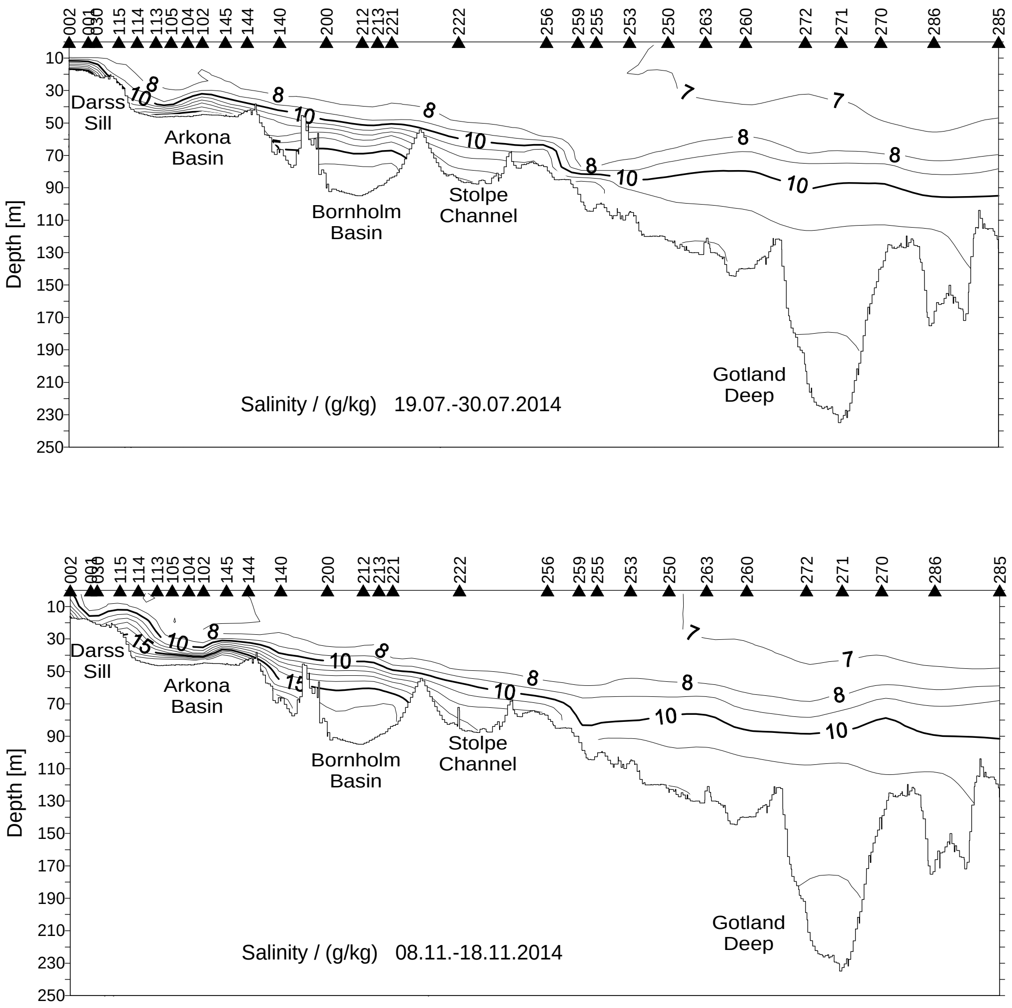


Fig. 27: Vertical salinity distribution 2014 between Darss Sill and northern Gotland Basin

Table 7: Annual means of 2010 to 2014 and standard deviations of surface water salinity in the central Baltic Sea (minimum values in bold, n= 13-29). The long-term averages of the years 1952-2005 are taken from the BALTIC climate atlas (FEISTEL et al., 2008a)

Station	1952-2005	2010	2011	2012	2013	2014
213 (Bornholm Deep)	7,60 ±0,29	**7,17 ±0.17**	7,23 ±0,11	7,64 ±0,11	7,28 ±0,12	7,65 ±0,18
271 (Gotland Deep)	7,26 ±0,32	7,20 ±0.20	7,15 ±0,19	7,10 ±0,13	**6.78 ±0,28**	6.87 ±0,17
286 (Fårö Deep)	6,92 ±0,34	6,74 ±0.41	6,96 ±0,24	6,91 ±0,16	**6,64 ±0,29**	6,73 ±0,21
284 (Landsort Deep)	6,75 ±0,35	6,37 ±0.40	6,68 ±0,40	**6,27 ±0,38**	6,52 ±0,12	6,60 ±0,24
245 (Karlsö Deep)	6,99 ±0,32	**6,60 ±0.22**	6,81 ±0,24	6,97 ±0,21	6,77 ±0,10	7,00 ±0,13

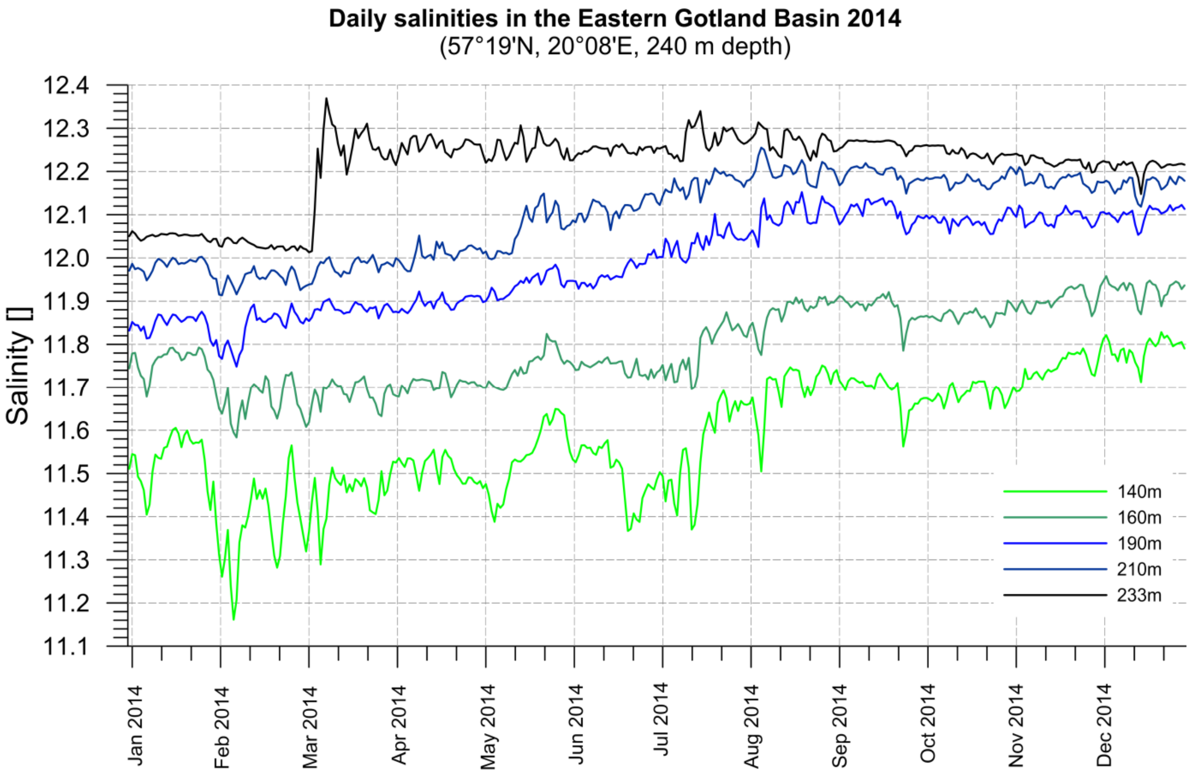


Fig. 28: Temporal development of deep water salinity in the Eastern Gotland Basin (station 271) from January to December 2014 (Daily averages of original data with 10 min sampling interval)

Changes in the deep water of the Gotland Basin can be graphically illustrated using a temperature-salinity diagram which in addition colour-codes oxygen concentrations (Figure 29). At the beginning of 2014, anoxic conditions with only slight variations in temperature and salinity prevailed in the deep water of the Gotland Deep (water mass A). At the beginning of March 2014, anoxic water, displaced from the Bornholm Basin by the inflow of November 2013, reached the Gotland Deep (water mass B). At the beginning of May, water masses from the spring inflows reached the Gotland Basin. They were lower in temperature, and for the first time in many years imported small amounts of oxygen into the Gotland Deep (water masses C and D). As a result of mixing with old, deep water and oxygen consumption, oxygen concentrations in the deep water fell again (water mass E). Towards the end of 2014, the first portions of that summer's warm inflows reached the Gotland Basin, and again imported small amounts of oxygen into its deep water (water mass F). In the course of these inflows, the density of the deep water in the Gotland Basin increased slowly from 1009.4 kg/m³ to 1009.6 kg/m³.

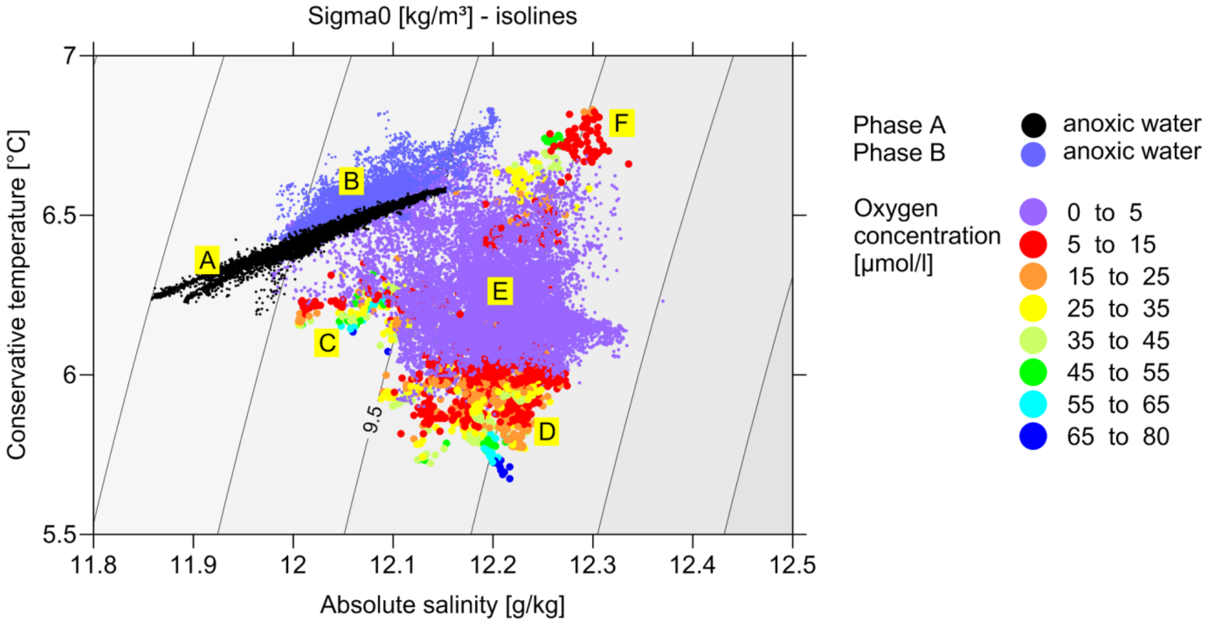


Fig. 29: Temperature-salinity-oxygen diagram of the deep water in the eastern Gotland Basin (TF271) from January to December 2014 (data at 200 m depth with 10 min sampling interval)

6.3 Oxygen distribution

The surface water's oxygen supply is generally considered to be good thanks to strong exchange processes with the atmosphere and the primary production by phytoplankton in the sunlit surface layer. Fluctuations in oxygen concentrations are essentially determined by the annual cycles of temperature and salinity, and by seasonally-variable production and consumption processes. Hydrodynamic processes can also play an important role, especially in the case of the western Baltic that is highly variable. Below permanent or temporary thermoclines (temperature gradients) or haloclines (salinity gradients), in contrast, significant oxygen consumption can occur. As sunlight does not reach these layers, only consumption processes occur there.

A typical annual cycle of oxygen concentrations is observed in the mixed surface layer (MATTHÄUS, 1978, NAUSCH et al., 2008a). High oxygen solubility at low temperatures leads to high oxygen concentrations in winter and spring. The winter of 2014 was mild. Only in February were water temperatures in the range of the long-term average. From March, the monthly mean values were almost always +1 K to +3 K higher than the long-term mean values (cf. chapter 6.1.1). The relatively low oxygen values in March in the western Baltic (Table 8) were attributable to the increased temperature on the one hand. Saturation values on the other hand suggest that the first phase of the spring bloom had already passed (see below). In the Arkona Basin, in contrast, oxygen concentrations increased due to the strong bloom that occurs there in March. The highest oxygen concentrations in the Bornholm Basin and in the eastern Gotland Basin were not found until May. Combined with the above-average water temperatures, that indicates a strong phytoplankton bloom. Throughout the rest of the year, the rapid rise in temperature markedly reduced oxygen solubility, which was more quickly seen in the shallower stretches of the western Baltic Sea than in the Arkona Basin. Oxygen concentrations in the summer are generally well below 7 ml/l. In all sea areas, the differences between 2013 and 2014 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 2013 and 2014

	February	March/April	May	July	November
western Baltic					
O_2 (ml/l)	**8.21/8.76**	**8.89/7.77**	**8.32/7.89**	**6.27/6.32**	**6.50/6.55**
std. dev. (ml/l)	0.23/0.19	0.15/0.25	0.16/0.27	0.03/0.21	0.12/0.13
n	5/5	5/5	5/5	4/4	5/5
Arkona Basin					
O_2 (ml/l)	**8.63/8.75**	**9.36/9.15**	**9.28/8.40**	**6.40/6.40**	**7.05/6.87**
std. dev. (ml/l)	0.06/0.11	0.05/0.10	0.25/0.11	0.13/0.16	0.05/0.14
n	13/13	13/13	13/13	13/13	13/13
Bornholm Basin					
O_2 (ml/l)	**8.61/8.66**	**9.15/8.67**	**9.70/9.82**	**6.38/6.44**	**7.19/7.01**
std. dev. (ml/l)	0.02/0.09	0.03/0.02	0.06/0.18	0.11/0.06	0.04/0.03
n	4/4	3/3	4/4	6/4	6/4
eastern Gotland Basin					
O_2 (ml/l)	**8.59/8.69**	**9.02/8.78**	**9.97/10.27**	**6.56/7.19**	**7.41/7.34**
std. dev. (ml/l)	0.08/0.05	0.07/0.07	0.25/0.25	0.15/0.23	0.10/0.15
n	7/7	8/8	9/9	9/9	9/9

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 water of the four study areas in 2014. The seasonal development described for oxygen concentrations becomes even more apparent in oxygen saturation values: 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). Again in March, we observed undersaturation in all sea areas with the exception of the Arkona Basin where, in contrast, the saturation level in March was 104.3 %. This suggests that the first peak of the spring bloom in the western Baltic Sea had already passed. In both sea areas, the spring bloom of 2014 did not culminate until May. This applies even more obviously to the Bornholm Basin and the eastern Gotland Basin where in 2014 saturation values between 120% and 125 % were observed. While this was higher than in previous years, the extreme saturation levels of between 140% and 160% as described for 1994 by Nehring et al. (1995) were not reached. It is worth noting, however, that the peak of the bloom might not have been recorded in every instance because of the low monitoring frequency. Summer presented a familiar picture with saturation values around 105 %. Only in the eastern Gotland Basin did saturation values around 115 % indicate an intensive cyanobacteria bloom. In the autumn, intensified degradation processes again led to undersaturation. 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.

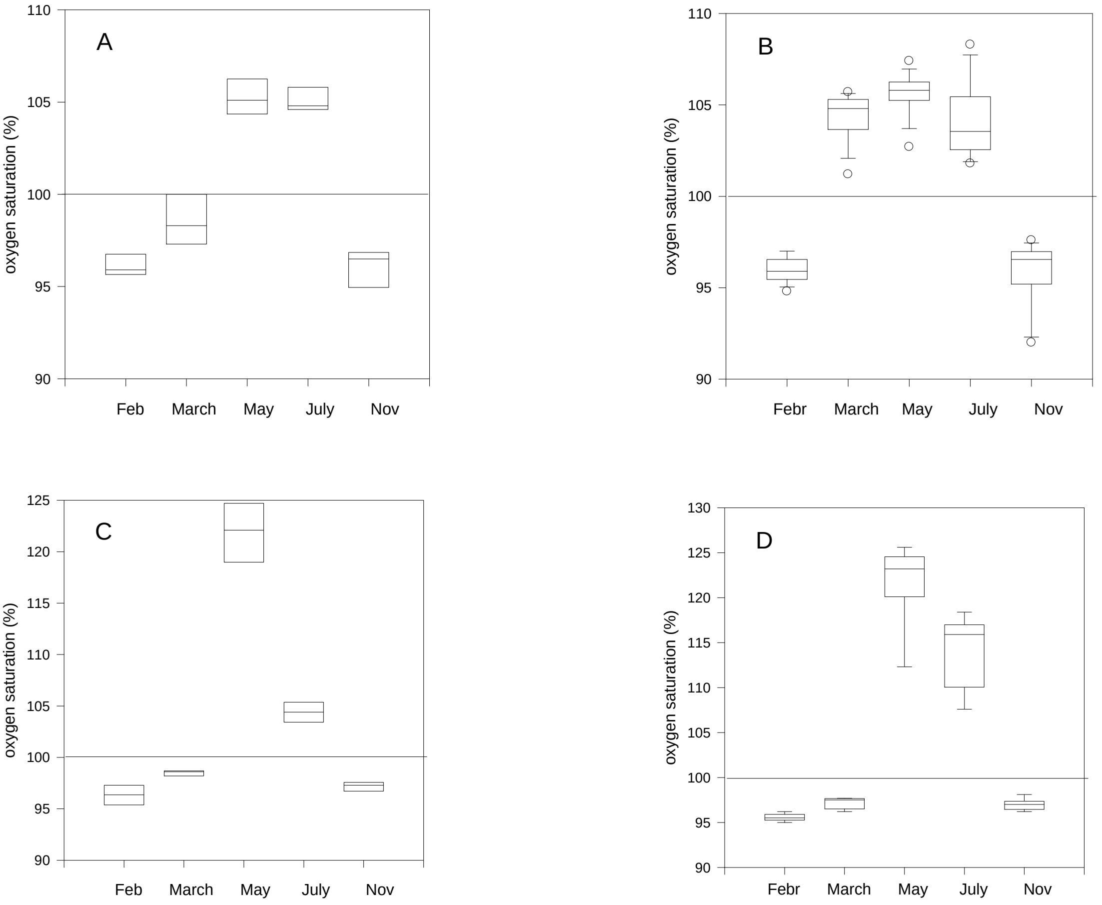
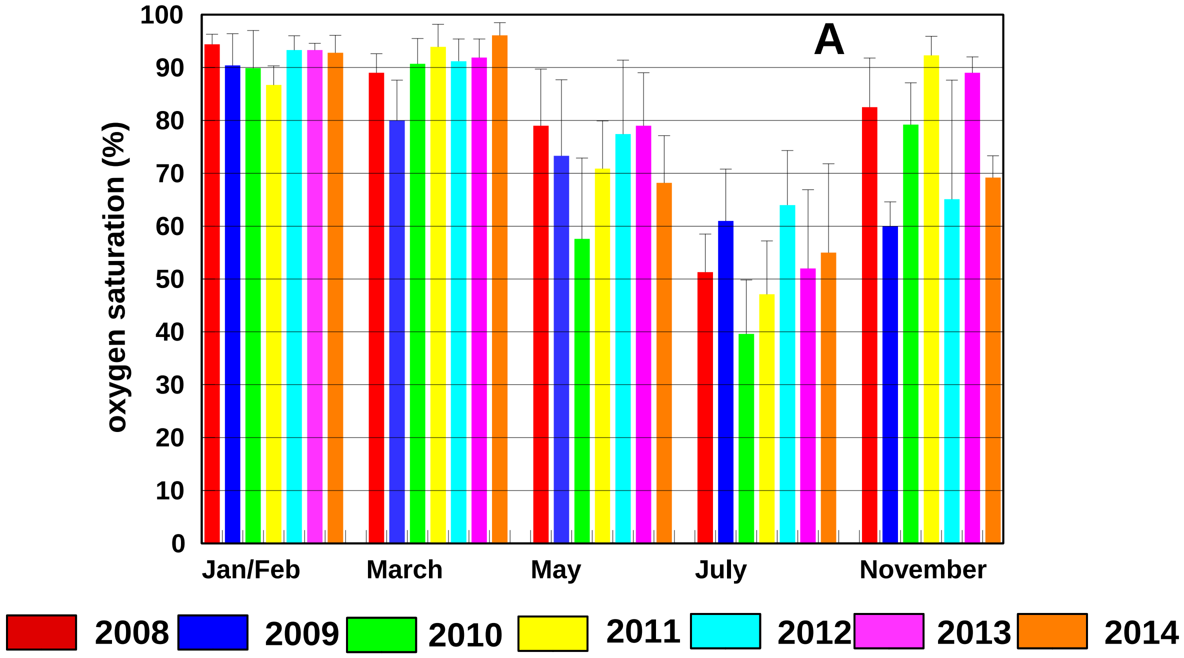


Fig. 30: Box-Whisker- Plots of oxygen saturation (%) in 2014 in the mixed surface layer (0-10 m) of the western Baltic (A), the Arkona Basin (B), the Bornholm Basin (C) and the eastern Gotland Basin (D)

A pronounced annual cycle of near-bottom oxygen is observed in the western Baltic and Arkona Basin. With vertical mixing occurring every year in winter, and inflow processes leading to the repeated renewal of the water there, by February and March a good supply of oxygen is found down to the seabed (Figure 31). 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. With near-bottom saturation values of 55.0 % ± 16.8 % (n = 5) in the western Baltic, summer 2014 can be considered average. In the Arkona Basin, the mean saturation value was only 26.9% ± 24.0 % (n = 10), which was mainly due to very low values in the central and northern sections of the basin. At stations TF069, TF104, TF105, TF109 and TF113, for instance, saturation values between only 2 % and 10.8 % were calculated (see Figure 1). Cooling of the water and storm-driven mixing in the autumn led to an increase in oxygen saturation.



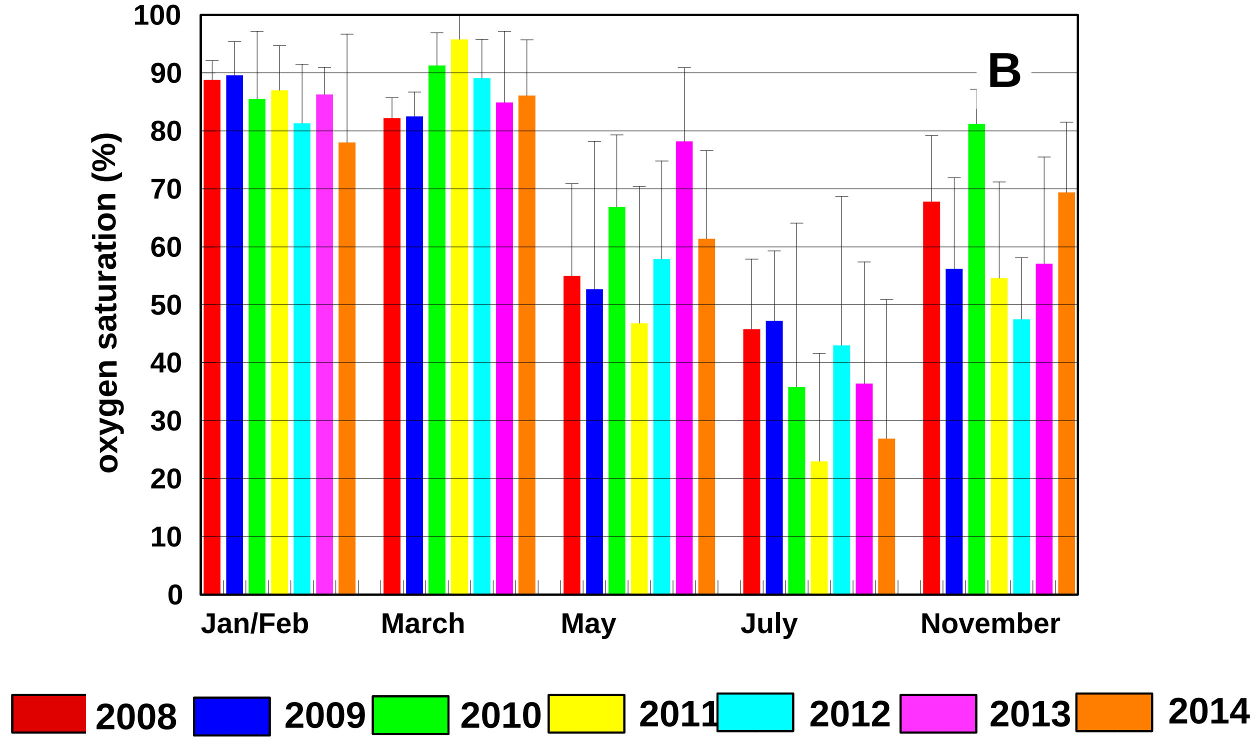


Fig. 31: Oxygen saturation in the near bottom layer in the western Baltic Sea (A) and the Arkona Basin (B) between 2008 and 2014

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 deployed RV *Haithabu* to measure near-bottom oxygen concentrations at that time of the year. Investigations in 2014 were conducted from 1–17 September. Near-bottom oxygen concentrations were measured at 37 stations, 31 of them at depths >15 m (Figure 32).

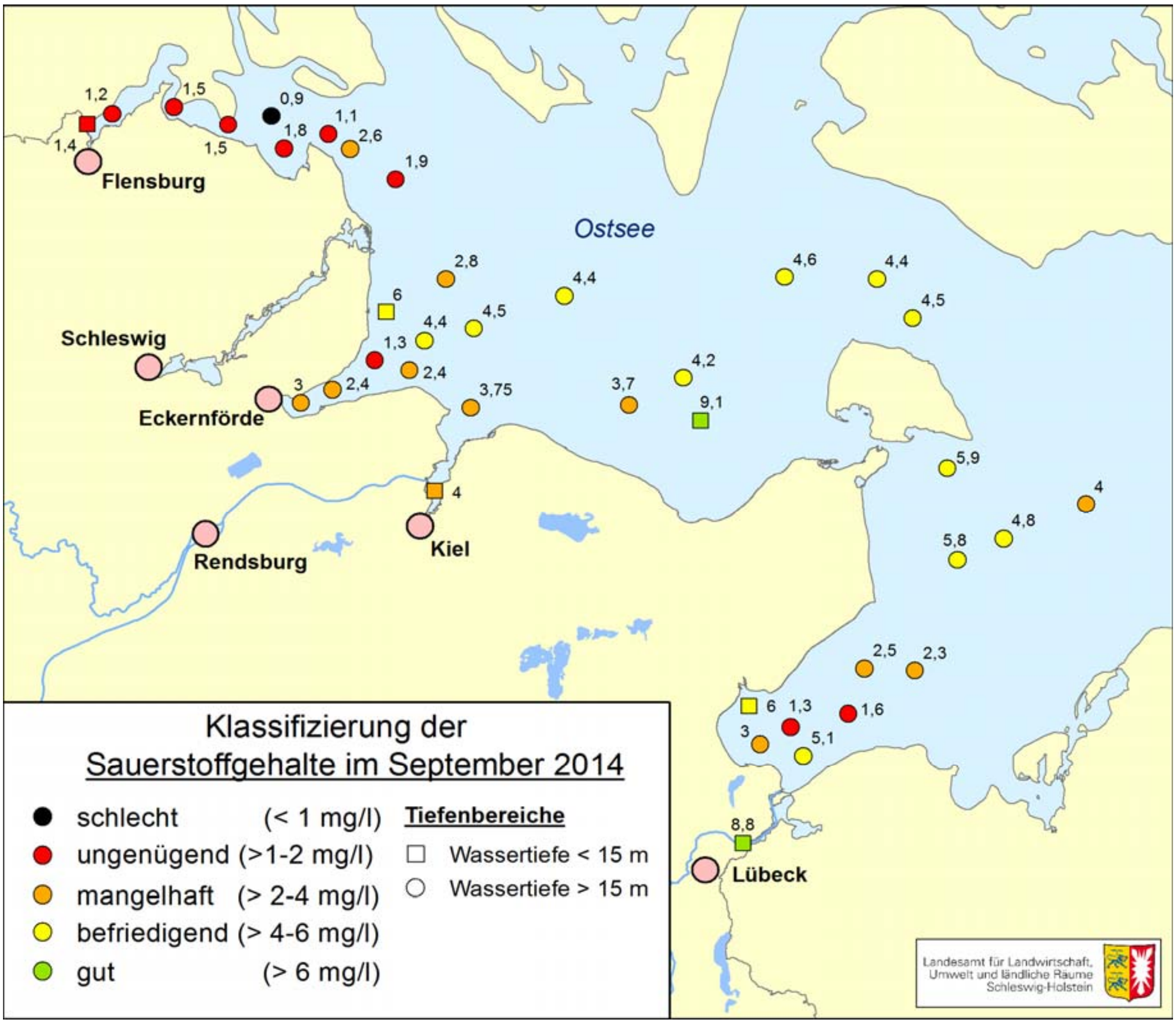


Fig. 32: Oxygen deficiency in the western Baltic Sea in September 2014 (LLUR, 2014) – O2 [mg/l] x 0.7005 = O2 [ml/l

Evaluation of measurements from 2014 (Figure 33) at stations with water depths >15 m shows that 30 % of all measurements were classified as *poor* or *inadequate* (<2 mg/l oxygen). In 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 33 % (2013: 39%, 2002: 4%). The quota of *satisfactory* (>4 to 6 mg/l) to *good* (>6 mg/l) oxygen concentrations was around 36% (2013: 24%, 2002: 4%).

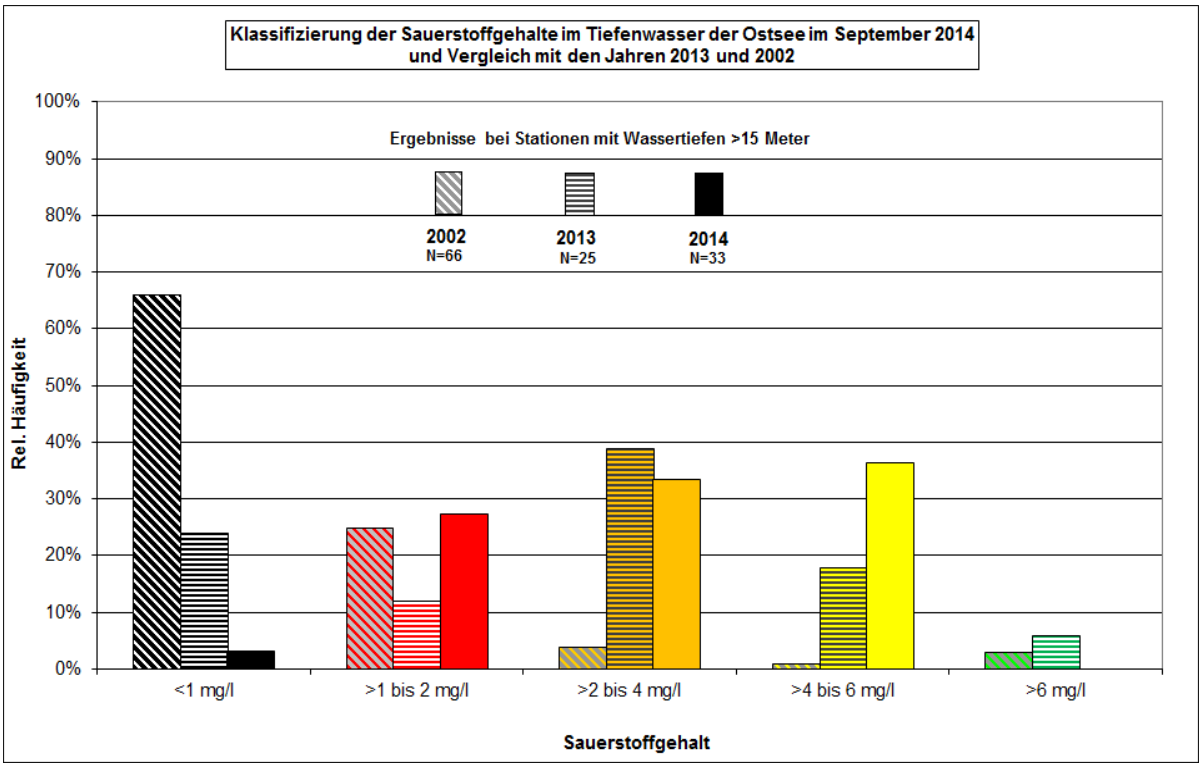


Fig. 33: Classification of the oxygen content in the deep water (water depth > 15 m) in the western Baltic Sea in the years 2002, 2013 and 2014 (LLUR, 2014)

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 34 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 2014, the smallest value in the time series was even observed. 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.

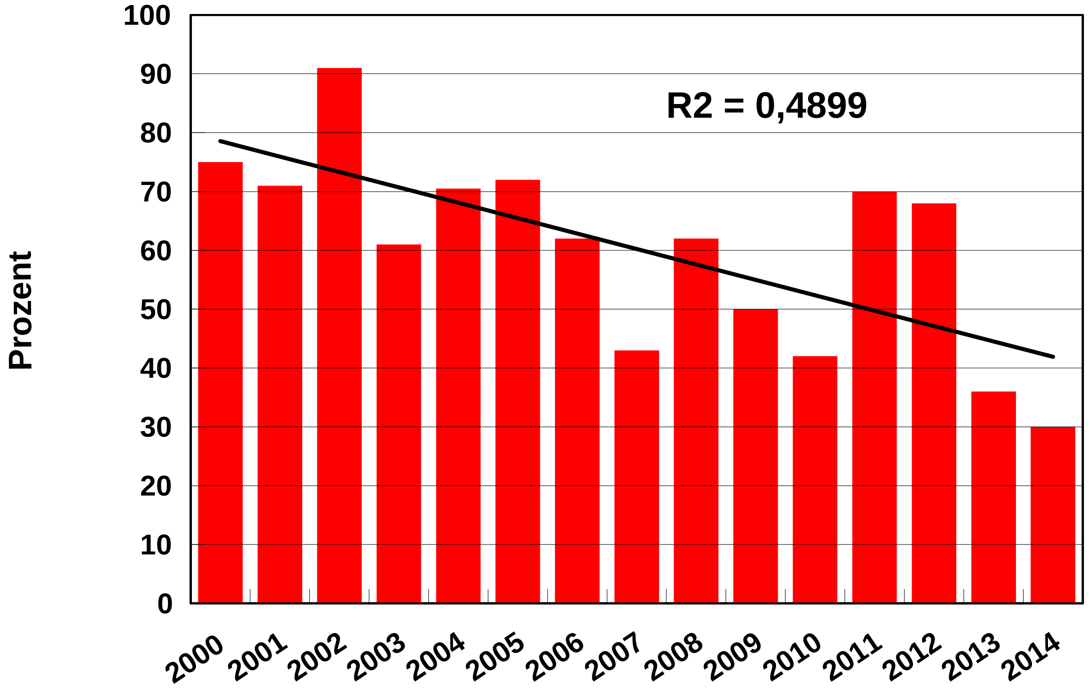


Fig. 34: Percentage of stations with an oxygen content < 2mg/l in the bottom near layer in the western Baltic Sea in autumn – data LLUR

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 Bay (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 35 shows oxygen conditions along a transect from Darss Sill to the northern Gotland Basin during the five monitoring cruises undertaken in 2014.

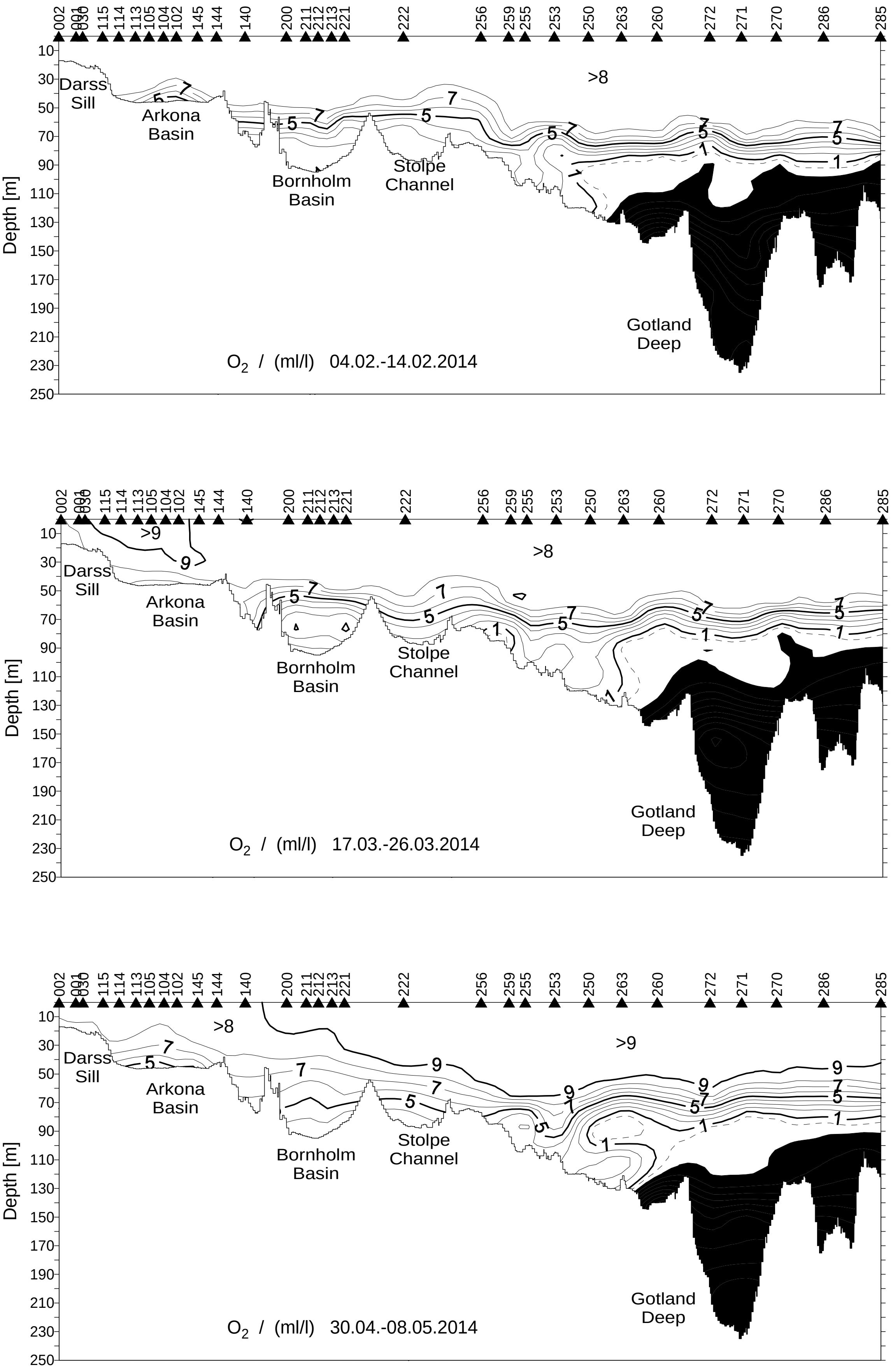


Fig. 35: Vertical distribution of oxygen resp. hydrogen sulphide 2014 between Darss Sill and northern Gotland Basin

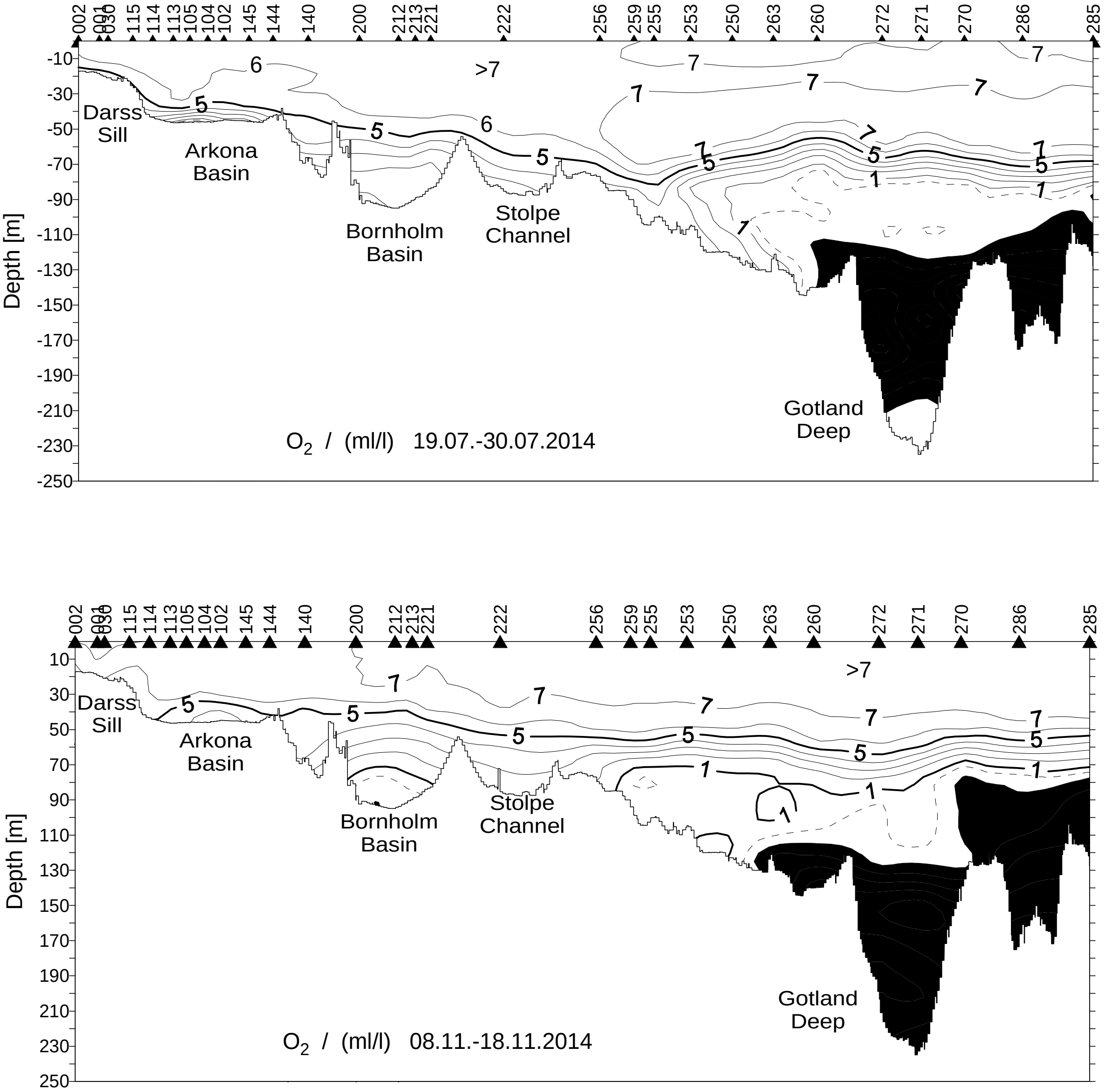


Fig. 35: Vertical distribution of oxygen resp. hydrogen sulphide 2014 between Darss Sill and northern Gotland Basin

The Bornholm Basin is the westernmost of the deep basins. Barotropic and baroclinic inflows are often able to ventilate its deep water, as evidenced by long-term developments since 2001 (NAUSCH et al., 2014). Since 2006, predominantly baroclinic inflow events have led to oxic conditions practically throughout the deep water of the Bornholm Basin. Low amounts of hydrogen sulphide have been measured only occasionally, for instance in November 2013. As described above, the inflow events in autumn 2013 (inflow volume of 147 km^3), in February (inflow volume of 141 km^3) and March 2014 (inflow volume of 203 km^3) led in the spring to lasting improvements in oxygen conditions in the deep water of the Bornholm Basin, where at the end of April 5.65 ml/l oxygen was recorded (Figure 36).

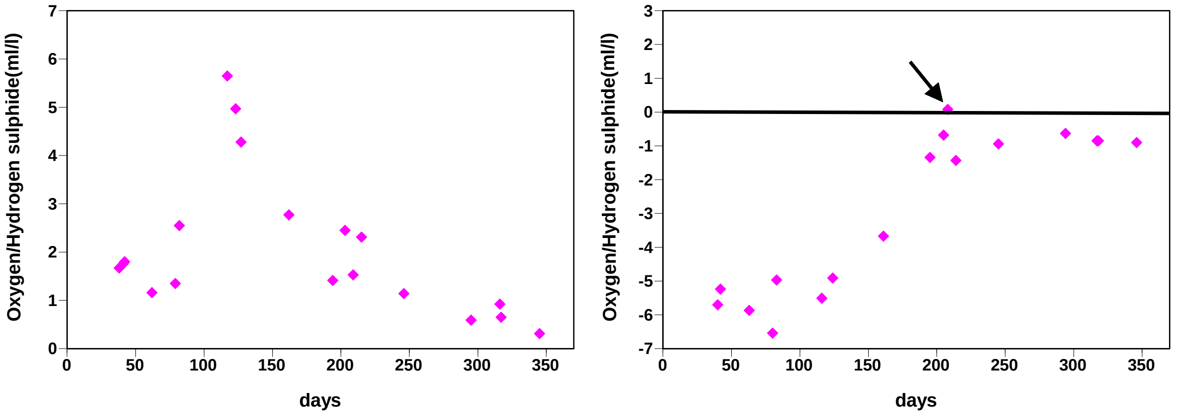


Abb. 36: Development of the oxygen/hydrogen sulphide content in the Bornholm Deep (80 m depth, left) and the eastern Gotland Basin (200 m depth, right) – IOW and SMHI data

Oxygen concentrations fell again as the year progressed, however. The complex interaction of these three inflow events led to their water masses spilling over Stolpe Sill in late April / early May. They were then able to advance into the Gotland Basin whose deep water they oxygenated repeatedly - if briefly - for the first time since 2003 (Figures 34 and 35). 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 the year 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. Towards the end of 2014, therefore, there were favourable conditions for the Major Baltic Inflow of December 2014.

6.4 Inorganic Nutrients

Eutrophication is still considered to be the most serious anthropogenic threat to the Baltic Sea (HELCOM, 2007). The effects of eutrophication were detected near towns and cities along the Baltic Sea coast even in the first half of the twentieth century (ELMGREN & LARSSON, 2001). First signs of it in the open waters of the Baltic were detected in the 1960s (FONSELIUS, 1969), as supported by IOW's long-term data series (NAUSCH et al., 2008b). By the mid-1980s, eutrophication had assumed serious proportions; more recently, wide-ranging measures have been taken to reduce its effects. Nevertheless, almost the entire Baltic Sea area continues to be affected by it. Only small areas of the Bothnian Bay have been classified as “unaffected by eutrophication” (HELCOM, 2014).

Excessive inputs of nitrogen and phosphorus compounds from the Baltic Sea's drainage basin represent the main cause of eutrophication. 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.

Again in terms of the German drainage basin of the Baltic, riverine inputs of total phosphorus from 1986 to 1990 and from 2004 to 2008 fell 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 run-off (NAUSCH et al., 2011). Nevertheless, all German coastal waters and adjacent sea still need to be assessed as eutrophic (HELCOM, 2014).

For this reason, nutrient components have been regarded as prime indicators 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.

Nitrate and phosphate present a typical annual cycle in the surface layer of the temperate latitudes (NEHRING & MATTHÄUS, 1991, NAUSCH & NEHRING, 1996). Figure 37 illustrates the annual cycle of nitrate and phosphate in the eastern Gotland Sea in 2014.

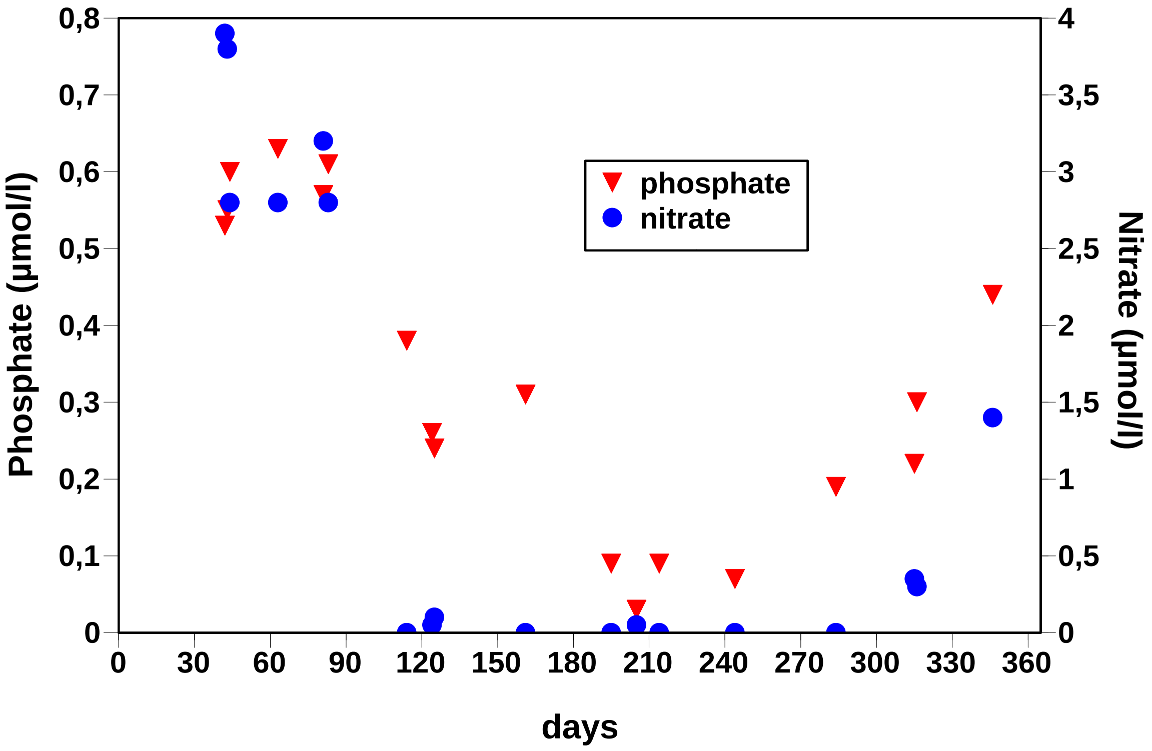


Fig. 37: Annual phosphate and nitrate cycle 2014 in the surface layer (0-10 m) of the eastern Gotland Basin (TF271) – IOW and SMHI data

During the winter in the central Baltic Sea, a typical plateau phase develops; depending on weather conditions, it lasts two to three months (NAUSCH et al, 2008b). In 2014, however, it finished even before the end of March (Figure 37). The mild winter (see chapter 2) led to an early spring phytoplankton bloom. As a result of the low N/P ratio in the winter (7.5; Table 9), nitrate reserves were already exhausted by the last decade of April. The spring bloom collapsed due to nitrogen limitation; residual phosphate concentrations measured around 0.3 µmol/l. During the remainder of the year, phosphate values continued to fall, and they reached the detection limit at the end of July. Depending on the intensity of the cyanobacteria bloom, phosphate depletion can last for an extended period. When the bloom ended, mineralisation processes began, and phosphate concentrations increased again, while nitrate values remained in the range of the detection limit until late October. Both nutrients again reached winter concentrations by the end of the following February at the latest.

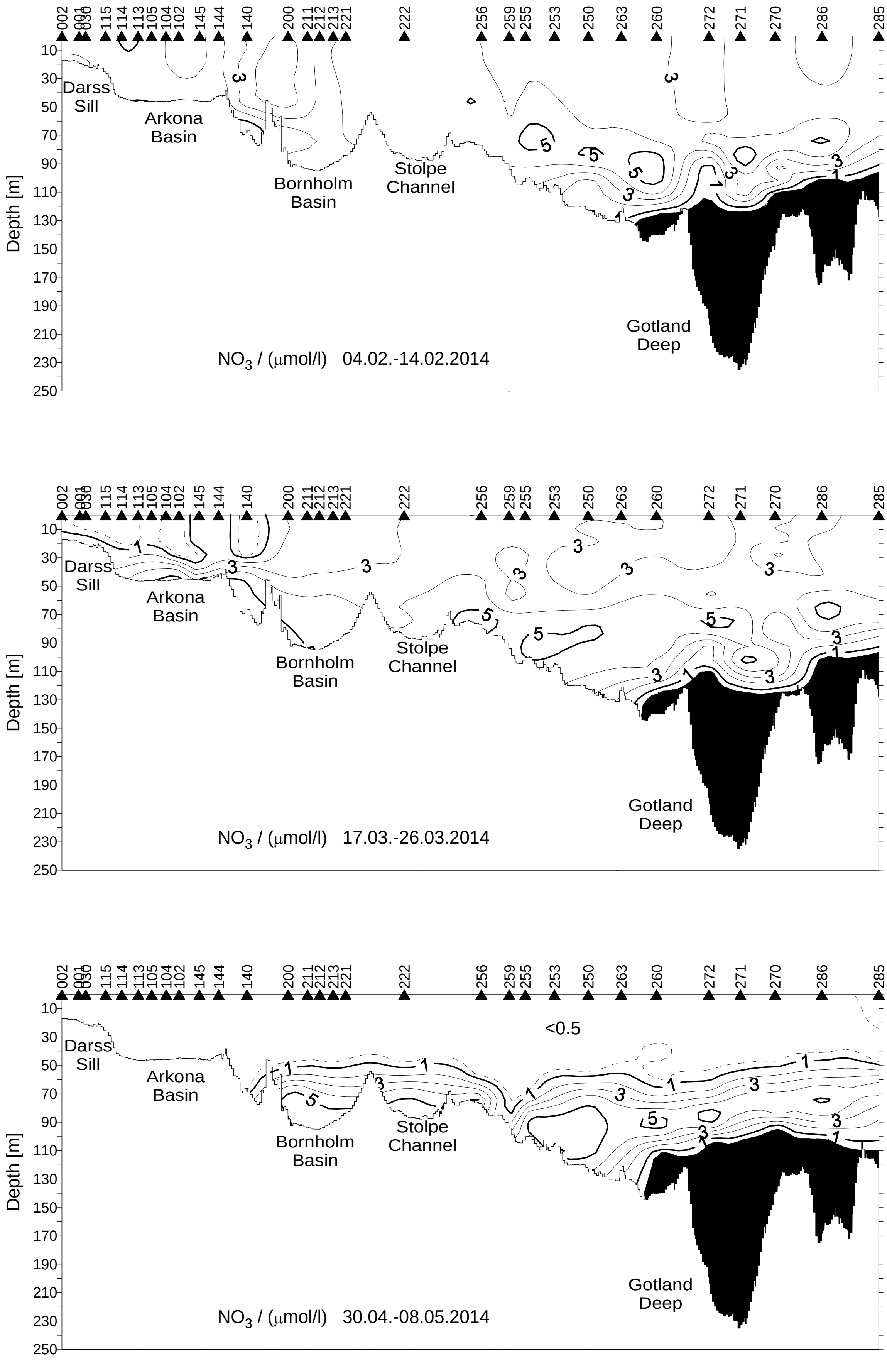


Fig. 38: Vertical distribution of nitrate 2014 between Darss Sill and northern Gotland Basin

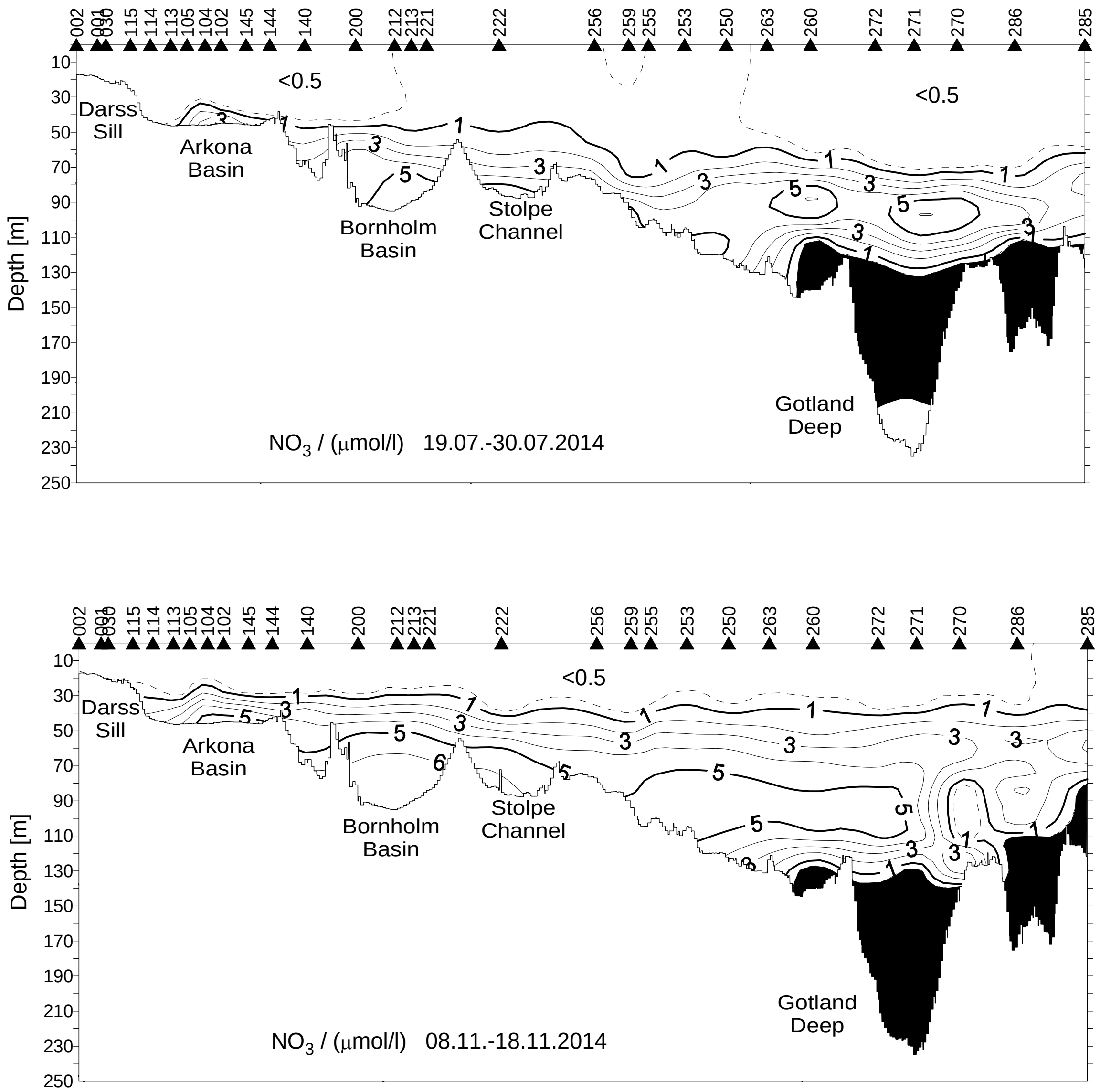


Fig. 38: Vertical distribution of nitrate 2014 between Darss Sill and northern Gotland Basin

The annual cycle of nitrate and phosphate described above can also be inferred from the five monitoring cruise transects illustrated in Figures 38 and 39. Table 9 summarises winter nitrate and phosphate values; they are in the range of previous years - even if very high phosphate concentrations were found in the northern and western Gotland Basin.

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.

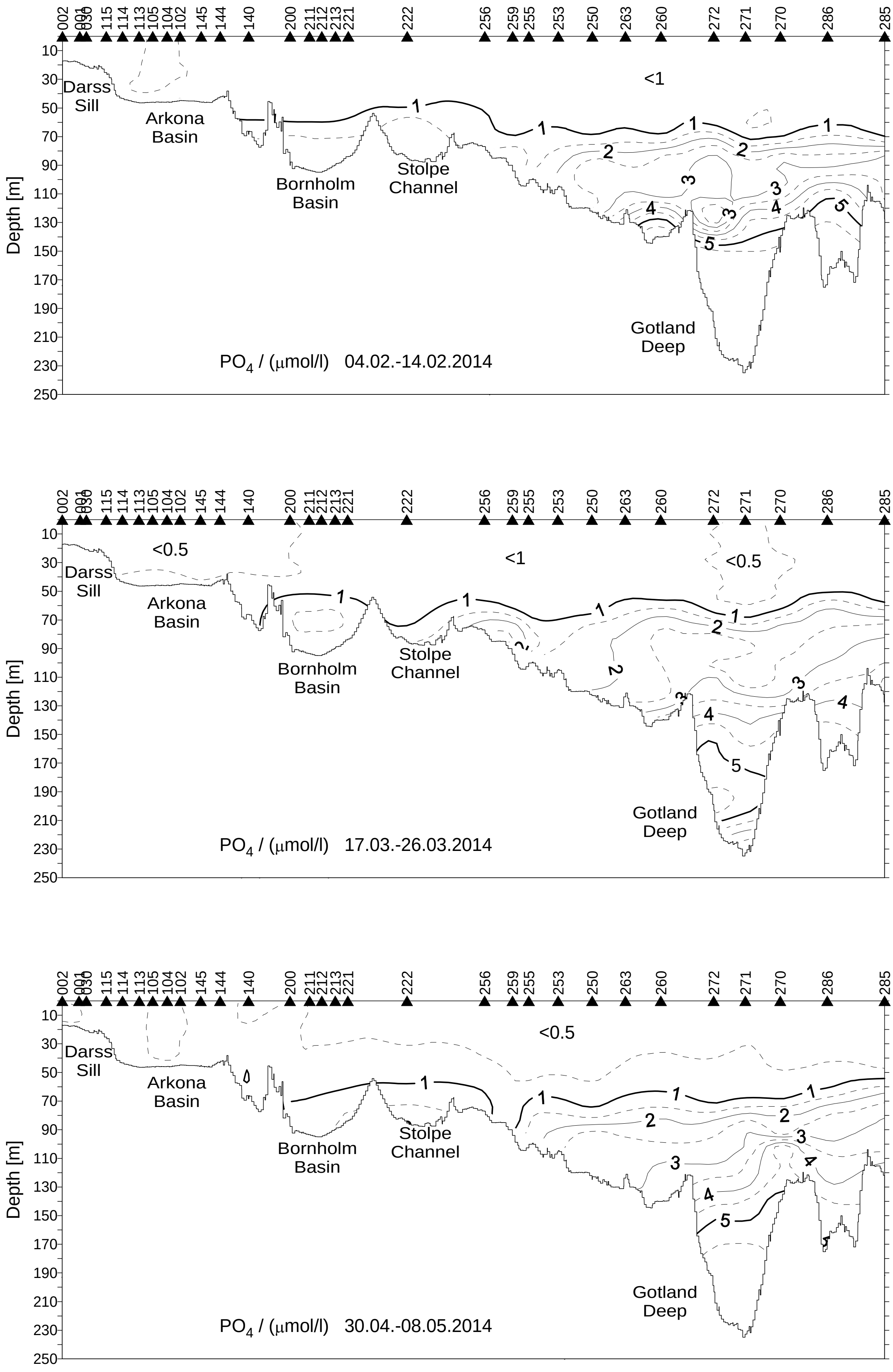


Fig. 39: Vertical distribution of phosphate 2014 between Darss Sill and northern Gotland Basin

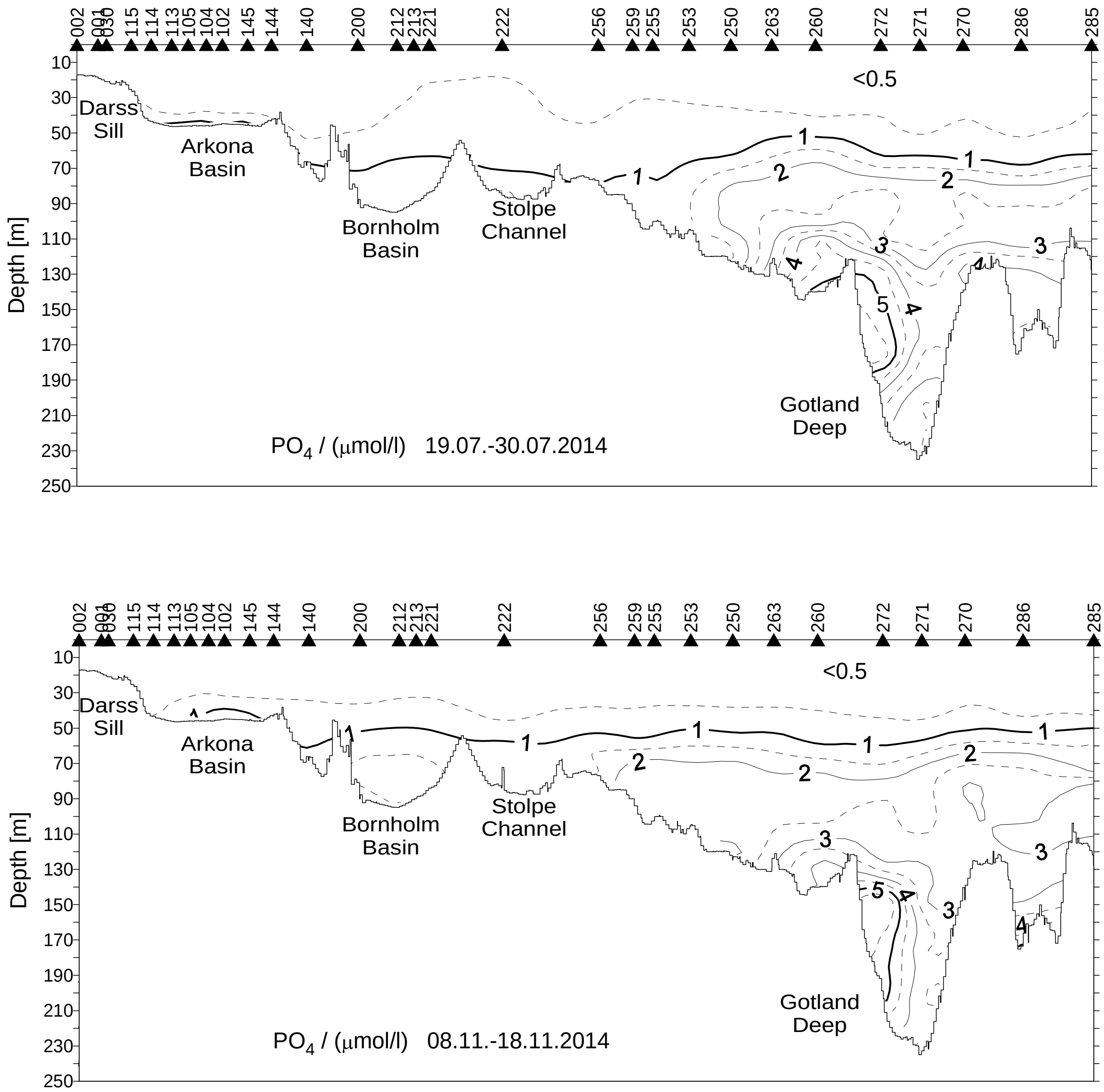


Fig. 39: Vertical distribution of phosphate 2014 between Darss Sill and northern Gotland Basin

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	Month	2010	2011	2012	2013	2014
360 (Fehmarn Belt)	Feb.	**0.47 ± 0.01**	0.58 ± 0.01	0.71 ± 0.01	0.72 ± 0.01	0.57 ± 0.01
022 (Lübeck Bight)	Feb.	**0.61 ± 0.01**		0.71 ± 0.01	0.85 ± 0.01	0.71 ± 0.04
012 (Meckl. Bight)	Feb.	0.62 + 0.02	**0.55 ± 0.00**	0.73 ± 0.02	0.85 ± 0.01	0.56 ± 0.00
113 (Arkona Sea)	Feb.	0.56 ± 0.02	**0.51 ± 0.01**	0.73 ± 0.00	0.63 ± 0.01	0.53 ± 0.00
213 (Bornholm Deep)	Feb.	0.56 ± 0.01	**0.54 ± 0.01**	0.66 ± 0.01	0.71 ± 0.0	0.70 ± 0.01
271 (Gotland Deep)	Feb.	0.62 ± 0.0*	0.54 ± 0.01	0.64 ± 0.01	0.54 ± 0.02	**0.52 ± 0.01**
286 (Fårö Deep)	Feb.	0.62 ± 0.0*		0.56 ± 0.00	**0.50 ± 0.01**	0.78 ± 0.01
284 (Landsort Deep)	Feb.	0.63 ± 0.0*		0.63 ± 0.01	**0.56 ± 0.02**	0.84 ± 0.01
245 (Karlsö Deepf)	Feb.	0.65 ± 0.0*		0.80 ± 0.02	**0.60 ± 0.02**	0.85 ± 0.00

* SMHI data

Nitrate (µmol/l; Minima in bold)

Station	Month	2010	2011	2012	2013	2014
360 (Fehmarn Belt)	Feb.	4.9 ± 0.0	5.9 ± 0.2	5.7 ± 0.1	**4.1 ± 0.0**	4.9 ± 0.2
022 (Lübeck Bight)	Feb.	6.4 ± 0.2		**6.2 ± 0.2**	6.7 ± 0.1	6.6 ± 0.1
012 (Meckl. Bight)	Feb.	4.5 ± 0.0	4.8 ± 0.0	**3.8 ± 0.2**	5.8 ± 0.0	4.5 ± 0.1
113 (Arkona Sea)	Feb.	4.1 ± 0.1	**2.6 ± 0.0**	2.9 ± 0.0	3.2 ± 0.0	5.2 ± 0.2
213 (Bornholm Deep)	Feb.	3.6 ± 0.0	3.7 ± 0.0	**2.6 ± 0.0**	3.0 ± 0.0	4.0 ± 0.1
271 (Gotland Deep)	Feb.	3.5 ± 0.0	3.2 ± 0.0	**2.6 ± 0.2**	2.9 ± 0.0	3.9 ± 0.0
286 (Fårö Deep)	Feb.	3.9 ± 0.0		3.3 ± 0.0	**3.0 ± 0.0**	4.5 ± 0.1
284 (Landsort Deep)	Feb.			4.6 ± 0.1	4.4 ± 0.0	**3.8 ± 0.3**
245 (Karlsö Deep)	Feb.	**3.5 ± 0.0**		4,0 ± 0.1	3.8 ± 0.1	**3.5 ± 0.2**

The great variability in the measured values in Table 9 is remarkable. Even a correlation analysis of the ten-year data series for 2004 to 2013 reveals no significant changes (NAUSCH et al., 2014). The coefficient of determination R^2 for station TF012 in Mecklenburg Bight, for instance, is 0.09 (phosphate), 0.01 (nitrate); for station TF113 in the Arkona Sea 0.00 (phosphate), 0.02 (nitrate); for station TF213 in the Bornholm Sea 0.09 (phosphate) and 0.17 (nitrate) ; and for station TF271 in the eastern Gotland Sea 0.09 (phosphate) and 0.02 (nitrate). 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).

In various scientific projects, HELCOM has developed target values for winter nutrient concentrations (HELCOM, 2013):

	DIN (µmol/l)	PO4 (µmol/l)
Kiel Bight	5.5	0.59
Mecklenburg Bight	4.2	0.49
Arkona Sea	2.9	0.36
Eastern Gotland Basin	3.0	0.29
Western Gotland Basin	2.0	0.33

A comparison with the winter values in table 9 reveals clearly that these target values are not being reached. Actual values and target values approximate only in the area near Fehmarn Belt. It should be noted, however, that the winter months of December to February were used as the reference period when determining the target values. As Figure 37 shows, the plateau phase in December was yet to be reached, i.e. the winter nutrient level had not yet become established. As HELCOM also uses the same reference period in its assessment, the discrepancy would not be as extreme, although any assessment would certainly be ‘eutrophied’ (HELCOM, 2013). This shows that further efforts are needed to reduce nutrient inputs.

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 = 15-28)

Phosphate (µmol/l; Maxima in bold)

Station	Deep/ m	2010	2011	2012	2013	2014
213 (Bornholm Deep)	80	2.22 ± 0.62	**2.66 ± 1.39**	1.81 ± 0.85	1.62 ± 0.35	1.49 ± 0.31
271 (Gotland Deep)	200	5.39 ± 0.29	5.66 ± 0.28	5.87 ± 0.16	**6.32 ± 0.92**	4.50 ± 1.54
286 (Fårö Deep)	150	4.27 ± 0.33	4.34 ± 0.61	4.45 ± 0.23	**4.77 ± 0.58**	4.60 ± 0.67
284 (Landsort Deep)	400	3.82 ± 0.17	3.67 ± 0.5	**3.92 ± 0.25**	3.89 ± 0.21	3.85 ± 0.35
245 (Karlsö Deep)	100	**4.37 ± 0.44**	4.22 ± 0.33	3.47 ± 0.47	3.91 ± 0.53	3.99 ± 0.51

Nitrate (µmol/l; Minima in bold)

Station	Deep/ m	2010	2011	2012	2013	2014
213 (Bornholm Deep)	80	7.5 ± 0.1	**4.6 ± 2.8**	7.9 ± 3.1	6.4 ± 1.9	8.24 ± 1.83
271 (Gotland Deep)	200	**0.0 ± 0.0**	**0.0 ± 0.0**	**0.0 ± 0.0**	**0.0 ± 0.0**	**0.0 ± 0.0**
286 (Fårö Deep)	150	**0.0 ± 0.0**	**0.0 ± 0.0**	**0.0 ± 0.0**	**0.0 ± 0.0**	**0.0 ± 0.0**
284 (Landsort Deep)	400	**0.0 ± 0.0**	**0.0 ± 0.0**	**0.0 ± 0.0**	**0.0 ± 0.0**	**0.0 ± 0.0**
245 (Karlsö Deep)	100	**0.0 ± 0.0**	**0.0 ± 0.0**	1.51 ± 2.08	0.1 ± 0.2	**0.0 ± 0.0**

Ammonium (µmol/l; Maxima in bold)

Station	Deep/ m	2010	2011	2012	2013	2014
213 (Bornholm Deep)	80	0.1 ± 0.1	**2.1 ± 3.4**	0.1 ± 1.9	0.1 ± 0.1	0.1 ± 0.2
271 (Gotland Deep)	200	21.3 ± 2.6	20.2 ± 2.8	**26.2 ± 2.8**	22.1 ± 8.7	18.4 ± 10.9
286 (Fårö Deep)	150	9.8 ± 1.3	9.0 ± 1.4	12.2 ± 1.5	12.6 ± 3.0	**12.8 ± 3.6**
284 (Landsort Deep)	400	6.8 ± 1.0	6.3 ± 1.7	**8.5 ± 1.6**	7.2 ± 2.3	7.9 ± 1.7
245 (Karlsö Deep)	100	8.4 ± 2.3	**9.7 ± 3.5**	4.4 ± 2.9	6.5 ± 3.1	7.7 ± 2.1

Few generalisations can be made about the vertical distribution of nutrients in the shallow areas of the western Baltic Sea. Nutrient gradients are essentially determined by variations in salinity and temperature stratification. Here discussion is limited to the central Arkona Basin (station TF113) with a water depth of 47 m (Figure 39). In winter, the water column was mixed almost down to the bottom, with the result that consistent concentrations of phosphate and nitrate were observed. As early as March, nitrate was depleted down to a depth of 25 m; in May and July, the entire water column was nitrate-free; a gradual increase was observed again only in autumn. In March, a reduction in phosphate concentrations to some 0.15 µmol/l was observed in the surface water. The unusual phosphate concentrations throughout the water column in May are difficult to explain. In July, phosphate concentrations above the thermocline were in the range of the detection limit; in autumn, mineralisation and mixing led to an increase in phosphate concentrations.

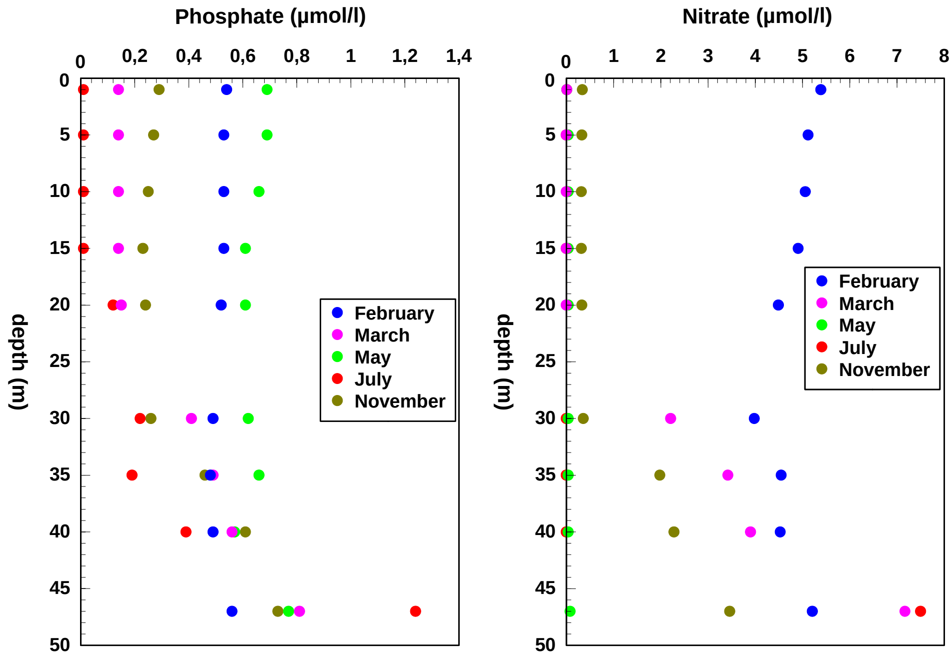


Fig. 40: Vertical distribution for nitrate and phosphate in the Arkona Basin (station 113) during 2014

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 38 and 39 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 (Tables 6 and 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 (NAUSCH et al., 2014). The inflow events in autumn 2013 and in February and March 2014 to a large extent produced favourable oxygen conditions. 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. Ammonium concentrations of 0.1 ± 0.2 µmol/l (Table 10) are thus in the range of the detection limit. With two exceptions, nitrate values are between 7 µmol/l and 9 µmol/l (Figure 41).

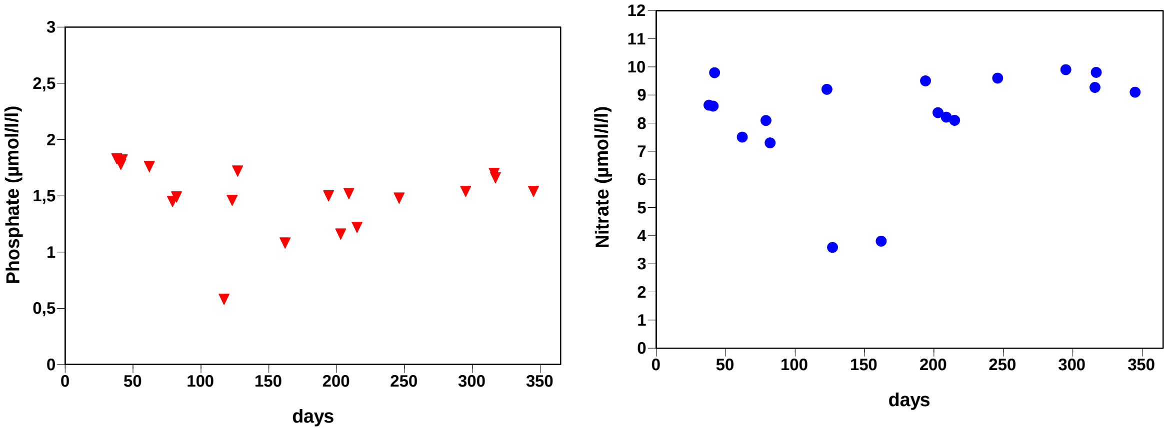


Fig. 41: Development of the phosphate concentrations (left) and the nitrate concentrations (right) in the Bornholm Deep (80 m depth) in 2014 – IOW and SMHI data

The complex interaction of the three inflow events led to their water masses spilling over Stolpe Sill at the end of April / beginning of May. This allowed oxygenic water masses with low concentrations of phosphate and high concentrations of nitrate to enter the Gotland Basin. Besides a reduction in hydrogen sulphide (chapter 6.3), this inflow also led to a decline in phosphate concentrations (Figure 42). The brief ventilation of its deep water in July 2014 led to the brief formation of nitrate (Figure 42), and ammonium values were also lower than in previous years (Table 10).

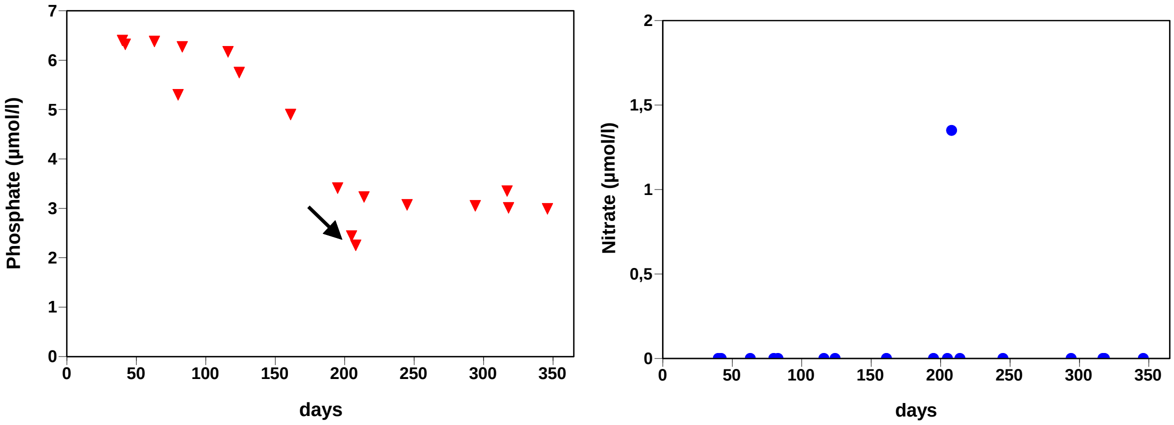


Fig. 42: Development of the phosphate concentrations (left) and the nitrate concentrations (right) in the eastern Gotland Basin (200 m depth) in 2014 – IOW and SMHI data

By the end of 2014, therefore, favourable conditions had developed for the Major Baltic Inflow of December 2014.

Summary

The winter of 2013/14 in the southern Baltic Sea area was a mild one, with a cold sum at Warnemünde of 65.8 Kd, a value that falls well short of the long-term average of 104.5 Kd. The winter of 2013/14 is thus the twenty-seventh warmest winter since the comparative record began in 1948. This cold sum was due exclusively to the month of February; all other months had a cold sum of 0 Kd. The coldest winter in the observation series was that of 1962/63 with a cold sum of 395.2 Kd.

With a warm sum of 236.9 Kd, recorded at Warnemünde, 2014 comes in tenth place in the time series that began in 1948, forcing 2013's value of 230.4 Kd into eleventh place. The 2014 value far exceeds the long-term average of 150 K d, and exceeds the standard deviation. 2014 can therefore again be classed as a particularly warm year, even if average monthly temperatures in June and August were slightly below the long-term average, and April and October were balanced. In comparison, May, July and September present warm sums that are twice as high; they are exceptionally warm months that come eighth, fourth, and sixth respectively in the time series since 1948.

In terms of Sea Surface Temperature, 2014 was the warmest year since 1990, and was about 1.2 K above average for 1990-2014; it was 0.4 K higher than 2008, formerly the warmest year. Except for February and June, all other months, and especially July and August in the north of the Baltic Sea, contributed to that value. The western Baltic Sea exceeded long-term mean values by +1 to +3 K in every month except February. After a mild start to the year, a cold spell starting around 20 January produced strong cooling until the beginning of February. Nevertheless, the monthly average for January exceeded the long-term averages for 1990-2014 by +2 K; January was the second-warmest month in the western Baltic since 2007. February lay in the range of long-term averages, and in the Arkona Sea and Gulf of Bothnia was the coldest month of the year. As usual, March developed into the coldest month of the year in the Gotland Sea. From March to May throughout the Baltic Sea, and even from March to December in its western section, anomalies of +1 to +3 K were recorded.

Inflow events with estimated volumes between 100 and 400 km³ occurred in the Baltic Sea on four occasions in 2014. In February, an inflow volume of 141 km³ was calculated based on changes in sea level at Landsort Norra. After a brief outflow phase, another inflow occurred in March with an estimated volume of 203 km³. In combination with the earlier effects of hurricane 'Xaver' in December 2013 (inflow volume of 147 km³) and the long phase of westerly winds from the end of October to the beginning of November 2013, both these events produced a complex interaction that resulted in water spilling over Stolpe Channel in late April / early May. These water masses reached the Gotland Deep in late May and oxygenated its deep water for the first time since 2003. Although none of these three events fulfilled the typical characteristics of a Major Baltic Inflow, combined they imported comparably large amounts of water, salt, and oxygen into the deep water of the Baltic Sea (a novel form of deep-water ventilation that was described for the first time). In August, another inflow phase with a volume of some 164 km³

was detected. In terms of ventilation of the deep basins, its effects were more restricted to the Arkona Basin and the Bornholm Basin.

A very large inflow began on 13 December; it had a volume of 358 km^3, of which 198 km^3 was saline water bearing around 4 Gt salt. According to latest estimates, this event represents the third-largest salt-water inflow into the Baltic Sea since the beginning of the record in 1880.

The annual cycle of oxygen saturation in the surface water was again typical in 2014. As a result of 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 %. In March, too, undersaturation continued to be observed in all sea areas except the Arkona Basin where saturation levels were 104.3 %. The peak of the 2014 spring bloom occurred in all sea areas in May: in the Bornholm Basin and in the eastern Gotland Basin, saturation values between 120 % and 125 % were determined. Summer presented a familiar picture with saturation values around 105 %. Only in the eastern Gotland Basin did saturation values around 115 % indicate an intensive cyanobacteria bloom. In the autumn, intensified degradation processes again led to undersaturation. Overall it can be concluded that the annual range of variation for saturation was relatively small, as in previous years. This indicates a healthy oxygen balance in the surface water.

Oxygen conditions in the deep water of the basins of the central Baltic Sea are primarily influenced by the occurrence or absence of strong barotropic and/or baroclinic inflows. The Bornholm Basin is the westernmost of the deep basins, and inflows are often able to ventilate its deep water. As described above, the inflow events of autumn 2013, and February and March 2014 led in the spring to a lasting improvement in oxygen conditions in the deep water of the Bornholm Basin, where at the end of April 5.65 ml/l oxygen was measured. Once these water masses had spilled over Stolpe Sill, they advanced into the Gotland Basin whose deep water they repeatedly - if briefly - ventilated for the first time since 2003.

At the same time, this meant that towards the end of the year relatively low concentrations of hydrogen sulphide were measured in the eastern Gotland Basin. 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 the year. By the end of 2014, therefore, favourable conditions had developed for the Major Baltic Inflow in December.

Oxygen conditions in the deep water were also reflected in nutrient concentrations. The good oxygen supply in the deep water of the Bornholm Basin resulted in phosphate concentrations <2 µmol/l because dissolved phosphate is precipitated under oxic conditions. In contrast, ammonium concentrations of 0.1 ± 0.2 µmol/l were in the range of the detection limit, while nitrate values, with two exceptions, were between 7 µmol/l and 9 µmol/l.

The water masses that advanced into the eastern Gotland Basin were characterised by low concentrations of phosphate and high concentrations of nitrate, and led to a reduction in concentrations of phosphate there. The brief ventilation of its deep water in July led to the equally brief formation of nitrate, and ammonium values were also lower than in previous years. Also in terms of nutrients, favourable conditions existed for the Major Baltic Inflow of December 2014.

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Hydrographic-hydrochemical assessment of the Baltic Sea 2014

CONTENT

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