Indicator Report 2017

WATER EXCHANGE BETWEEN THE BALTIC SEA AND THE NORTH SEA, AND CONDITIONS IN THE DEEP BASINS

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Key message

Before the recent phase of intensified inflow activity started in 2014, the last strong Major Baltic Inflow took place in January 2003.
After nearly a decade without a Major Baltic Inflow (MBI), a relative large inflow was detected in the western Baltic during winter 2011/12 which ventilated the Bornholm Basin and could be traced until the southern part of the eastern Gotland Basin but was not able to renew the deep water there.
A weak Major Baltic Inflow occurred in March 2014. Previously, two smaller inflow events in November 2013 and February 2014 filled already the Bornholm Basin. In combination with the main event in March an overflow of the Stolpe Channel to the south-eastern Gotland Basin was triggered. A deep-water renewal up to the Gotland Deep (station BY 15) was registered in July 2014. Hydrogen sulphide was displaced in the southern and central part of the eastern Gotland Basin (Fig. 3).
In December 2014 a strong MBI brought large amounts of saline, and well oxygenated water into the Baltic Sea. Based on observations and numerical modeling the inflow was classified as one of the rare very strong events. The inflow volume and the amount of salt transported into the Baltic were estimated with 198 km^3 and 4 Gt, respectively. The strength of the MBI exceeded considerably the 2003 event. In the list of the MBI's since 1880 (Matthäus, 2006) the 2014 inflow is the third strongest event together with the MBI in 1913 (Mohrholz et al., 2015).
During the wintertime 2015/2016 again two Major Baltic Inflows of moderate intensity followed the previous ones. In November 2015 a series of twelve low pressure cells crossed the Baltic Sea and caused the transport of 1.5 Gt of salt into the Baltic Sea. In this warm winter only one phase of cold continental weather conditions triggered an outflow in the beginning of January. Afterwards warm maritime weather continued again with storms in the end of January /beginning February. A next MBI of 1.6 Gt entered the western Baltic. In September 2016 a baroclinic inflow with ~~of~~ low oxygen concentrations was observed at the Darss Sill.
The latest wintertime 2016/2017 three weak inflow events occurred from October-December and after a strong outflow a fourth one in February (Naumann et al. 2016). None of them fulfilled the criteria of a MBI.

Results and assessment

- In the Baltic Sea, two types of lateral deep water renewal processes can be distinguished, the "classical" barotropic Major Baltic Inflows (MBIs) and the "new" baroclinic inflows (Matthäus et al. 2008). MBIs which occur in winter and spring are causing higher salinities, low temperatures and increased oxygen levels in the deep basins, while those of either type in summer and autumn increase salinity along their pathway with high temperatures, but carry only low amounts of oxygen.
- Before about 1980, MBIs were relatively frequent and could be observed on average once a year (Matthäus et al. 2008). In the subsequent decades, however, they became rather scarce; the last major inflows took place in 1993, 1997, 2003.

- 8 years after the MBI in 2003, a relatively large inflow from the Kattegat took place in November/December 2011. In a series of medium and small inflow pulses through the Sound and the Belt, about one billion tons (1.0 Gt) of salt were imported. However, this MBI of 2011 remains clearly behind the earlier MBI's in winter 2003 (with 2.0 Gt) and 1993 (with 3.4 Gt). The succession of three smaller inflow events (winter 2013/2014 and March 2014) transported in total 2.8 Gt salt and a volume of 169 km^3 of highly saline water into the deep-water of the Baltic Sea (Naumann et al. in prep).
- The above mentioned series of MBI's starting in 2014 cause again a frequent ventilation of the central Baltic Sea.
- In 2003, the very contrasting thermal signatures of both inflow types provided natural 'tracers' and allowed a clear insight into the dynamics of deep water propagation through the main basins of the western and central Baltic (Fig. 1).
  In the largest Baltic basin, the eastern Gotland Basin (EGB), the barotropic inflows in September 1997 and October 2001 increased the temperature at about 200 m depth to more than 6.5 °C but did not improve the oxygen conditions significantly.
  In addition, the exceptional baroclinic inflow in summer/autumn 2002 carried very warm water into this basin. Thereafter, the water was immediately replaced by a very cold and dense MBI in January 2003, enhanced by some smaller events in spring. Temperature dropped down to around 4.5 °C. Subsequently, the near-bottom temperatures increased again and exceeded the long-term mean as a consequence of the baroclinic inflow of August 2003, and were rising even further in 2007 due to the baroclinic inflows of 2006 (Nausch et al. 2007, 2008, Fig. 1) and 2009/2010 (Nausch et al. 2010, 2011). In particular, the baroclinic inflow of August/September 2006 carried very warm water into the Bornholm Deep, residing there from November 2006 onward. Apparently it was lifted over the Slupsk Sill in January 2007 and reached the Gotland Basin in April 2007, when extremely high values of 7.1 °C were measured there in the near-bottom layer. Despite its drastic temperature signal (Fig. 1), this was a rather smooth substitution process without significant signals in salinity. In September/October and November/December 2009, two minor barotropic inflows occurred that resulted in a salinity signal of 22 g/kg in the near-bottom layer of the MARNET Arkona Basin buoy in December, the highest value ever recorded there since it went on service in September 2003 (Nausch et al. 2010). Their thermal signals arrived at the Gotland Deep in February and March 2010, see Fig. 1. Since the beginning of 2011, the deep water of the eastern Gotland Basin between 170 m and 220 m had a constant temperature of 6.43 °C. Such a constancy of a year-long temperature record was never observed before. From 2012 onwards, temperature started to decrease as in the other deeps, with the exception of Karlsö Deep. Most probably, the inflow event of November 2013 caused a temperature increase in the eastern Gotland Basin in March 2014 (Fig. 1). At July 27th 2014 the arrival of the barotropic inflow from March 2014 caused a temperature decrease to 5.92 °C in 200 m depth at the Gotland Deep. The near bottom values in 231 m depth decreased from 6.71 °C (March 21th) to 5.69 °C (July 27th). Afterwards warmer water masses of the recent strong MBI of December 2014 arrived quickly, causing an abrupt warming in the deep-water of the eastern Gotland Basin. In the initial phase the former bottom water of the Bornholm Basin arrived with extremely warm temperatures up to 7.5 °C since February 2015. This warm water was uplifted over the Slupsk Sill by the recent inflow, arriving the Bornholm Basin in the beginning of January. Since March 2015 it was followed by the new water masses (6.8 °C) which entered the western Baltic Sea in December. The inflow activity of the wintertime 2015/2016 can be traced by the temperature as well. The warm autumn water of the November MBI arrived in the end of January at the Gotland Deep and increased the bottom water temperature to 7.9 °C.

The following event transported from 31st January to 7th February 2016 cold winter water across the sills in the western Baltic and showed a mean temperature of 3.9 °C. This water masses arrived in early summertime at the Gotland Deep, but reaching not directly the bottom water. At the bottom the temperate cooled slightly down to 7.4 °C. The four weak inflows of the last winter 2016/2017 arrived the Gotland Deep as well, passing the Bornholm Basin below the halocline on top of the highly saline bottom water of earlier MBI's. The three events of October-November raised the bottom temperature up to 7.8 °C, meanwhile the last one of February 2017 cooled down the deep-water in the eastern Gotland Basin to 6.5 °C (Fig. 1). The Farö Deep as well as the farther north Landsort Deep and the Karlsö Deep in the western Gotland Basin showed an ongoing trend of slightly temperature increase since 2015.

Deep	depth [m]	May 2012 [°C]	May 2013 [°C]	May 2014 [°C]	July 2014 [°C]	May 2015 [°C]	May 2016 [°C]	May 2017 [°C]
Bornholm D.	80	6.20	5.20	5.36	5.98	7.00	6.24	7.06
Gotland D.	200	6.42	6.37	6.37	5.92	6.90	7.53	7.27
Farö D.	150	6.18	5.88	5.64	5.73	6.33	6.81	7.07
Landsort D.	400	5.74	5.38	5.32	5.19	5.42	5.85	5.93 March 2017
Karlsö D.	100	5.05	5.32	4.98	4.99	5.01	5.21	5.4

- Before December 2014 the major Baltic inflow from January 2003 was the last strong inflow event into the Baltic Sea. The deep basins were subsequently influenced by a warm summer inflow in 2003. The salinity development in the Gotland Basin reflects these inflow processes (Fig. 2). In the deep water, steep increases after inflows are followed by slow decreases in the stagnation periods afterwards. It was particularly the short inflow of August 2003 which elevated the salinity again to levels typical for the 1960s and 1970s. The surface salinity is following this trend delayed by a decade. The effects of those events in 2003 are phasing out; a new stagnation period had started already in 2004 and continued until mid 2014 in all deep basins of the central Baltic Sea. At the end of July, salinity indicated the inflow event in the Gotland Deep. It can be seen by the small peaks in the 200 m and 120 m salinity levels (Fig. 2). Since February 2015 an abrupt increasing of the deep-water salinity has started, indicating the Major Baltic Inflow of December 2014. Maximum values of 13.3 g/kg were reached in April at the 200 m level (Fig.2). The inflow activity of wintertime 2015/2016 further increased the salinity situation of the deep-water. All three depth levels in 90 m, 120 m and 200 m are showing this trend (Fig.2) and a maximum value of 13.5 g/kg was observed at 200 m in June 2016. In contrast, frequent renewals were observed in the Bornholm Deep and the Slupsk Channel. During 2017 the bottom salinity at the Gotland Deep decreased slightly, but the 90 m and 120 m showed an ongoing increase triggered by the weak inflows of wintertime 2016/2017. The bottom salinity at the Farö Deep as well slightly decreased, in contrast to the Landsort Deep and Karlsö Deep where an ongoing increase was measured.

Deep	depth [m]	May 2012 [g/kg]	May 2013 [g/kg]	May 2014 [g/kg]	July 2014 [g/kg]	May 2015 [g/kg]	May 2016 [g/kg]	May 2017 [g/kg]
Bornholm D.	80	14.75	15.39	15.68	16.24	19.05	18.84	17.23
Gotland D.	200	12.15	12.03	11.98	12.16	13.18	**13.77**	13.34
Farö D.	150	11.56	11.38	11.30	11.37	11.87	12.70	12.55
Landsort D.	400	10.49	10.52	10.31	10.36	10.53	10.99	11.07 March 2017
Karlsö D.	100	9.43	9.95	9.45	9.58	9.59	9.87	10.19

- Changes of the near-bottom distribution of dissolved oxygen resp. hydrogen sulphide reflect these processes and are displayed here for the years 2012 – 2016 (Fig. 3). A comprehensive compilation of these maps indicating changes of hypoxic and anoxic regions since the year 1969 is published in Feistel et al. 2016. In 2003, the MBI of January had ventilated the Bornholm, Gdansk and Eastern Gotland Basins with considerable amounts of oxygen. In the latter basin an oxygen content of 3.96 ml/l could be measured in the near-bottom layer. Since then, with a short interruption in 2007, a deterioration of the oxygen situation in the deep water was observed until the weak inflow of March 2014 arrived in July 2014. Hydrogen sulphide concentrations (expressed as negative oxygen equivalents) in the near-bottom layer increased continuously up to this time. In the Gotland and Farö Deeps, hydrogen sulphide concentrations in 2012 were among the highest recorded so far. Since February 2015 the latest arrival of oxygenated saline water caused a change to oxic conditions in the eastern Gotland Basin during springtime. In April 2015 values of 2.19 ml/l (southern part of the eastern Gotland Basin) and 2.99 ml/l oxygen content at the near bottom layer of the Gotland Deep were observed (Naumann 2015). Since that time rapid oxygen depletion started again and since October 2015 the deep-water oxygen concentration was below 1 ml/l. The MBI's of November 2015 and January-February 2016 delivered again new oxygenated water masses to the central Baltic, but the values stayed below 2 ml/l in the eastern Gotland Basin during the year 2016. The northern areas and the western Gotland Basin stayed anoxic. In February 2017, a ventilated Farö Deep was found. For the first time during this intense inflow phase since 2014 oxygenated water bodies passed the sill to the northern areas and the Farö Deep showed bottom values of 0.2 ml/l and up to 1.2 ml/l in 115-130 m water depth.

Deep	May 2012 [ml/l]	May 2013 [ml/l]	May 2014 [ml/l]	July 2014 [ml/l]	May 2015 [ml/l]	May 2016 [ml/l]	May 2017 [ml/l]
Gotland Deep	−6.46	−5.83	-6.03	0.54	1.54	0.08	**0.08**
Farö Deep	−4.04	−2.78	-3.58	-5.33	-1.05	0.05	**0.88**
Landsort Deep	−1.83	−0.67	-3.13	-3.29	-0.55	-1.05	-0.67 March 2017
Karlsö Deep	0.06	−0.53	-0.74	-2.44	-0.50	-1.13	-0.04

The vertical extension of the layer containing hydrogen sulphide was changing since mid of 2014. In May 2014 in the Gotland Deep, H_2S was found from about 125 m depth to the bottom. At the Farö and Landsort Deep stations, the water column

between 100 m and the bottom was anoxic. One year later hydrogen sulphide was dissolved in the southern and central parts of the eastern Gotland Basin as a result of the recent inflow activity. The northern parts like the Farö Deep stay anoxic but the hydrogen sulphide values decreased to -1 ml/l negative oxygen equivalent during 2015. The subsequent inflows of wintertime 2015/2016 oxidized the hydrogen sulphide in this subbasin causing low oxygen concentration in May 2016, but it remained mainly-anoxic. At more distant basins of the deep-water circulation, like the northern and western Gotland Basin, the same effects of decreasing hydrogen sulphide values were observed. In 2017 this ongoing trend leads to a hydrogen sulphide free situation in the Farö Deep and the Karlsö Deep showed as well very low values close to zero.

In the Bornholm Basin, in contrast, the baroclinic inflows of 2006 and the small barotropic ones between 2007 and 2010 repeatedly oxygenated the deep water in those years. Thus, in 2008-2010 no hydrogen sulphide was found in the Bornholm Basin, while in the second half of 2011 anoxic conditions temporarily restored directly at the bottom but were terminated soon after by the MBI of November /December 2011. No hydrogen sulphide was found since that time in the Bornholm Basin. This favorable situation is supporting recruitment of the eastern cod. East of Bornholm, the cod population of 400 000 tons has returned to values found 20 years ago (ICES, 2011).

A surprising finding was the complete ventilation of the formerly increasingly anoxic water column at the Karlsö Deep in April 2008 when small concentrations of oxygen (0.5 ml/l) and nitrate (1 µmol/l) were measured near the bottom. Similar, but weaker events were also observed in January 2010 and May 2012. Since then, the bottom water remains anoxic. The stratification of the water column is not as stable as in other regions and apparently permitted partly winter convection.

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Additional Information

Cruise reports, oxygen deficiency maps:
http://www.io-warnemuende.de/research/en_datbild.html

MARNET Darss Sill records:
http://www.io-warnemuende.de/projects/monitoring/en_home.html

BSH MARNET:

http://www.bsh.de/Meeresdaten/Beobachtungen/MARNET-Messnetz/index.jsp

Marine Science reports:
http://www.io-warnemuende.de/research/mebe.html

BALTIC atlas:
http://www.io-warnemuende.de/projects/baltic/index.html

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Summary (<20 words)

An unexpected series of four MBI's since 2014 ventilated the central Baltic Sea until the Gotland Basin frequently causing remarkable changes of temperature, salinity and oxygen in the deep waters.

Figures

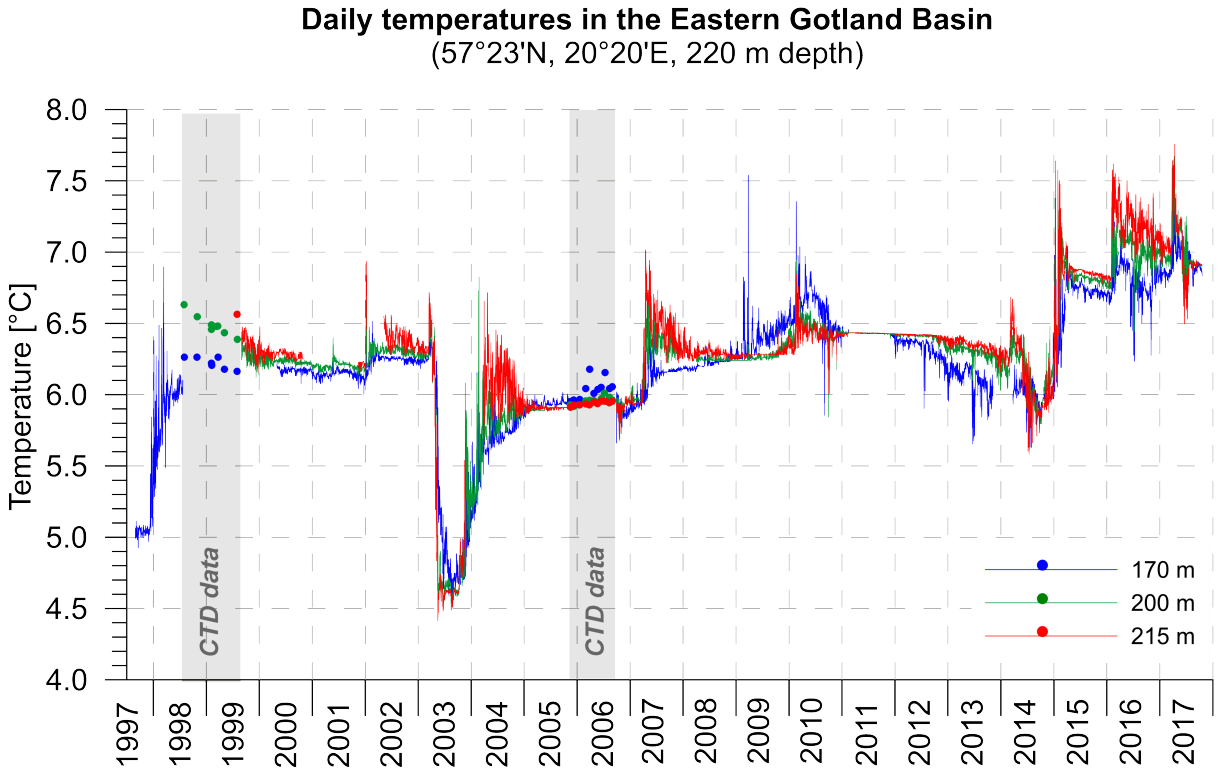


Fig. 1: Temperature series August 1997 - November 2017 of the EGB mooring near the Gotland Deep at 170, 200 and 215 m depth, referred to as the “Hagen curve”. The bathymetric depth at the anchor position is H = 220 m. The temperature signals caused by the warm and cold inflow events appear as sudden leaps with subsequently fading fluctuations over typically one year relaxation time. Note the exceptional thermal quiescence in 2011.

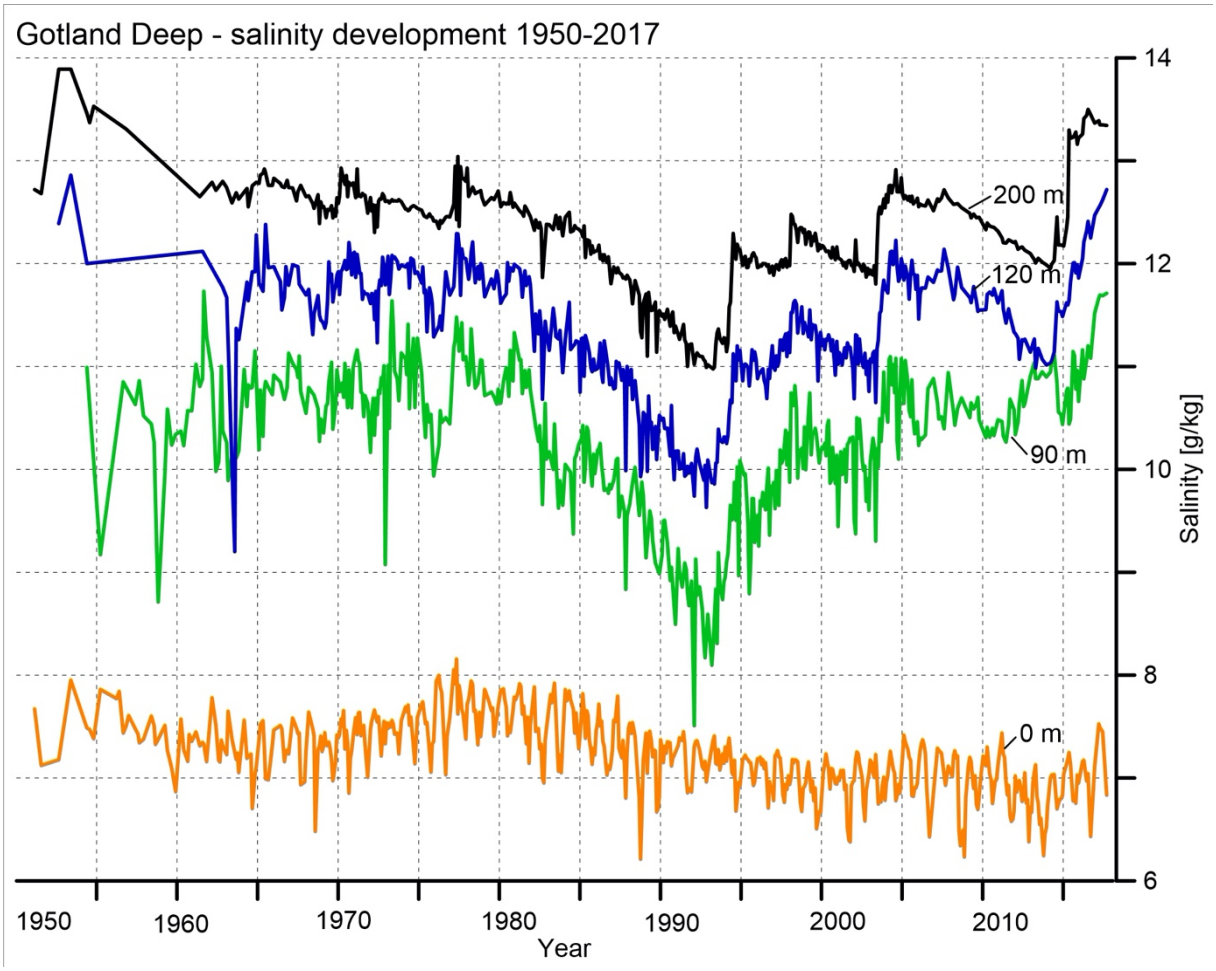
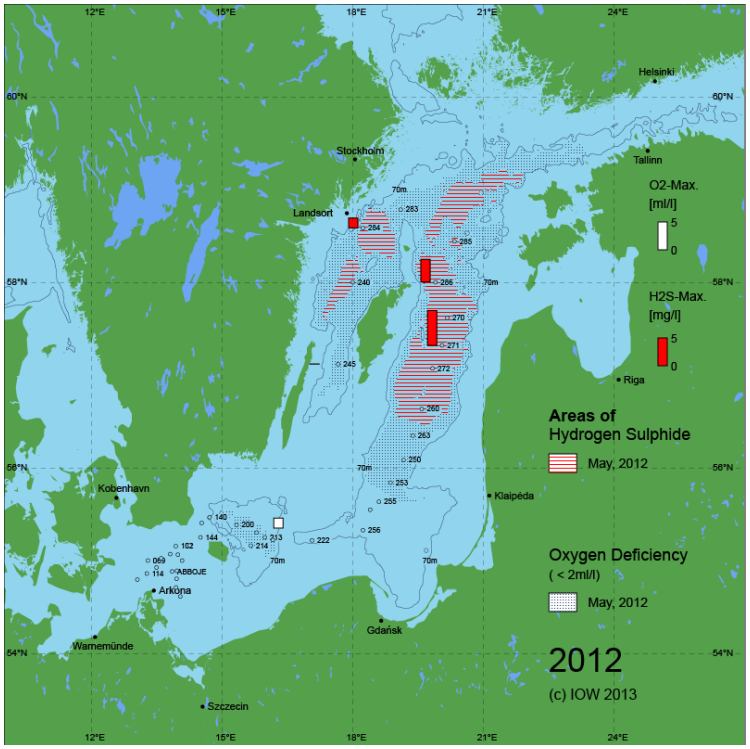


Fig. 2: Salinity in the Gotland Deep at the surface, at 90 m, 120 m and 200 m depth from 1952 to August 2017. Monthly mean time series till 2005 are available from the BALTIC atlas (Feistel et al. 2008). After the surface salinity minimum of 2002, values were gradually rising again until 2010 as a result of the high deep-water salinity after the 1993 inflow (Feistel et al., 2006; Matthäus et al., 2008; Reissmann et al., 2009; Holliday et al., 2011). The recent surface salinity decrease reflects the development of the deep water salinity with a delay of around 10 years. As a result of the very strong Major Baltic Inflow of December 2014, a high salinity value of the arriving water of 13.5 g/kg was observed at the bottom of 235 m water depth in April 2015. The following two Major Baltic Inflows of moderate intensity in November 2015 and January-February 2016 brought again oxygenated water bodies into the eastern Gotland Basin and the near bottom salinity slightly increased to 13.8 g/kg. This is the second largest bottom salinity value after the outstanding event in 1951. During the latest winter season only weaker inflow events occurred and reached the Gotland Deep in the upper part of the deep-water, indicated by the increase of salinity in 90 m and 120 m.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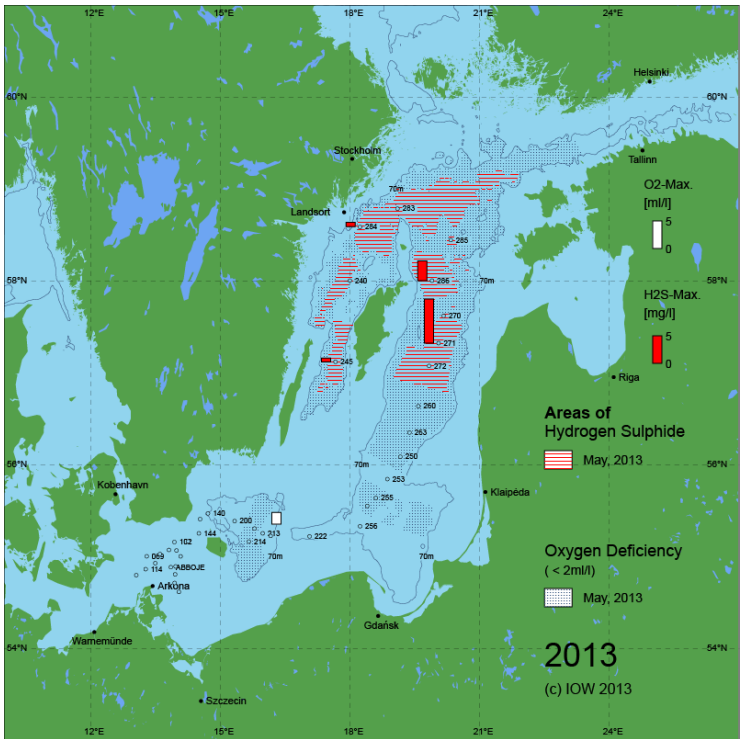
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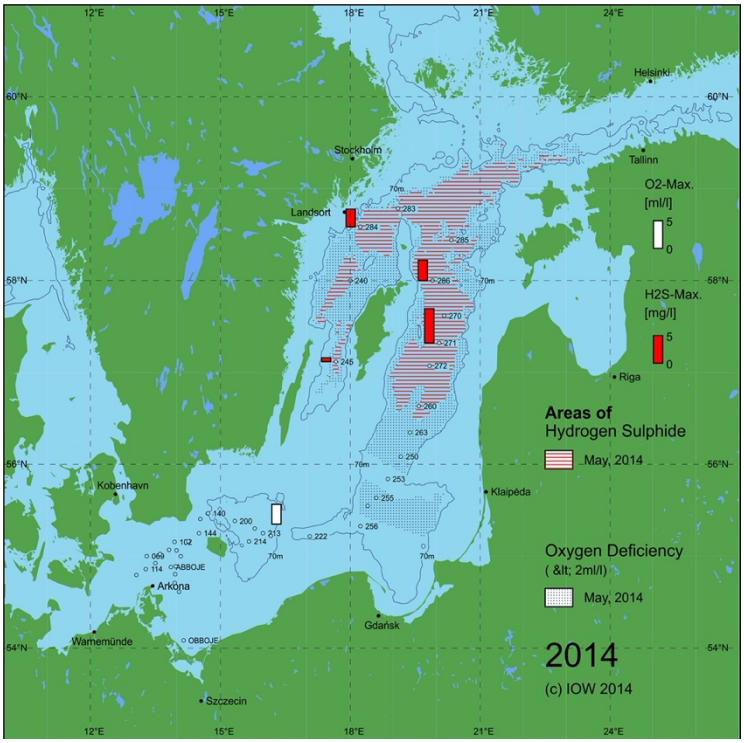
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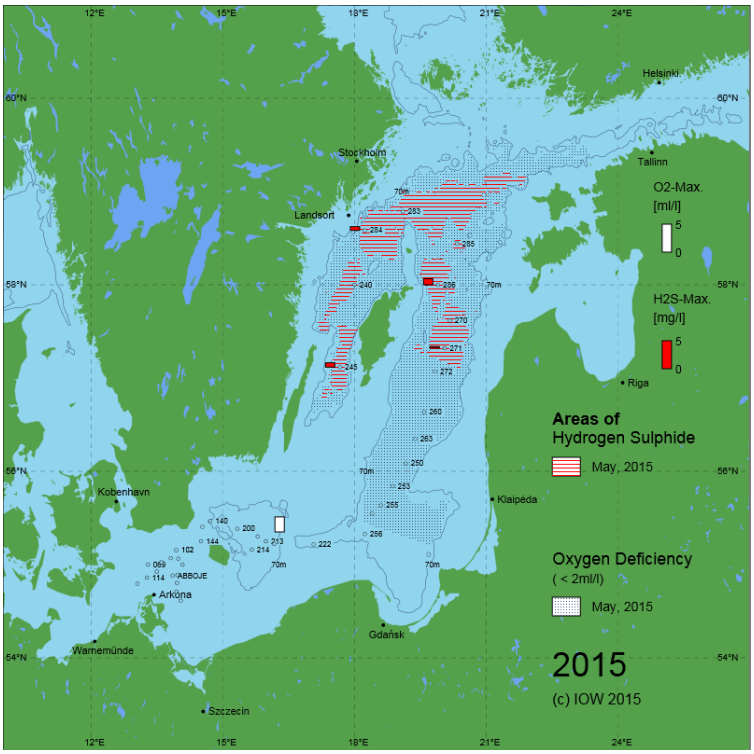
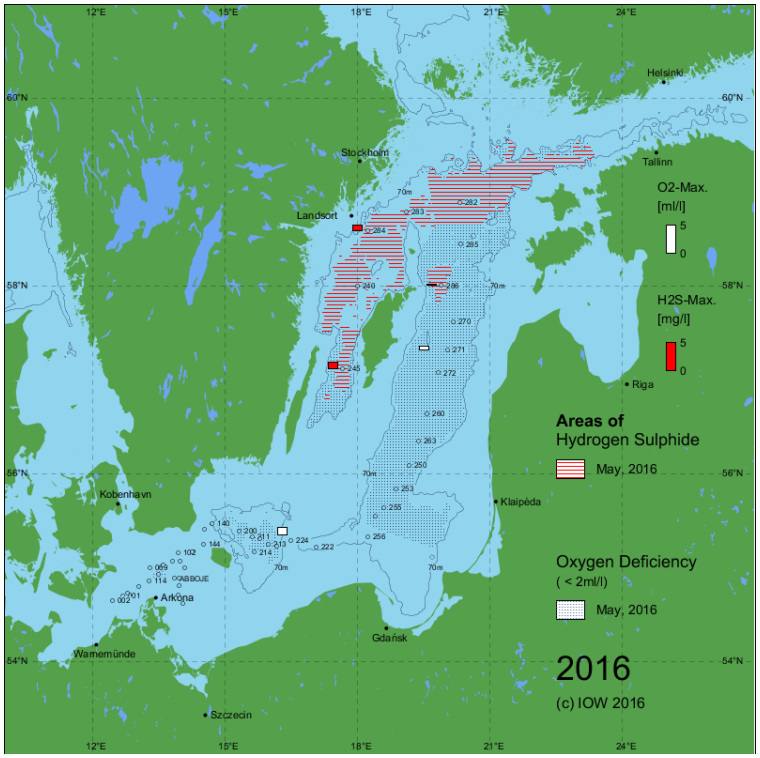
2014
(c) IOW 2014


12°E
15°E
18°E
21°E
24°E
60°N
58°N
56°N
54°N
Helsinki
Stockholm
Tallinn
Landsort
Riga
Kobenhavn
Klaipéda
Arkona
Gdańsk
Warnemünde
Szczecin
ABBOJE
O2-Max.
[ml/l]
5
0
H2S-Max.
[mg/l]
5
0
Areas of
Hydrogen Sulphide
May, 2015
Oxygen Deficiency
(< 2ml/l)
May, 2015
2015
(c) IOW 2015



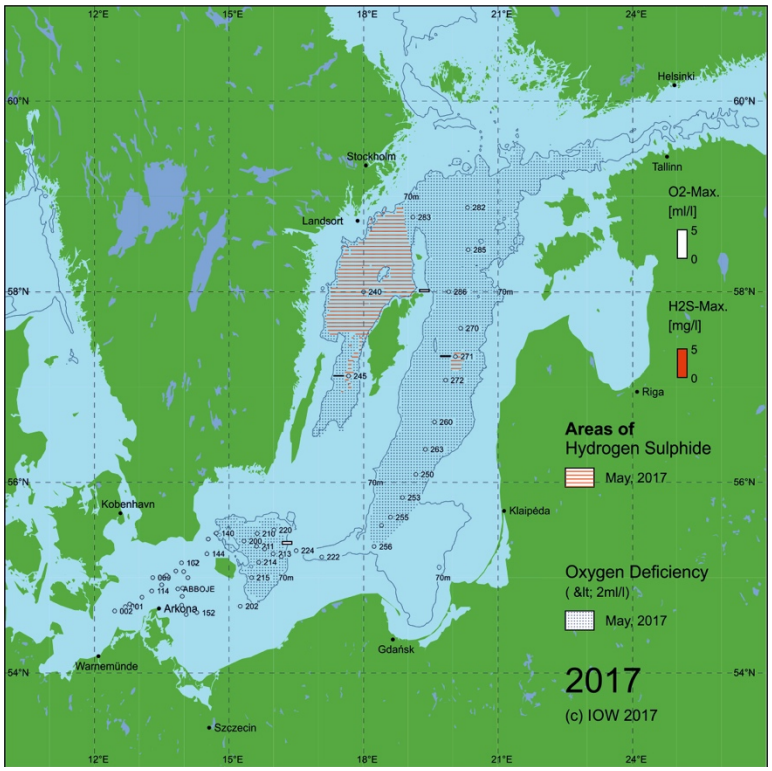


Fig. 3: Areas with oxygen deficiency and hydrogen sulphide in the near bottom layer of the Baltic Sea in May in the years 2012 – 2017. Histograms show the maximum oxygen and hydrogen sulphide concentrations of this layer. The figure contains additionally the 70 m isobath.