Meereswissenschaftliche Berichte

Marine Science Reports

Leibniz-Institut für
Ostseeforschung
Warnemünde

No 100 2016

Hypoxic and anoxic regions in the Baltic Sea, 1969 - 2015

Susanne Feistel, Rainer Feistel, Dietwart Nehring, Wolfgang Matthäus,
Günther Nausch, Michael Naumann

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

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

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

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

ISSN 2195-657X

Susanne Feistel[1], Rainer Feistel[1], Dietwart Nehring[2], Wolfgang Matthäus[1], Günther Nausch[1], Michael Naumann[1]: Hypoxic and anoxic regions in the Baltic Sea, 1969 - 2015. Meereswiss. Ber., Warnemünde, 100 (2016)
DOI: 10.12754/msr-2016-0100

Adressen der Autoren:
[1] Leibniz Institute for Baltic Sea Research (IOW), Seestraße 15, D-18119 Rostock-Warnemünde, Germany
[2] Am Feldrain 71, D-18059 Rostock

E-mail des verantwortlichen Autors: *susanne.feistel@io-warnemuende.de*

Preface

The publication “Meereswissenschaftliche Berichte – Marine Science Reports“, **Volume 100,** of the Leibniz Institute for Baltic Sea Research (IOW) calls for a review of the development of this journal. The first volume dates back to the year 1990 when new ideas and initiatives evolved with the German reunification. The journal was initiated in the last years of the Institute of Marine Research of the Academy of Sciences of the GDR, which was replaced by the new Institute for Baltic Sea Research in 1992. The existing infrastructure, expertise and valuable data were retained, and also the Marine Science Reports were perpetuated.

Today, all volumes of our journal are openly accessible on the IOW homepage as well as on LeibnizOpen, the repository of the Leibniz Association. It contributes increasingly to the dissemination of research results of scientists of the IOW and cooperating institutions and increases the international visibility of the Leibniz Institute for Baltic Sea Research.

“Meereswissenschaftliche Berichte – Marine Science Reports“ releases monographs and reports which are too voluminous for publication in regular peer-reviewed journals. It also presents substantial background information associated to peer-reviewed papers. In addition, our journal is the medium to publish the annual hydrographic-hydrochemical and biological assessments of the Baltic Sea.

The **Volume 100** spotlights a specific feature of research in the IOW: the long-term investigations on highly relevant processes in the Baltic Sea. Hypoxic and anoxic conditions are unique characteristics of the deep water layers in the Baltic basins. They prevent higher life in these waters and influence eutrophication via nutrient resolution. As bioturbation is prevented, undisturbed sediment cores can be obtained from these areas. These cores reveal that oxygen conditions changed drastically in historical times. Superimposed to these general structures, short-term increase of deep-water oxygen concentrations occur after major inflows of North Sea water into the Baltic basins. A recent Major Baltic Inflow period (2014-2015) is just under intense scientific evaluation. It can only be assessed against the background of long-term monitoring data. The IOW possesses these long-term data and the expertise to perform such a detailed evaluation. Based on these data series, our **Volume 100** compiles maps of deep-water conditions since 1969 with seasonal resolution and makes it available to the scientific community. This research is going on and the data series will extend. Annual updates of the maps will be presented on the IOW-homepage at http://www.io-warnemuende.de/msr-2016-0100/. They will refer to this publication, which will attract the attention of researchers also in the following years. Substantial background information, comprehensive data collection and up-dating information, just three out of many reasons worth celebrating the **Volume 100** of the **Marine Science Reports**.

Dr. Norbert Wasmund (Editor)

Prof. Dr. Ulrich Bathmann (Director of IOW)

Warnemünde, June 2016

Content

Abstract

The Baltic Sea is a complex ecosystem characterized by a strongly fluctuating, fragile balance between high freshwater runoff and saline water inflows, a stable stratification and a topography composed of connected basins. The sensitivity of the system “Baltic Sea” amplifies climatological fluctuations on the decadal scale. Such changes may be irrelevant in the open ocean but constitute significant indicators in the Baltic Sea. Salt and nutrients in the Baltic Sea remain present there for 20 and more years before being flushed to the Atlantic along with the freshwater export. This long residence time attenuates short-time fluctuations in environmental conditions, but highlights systematic, even small long-term anomalies.

The maps in this publication allow a visual evaluation of inflow events, of the progress of oxygen-consuming processes and of the development of hydrogen sulphide distribution over longer periods of time. The currently used method is a database- and software-based, transparent and reproducible way to represent the distribution of hypoxic and anoxic water in the near-bottom layer of the Baltic Sea. The datasets of IOWTOPO[1] and RANGS[2] form the framework for all created maps. The oceanographic database IOWDB[3] serves as the standard primary data source and contains harmonized, quality-controlled oxygen and hydrogen sulphide data from the regular seasonal monitoring cruises that have visited the western and central Baltic Sea since 1969. The final graphic is created in XML[4]-based format SVG[5] and is editable in any text editor. Furthermore SVG is a vector graphic that is editable with any software application capable of processing vector graphics.

---

[1] IOWTOPO: Digital Topography of the Baltic Sea, http://www.io-warnemuende.de/topography-of-the-baltic-sea.html (accessed June 13th, 2016)
[2] RANGS: Regionally Accessible Nested Global Shorelines, http://www.io-warnemuende.de/rangs.html (accessed June 13th, 2016)
[3] IOWDB: Oceanographic database of the Leibniz Institute for Baltic Sea Research Warnemünde. The database contains georeferenced point data from the water column.
[4] XML: Extensible Markup Language, https://en.wikipedia.org/wiki/XML (accessed June 13th, 2016)
[5] SVG: Scalable Vector Graphic, https://en.wikipedia.org/wiki/Scalable_Vector_Graphics (accessed June 13th, 2016)

Kurzfassung

Die Ostsee is ein komplexes Ökosystem, welches charakterisiert wird durch ein instabiles, stark schwankendes Gleichgewicht aus Süßwassereintrag und Salzwassereinstrom, durch eine stabile Schichtung und durch eine Topographie aus miteinander verbundenen Becken. Die Empfindlichkeit des Systems „Ostsee“ verstärkt klimatologische Fluktuationen auf der Skale von Dekaden. Derartige Veränderungen sind im offenen Ozean unbedeutend, aber in der Ostsee stellen sie signifikante Indikatoren dar. Salz und Nährstoffe verbleiben in der Ostsee für 20 und mehr Jahre, ehe sie mit dem Süßwasserausstrom in den Atlantik getragen werden. Diese lange Residenzzeit glättet kurzzeitige Schwankungen in den Umweltbedingungen, aber hebt systematische Langzeit-Anomalien hervor.

Die Karten, die in diesem Atlas veröffentlicht werden, erlauben eine visuelle Einschätzung von Einstromereignissen, vom Ausmaß der Sauerstoff zehrenden Prozesse und von der Entwicklung der anoxischen Gebiete über längere Zeiträume. Die derzeit angewandte Methode ist Datenbank- und Software-basiert. Sie stellt einen transparenten und reproduzierbaren Weg dar, um die Verbreitung von hypoxischen und anoxischen Gebieten im bodennahen Wasser der Ostsee grafisch anzuzeigen. Die Datensammlungen von IOWTOPO und RANGS bilden die Grundlage für alle erzeugten Karten. Die ozeanographische Datenbank IOWDB als Datengrundlage enthält harmonisierte, qualitätsgeprüfte Messdaten zu Sauerstoff und Schwefelwasserstoff von den regelmäßigen Monitoringfahrten, die seit 1969 Daten von der westlichen bis in die zentrale Ostsee erheben. Die endgültige Grafik wird im XML-basierten Format SVG generiert und kann mit jedem Texteditor bearbeitet werden. SVG ist ein vektorbasiertes Format, welches außerdem mit jedem Grafikprogramm bearbeitet werden kann, welches Vektorgrafiken prozessieren kann.

1. General information

The Baltic Sea is a semi-enclosed brackish sea in the humid climate zone of the northern hemisphere. Except the Kattegat, it is connected with the North Sea by three narrow channels, the Little Belt, the Great Belt and the Sound, and shallow sills, the Darss and Drogden Sills. These obstacles constrict the free water exchange with the world ocean and thus, have essential importance for the environmental conditions in the whole Baltic Sea (ELKEN & MATTHÄUS, 2008; MATTHÄUS et al., 2008). Due to high fresh-water runoff from the catchment area, outflow conditions are generally dominating. On the other hand, oceanographic conditions in the deep water of the Baltic Sea are strongly influenced by rare, unpredictable episodic inflows of highly saline and oxygenated water from the North Sea. Only great such inflow events caused by very specific meteorological and oceanographic conditions are capable of renewing the deep water in the central basins and to supply them with dissolved oxygen. When they take place, typically on a timescale between one per year and one per decade, these occasional inflows of considerable amounts of highly saline and, only in winter and spring, also oxygenated water replace step by step the deep and bottom water of the central Baltic basins; they represent a special and basic phenomenon of the Baltic Sea. The resulting strong vertical salinity and density gradient effectively seals the Baltic deep water against direct atmospheric gas exchange by wind and waves.

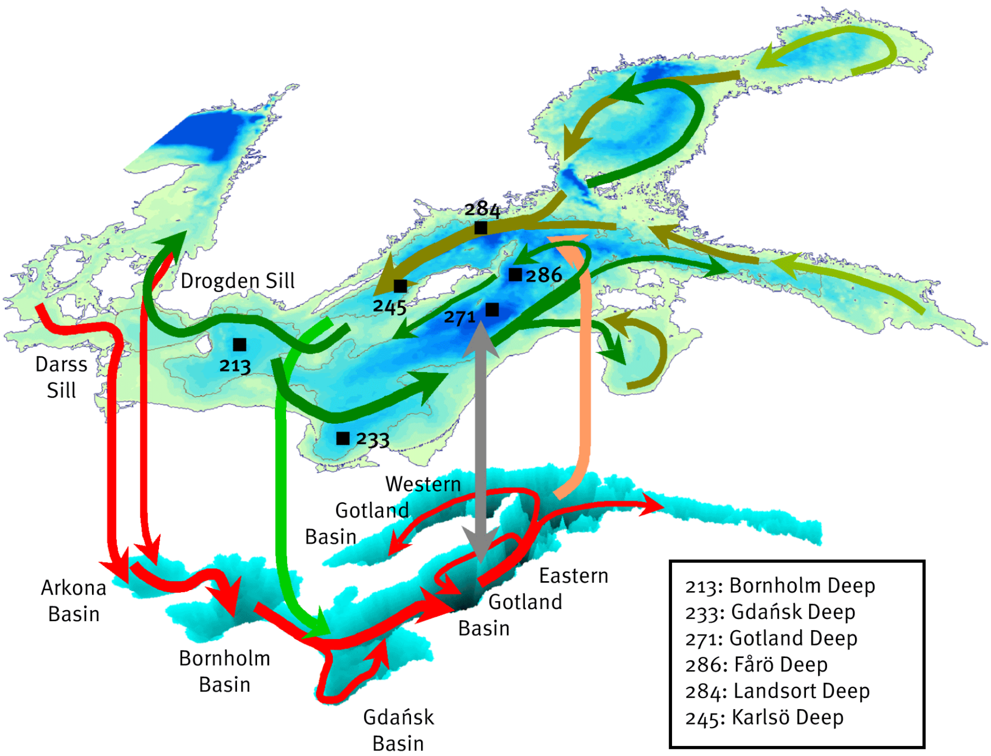

Fig. 1: Schematic of the large-scale circulation in the Baltic Sea (from ELKEN & MATTHÄUS, 2008, modified). Red arrows: Inflow of highly saline water and its circulation in the bottom layer. Numbers are standard hydrographic stations of IOW long-term observations.

WYRTKI (1953, 1954) introduced the German term “Salzeinbruch” for this process which was later renamed into “Salzwassereinbruch” (FRANCKE & NEHRING, 1971). The most frequently used English term is “Major Baltic Inflow” (MBI) introduced by DICKSON (1971, 1973). Due to the fact that MBIs occur only irregularly, periods with oxygenated water in the deep layers alternate with stagnation periods of different durations which are characterized by the occurrence of hydrogen sulphide on monthly, annual or multi-annual timescales.

The schematic view of the large-scale circulation in the Baltic Sea is presented in Fig. 1. Red arrows denote the main transport route of highly saline and oxygenated water. Inflowing water is spread and transformed in the Baltic Proper along the cascade of deep topographic basins. This process is controlled by the flow regime in the sill and channel areas and depends on the stratification existing in the downstream basin areas. Highly saline water flowing into the Arkona Basin forms a near-bottom water pool that baroclinically propagates across the Bornholm Strait further into the Bornholm Basin (St. 213). This basin has a maximum depth of more than 90 m and is separated from the next downstream basin by the Słupsk Sill (saddle depth of 60 m). The buffering properties of the Bornholm Basin with a volume of about 200 km^3 below the sill overflow play an essential part for the effectiveness of MBIs in the other central basins. The thermohaline conditions in the Bornholm Basin are also considerably important for the evolution of stagnation in the central Baltic deep water. The water penetrating during MBIs further downstream into the Gotland Basin interleaves between the halocline and the bottom according to its buoyancy passing counterclockwise around the Island of Gotland the different basins of the Baltic Proper (cf. Fig. 1).

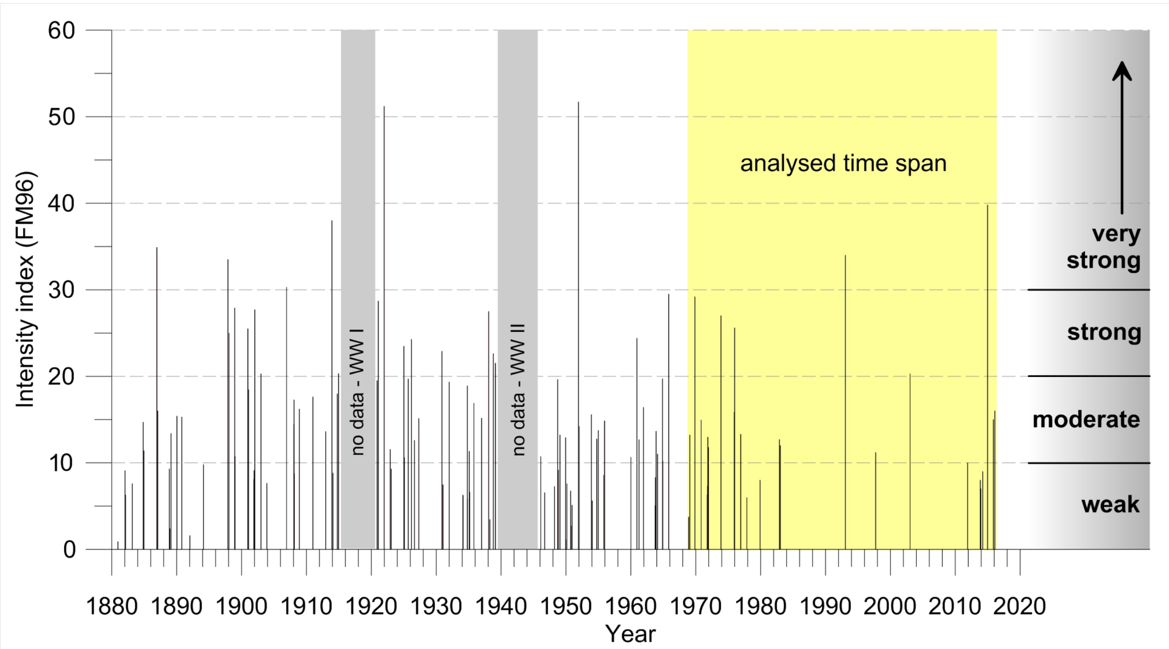

Fig. 2: Intensity index of MBIs between 1880 and 2015 according to MATTHÄUS (2006) extended by data from FEISTEL et al. (2003c), MOHRHOLZ et al. (2015) and NAUMANN et al. (2016). Emphasised part: Period 1969 – 2015.

MBIs were observed more or less regularly between the late 19th century and the mid-1970s (Fig. 2). During the period 1969 - 2015 considered in the following, their frequency and intensity has decreased in the beginning but at least the intensity increased considerably since the 1990s. Three most significant stagnation periods occurred during this period, between 1977 and 1992, between 1995 and 2002 and from 2005 to 2014 mainly in the eastern Gotland Basin (Fig. 3). Since about 2010th, the frequency of inflows of highly saline water seems to increase again (cf. Table 1).

Statistical analysis of MBIs has been done by MATTHÄUS & FRANCK (1992). Causes for the occurrence of MBIs are described by WYRTKI (1954), MATTHÄUS & LASS (1995) and SCHINKE & MATTHÄUS (1998).

The regime shift between oxic conditions and the increased occurrence of hydrogen sulphide in the deep water of the Baltic Proper during the period 1969 – 2015 can be recognized very well in the following maps. This graphical representation of data concerning the distribution of dissolved oxygen and hydrogen sulphide in maps, with marked areas of hypoxic or anoxic regions, is a long-standing tradition at the Leibniz Institute for Baltic Sea Research Warnemünde (IOW) and, before 1992 at its forerunner, the Institute of Marine Research of the GDR Academy of Sciences (IfMW). Those maps were in particular included in regular state assessments published since 1969 (FEISTEL et al., 2008; NAUSCH et al., 2016).

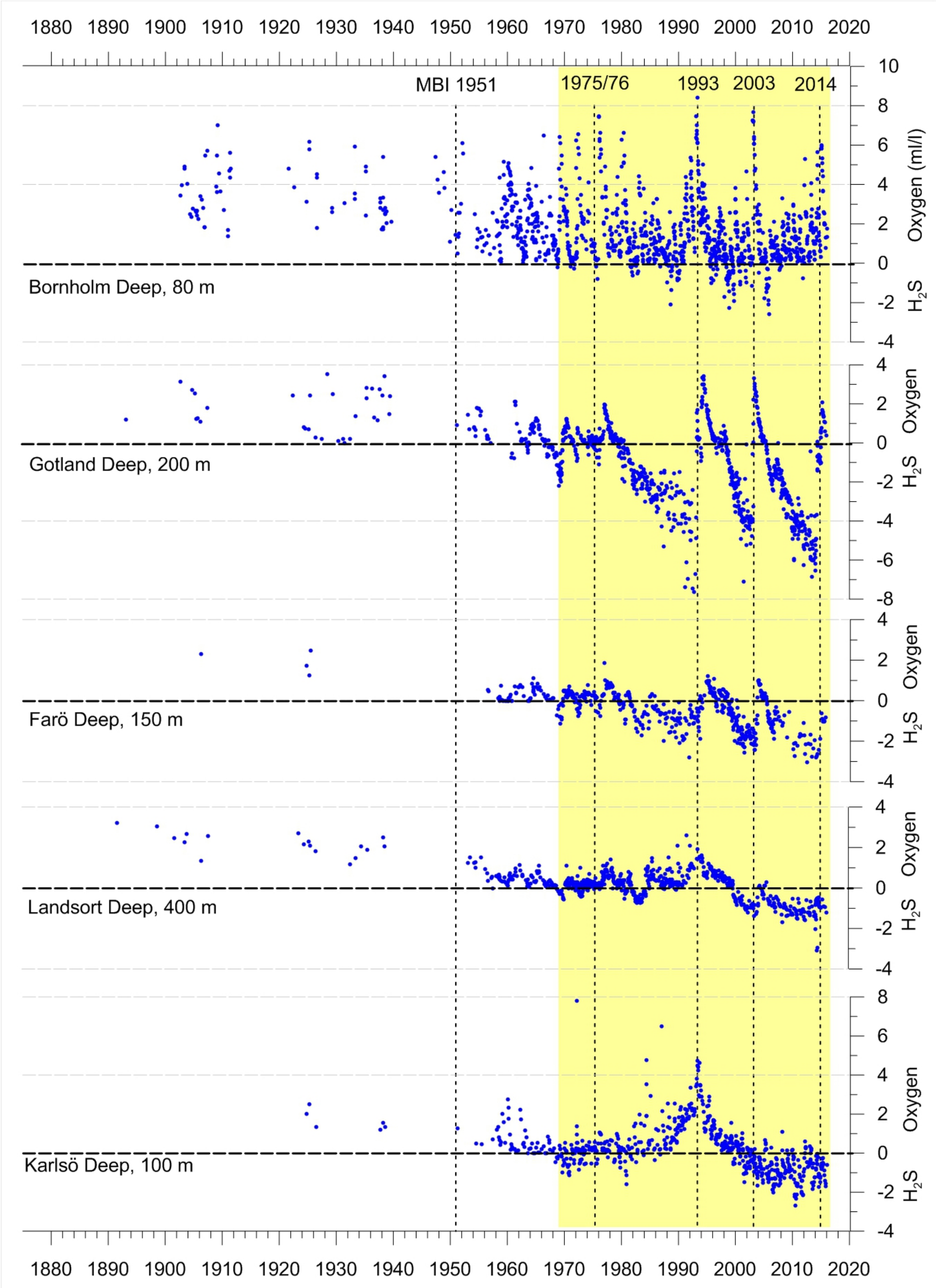

Fig. 3: Long-term variation of oxygen and hydrogen sulphide concentrations in the central Baltic deep water (hydrogen sulphide is converted into negative oxygen equivalents) (MATTHÄUS et al., 2008; supplemented). Emphasised part: Period 1969 – 2015.

Table 1: Major Baltic Inflows between 1969 and 2015 and their intensities Q_{FM96} calculated by means of special criteria defined by MATTHÄUS & FRANCK (1992) and FISCHER & MATTHÄUS (1996), extended by data from FEISTEL et al. (2003c), MOHRHOLZ et al. (2015) and NAUMANN et al. (2016).

Major Baltic Inflows	Intensity	Q_{FM96}	References
Feb 1969	Moderate	13.2	FRANCKE & NEHRING (1971)
Oct/Nov 1969	Strong	29.2	NEHRING & FRANCKE (1971)
Oct/Nov 1970	Moderate	15.0	
Mid-Oct 1971	Weak	6.3	
End of Oct 1971	Weak	7.3	
Nov 1971	Moderate	13.0	
Dec 1971	Moderate	11.8	
Nov 1973	Strong	27.0	FISCHER & MATTHÄUS (1996)
Dec 1975	Moderate	15.8	
Dec 1975/Jan 1976	Strong	25.6	LASS & SCHWABE (1990)
Nov/Dec 1976	Moderate	13.3	NEHRING & FRANCKE (1980a)
Nov 1977	Weak	6.0	
Nov/Dec 1979	Weak	8.0	NEHRING & FRANCKE (1982)
Dec 1982	Moderate	12.7	FRANCKE & NEHRING (1986)
Jan 1983	Moderate	12.0	FRANCKE & NEHRING (1986)
Jan 1993	Very strong	34.0	MATTHÄUS & LASS (1995)
Sep 1997	Moderate	11.2	MATTHÄUS et al. (2008)
Jan 2003	Strong	20.3	FEISTEL et al. (2003c)
Nov/Dec 2011	Moderate	10.0[6]	NAUSCH et al. (2012)
Nov 2013[7]	Weak	8[6]	
Dec 2013[7]	Weak	7[6]	NAUMANN & NAUSCH (2015)
Feb 2014[7]	Weak	4[6]	NAUSCH et al. (2015)
Mar 2014[7]	Weak	9[6]	
Dec 2014	Very strong	39.8[6]	MOHRHOLZ et al. (2015), NAUMANN et al. (2016)
Nov 2015	Moderate	15[6]	NAUMANN et al. (in prep.)
Jan/Feb 2016	Moderate	16[6]	

[6] Estimation of intensity according to the calculated amount of salt transported into the Baltic Sea (FISCHER & MATTHÄUS, 1996)

[7] Inflows do not fulfil the criteria for MBIs (see MATTHÄUS, 2006).

2. Development of the distribution map

Maps of the basin-wide distribution of hydrogen sulphide areas in the Baltic Sea date back to FONSELIUS (1969). Nehring designed the first map of this kind in 1971 (NEHRING & FRANCKE, 1971; FRANCKE & NEHRING, 1971) based on the measurements of the Institute of Marine Research Warnemünde during the International Baltic Year 1969/70 (Fig. 4). From 1991 on, the maps were supplemented by histograms of oxygen and hydrogen sulphide concentrations in the main Baltic basins (NEHRING & MATTHÄUS, 1991/92), as shown in Fig. 5.

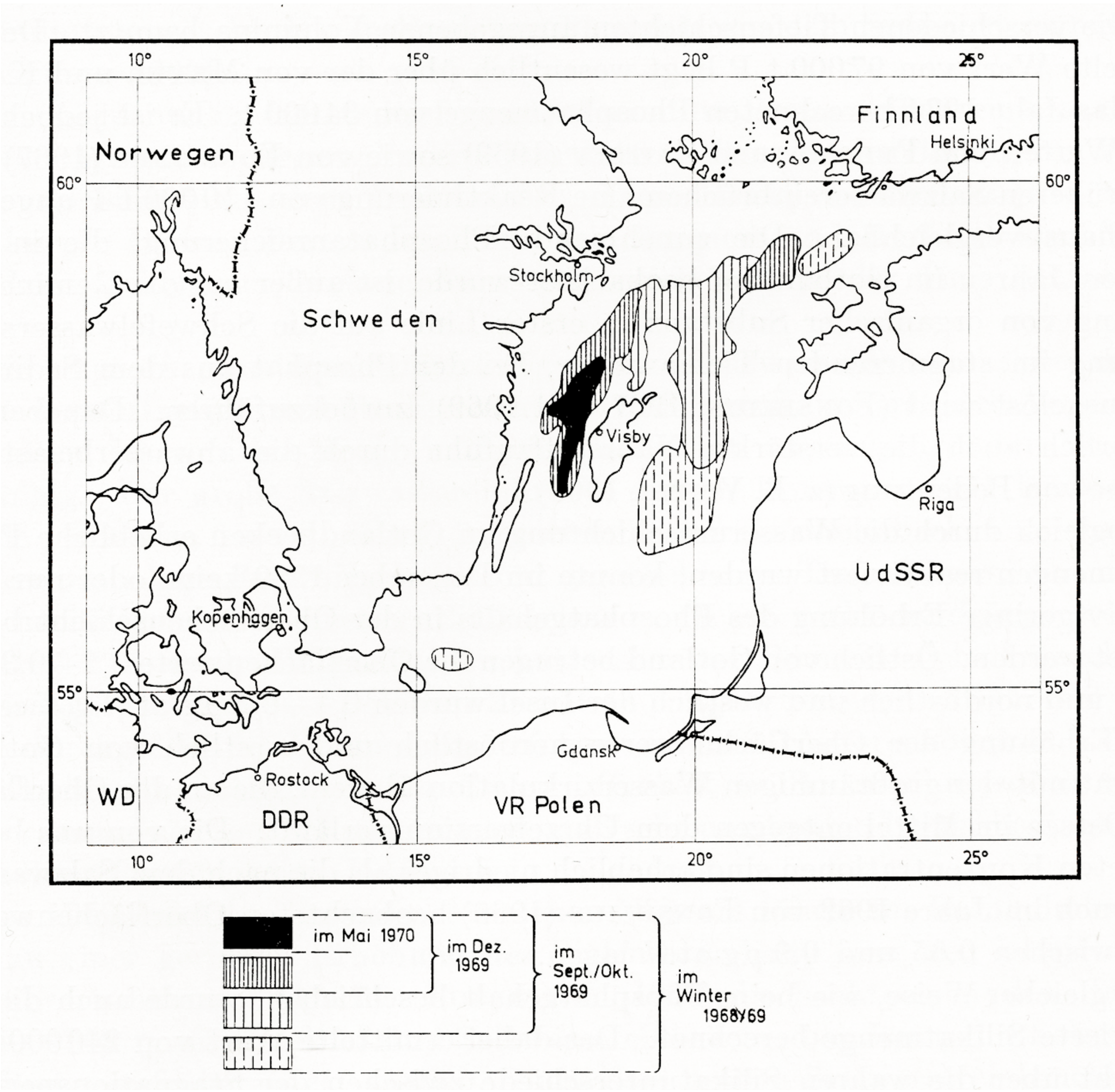

Fig. 4: Manually drawn distribution map of hydrogen sulphide in the bottom layer of the Baltic Sea in 1968 - 1970 (FRANCKE & NEHRING, 1971).

Previously drawn manually with oceanographic knowledge of the Baltic Sea and professional experience, this process was developed into an automatic software tool in 2002 (cf. Fig. 6; NAUSCH et al., 2002).

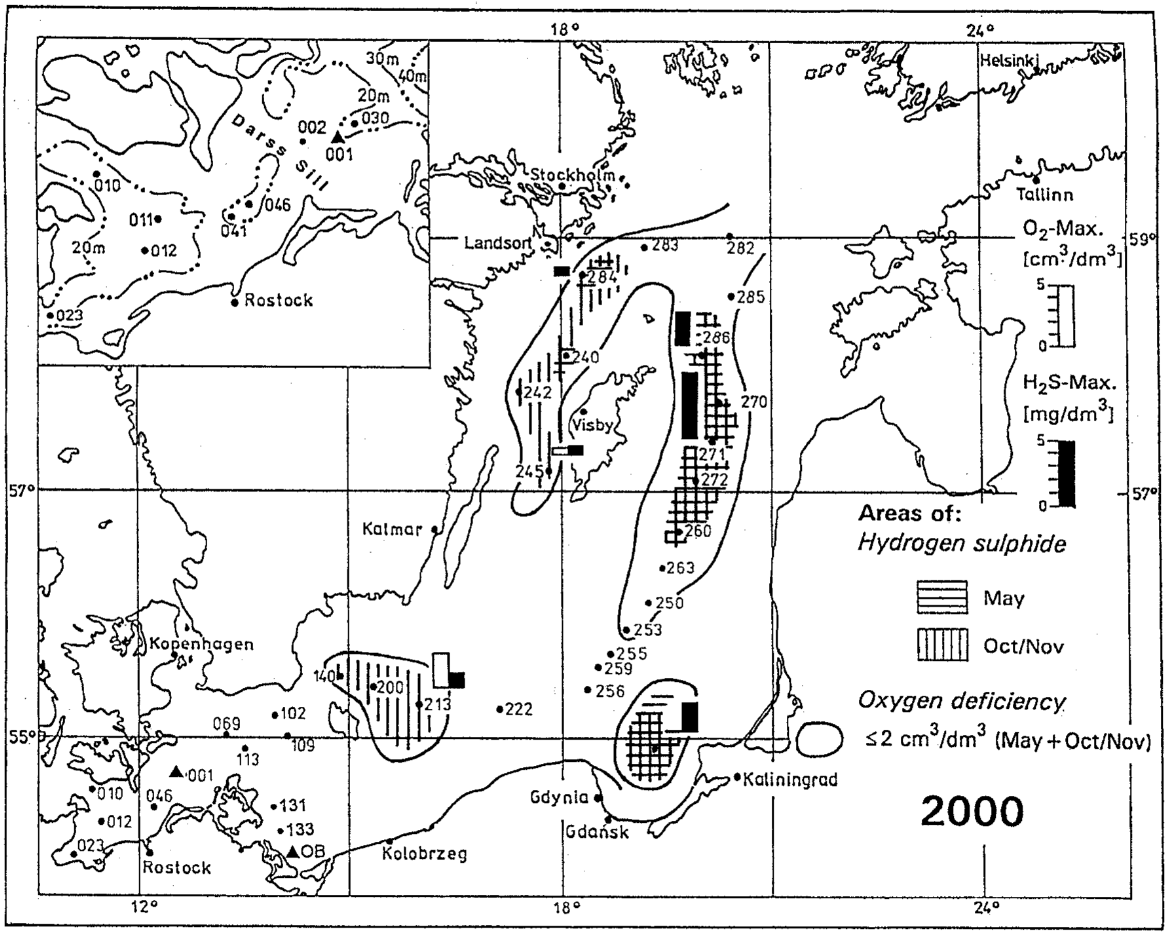

Fig. 5: The last manually drawn map for 2000, including 70 m depth line, striped oxygen deficiency areas, sampled stations and map legend (MATTHÄUS et al., 2001b).

The first software was written in Visual Basic and used standardized textual data input (NAUSCH et al., 2002). With the development of central databases and more advanced programming languages, a modernization of the technology was necessary and became implemented subsequently (NAUSCH et al., 2015). Based on this software tool the maps for hypoxic and anoxic regions in the Baltic Sea from 1969 onwards were digitally redrawn and made available in this atlas for the first time in this less subjective form.

The current version of the mapping program was implemented using the programming language PHP version 5.6[8]. It utilizes the RANGS dataset (FEISTEL, 1999; FEISTEL et al., 2008) for shoreline information, IOWTOPO for bathymetric information (SEIFERT & KAYSER, 1995; SEIFERT et al., 2001) and an interface to IOW's oceanographic database IOWDB (FEISTEL et al., 2008) for the hydrochemical research data.

[8] PHP: Hypertext Preprocessor, server-side scripting language, https://en.wikipedia.org/wiki/PHP (accessed June 13th, 2016)

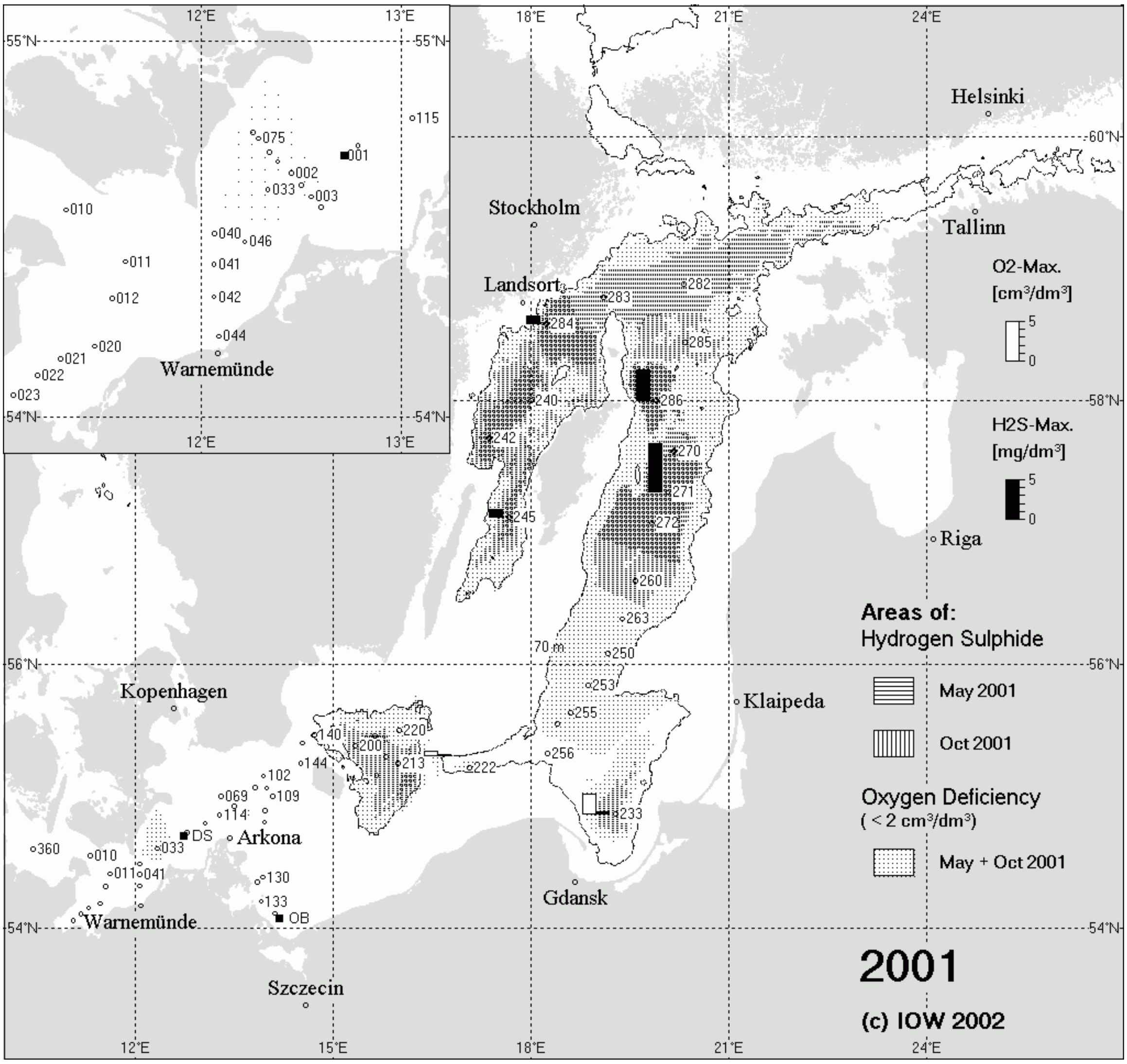

Fig. 6: First computed distribution map of low oxygen concentrations and hydrogen sulphide in the bottom layer of the Baltic Sea in 2001 (NAUSCH et al., 2002)

3. Map basis

3.1 RANGS / GSHHS

The dataset of "Regionally Accessible Nested Global Shorelines" (RANGS) makes "Global Self-consistent, Hierarchical, High-resolution Shoreline Database" (GSHHS) (WESSEL & SMITH, 1996) accessible in the form of closed nested polygons within each 1 ° x 1 ° grid cell of the global surface. A PHP interface was implemented to read out the RANGS data for a 1 ° x 1 ° grid cell and supply it to subsequent mapping. Building on this interface a software tool was created that transforms the polygon data from RANGS into polygons displayable by an image viewer. The RANGS dataset contains five resolutions for the shoreline data – ‹100 m, 200 m, 1 km, 5 km, 25 km – all of which can be used to create the basic map.

RANGS data are freely available from the digital supplement of FEISTEL et al. (2008) and from the IOW online mediathek[9].

3.2 IOWTOPO

For the digital topography IOWTOPO, gridded bathymetric datasets of the Baltic Sea and the Belt Sea were sampled from nautical sea charts. Available datasets of water depths and land heights were mapped onto a regular grid with a resolution of 2 ' in geographical longitude and 1 ' in latitude, which covers the whole Baltic Sea between 9 °E - 31 °E and 53 ° 30 'N - 66 °N. For the Belt Sea region in the rectangle 9 °E - 15 ° 10 'E and 53 ° 30 'N - 56 ° 30 'N, a sub-grid with a higher resolution of 1 ' in longitude and 30 '' in latitude is provided. The data are referenced by WGS-84 coordinates (FEISTEL et al., 2008) and are pointing to the centers of the grid cells. A PHP interface was implemented to read out the IOWTOPO data for any coordinates and supply it to subsequent mapping.

IOWTOPO data are available from the digital supplement of FEISTEL et al. (2008) and from the IOW online mediathek[10].

3.3 SVG

For the map graphics, an easily editable format SVG (ALEXANDER, 2002) was chosen. SVG has several advantages: it is highly adaptable, lossless resizable, web compatible and XML-based. A PHP interface was built to write the SVG-tags into a newly created XML-file. PHP's DOM[11] extension offers an easy way to create and export error-free XML documents.

3.4 Basic map creation

All following examples are based on a map with the size 800 px by 800 px, a section of the Baltic Sea with longitude 10 °E to 27 °E and latitude 52 °N to 60 °N and a RANGS resolution level of 3 (5 km).

The shoreline polygons in the RANGS dataset are ordered by the above mentioned 1 ° x 1 ° grid, the geographic information is layered with the first layer being ocean, the second layer land in ocean, the third layer is lakes on land and so on. This layering is directly translated to layers within the SVG file.

[9] Download RANGS at http://www.io-warnemuende.de/rangs.html (accessed June 13th, 2016)
[10] Download IOWTOPO at http://www.io-warnemuende.de/topography-of-the-baltic-sea.html (accessed June 13th, 2016)
[11] DOM: Document Object Model, https://de.wikipedia.org/wiki/Document_Object_Model (accessed June 13th, 2016)

For the generation of a basic underlying map the boundaries of the image are associated with the intended geographic extent of the new map. This serves as a calibration to match pixel positions in the image to definite geographic coordinates.

Subsequently the layers are assembled for each 1 ° x 1 ° grid cell as illustrated by the examples in Fig. 7.

```
1  <?xml version="1.0"?>
2  <svg xmlns="http://www.w3.org/2000/svg" version="1.1" baseProfile="full" width="801" height="801">
3
4      <rect x="329" y="0" width="47" height="100" style="fill: #91d4ee;"/>
5      <rect x="0" y="0" width="47" height="100" style="fill: #54a04b;"/>
6
7      <polygon fill="#54a04b" style="" points="47 25.3681, 47 28.4367, 47.979151 28.8889, 47.443868
       25.5556"/>
8      <polygon fill="#6da5f2" style="" points="235 78.9528, 235 81.6933, 232.284434 81.6389, 231.448868
       79.3056, 234.751934 79.75"/>
9
10     <polyline points="514.79950089 120.833, 515.48248797 122.5, 514.65 123.342054, 514.12969496 122.5,
       513.08349 120.867911, 513.06352863 120.833, 513.08349 120.770132, 514.65 120.596469, 514.79950089
       120.833" style="stroke: #395780; stroke-width: 0.5; fill: #91d4ee;"/>
11     <rect x="287.5" y="596.33333333333" width="16" height="8" style="fill: #91d4ee; fill-opacity: 1;"/>
12     <text x="287.5" y="602.75" style="font-family:arial,verdana; font-size:8px; font-weight:normal;
       color: #395780;">70m</text>
13
14     <rect x="419" y="404" width="1" height="1" style="fill: #ff0000; fill-opacity: 1;"/>
15     <rect x="420" y="208" width="1" height="1" style="fill: #395780; fill-opacity: 1;"/>
16
17     <circle cx="98.274494117647" cy="682.4722" r="2" style="fill: black;"/>
18     <text x="74.074494117647" y="696.4722" style="font-family:arial,verdana; font-size:11px;
       font-weight:normal; color: #000000;">Warnem&#xFC;nde</text>
19
20     <circle cx="126.54903529412" cy="630.3835" r="2" style="fill: #91d4ee; stroke: #000000;
       stroke-width: 0.4;"/>
21     <rect x="132.04903529412" y="626.71683333333" width="16" height="8" style="fill: #91d4ee;
       fill-opacity: 1;"/>
22     <text x="132.04903529412" y="633.1335" style="font-family:arial,verdana; font-size:8px;
       font-weight:normal; color: #000000;">001</text>
23 </svg>
```

Fig. 7: Example lines from the source code of the created SVG file.

- Line 2: base tag ‹svg› declares svg-standard and the size of the image
- Line 4: rectangle tag for ocean layer, declaring offset and size
- Line 5: rectangle tag for land layer, declaring offset and size
- Line 7: polygon tag for ocean layer, listing polygon points
- Line 8: polygon tag for lake on land layer, listing polygon points
- Lines 10-12: polygon, rectangle and text tags to display a 70 m depth line
- Lines 14, 15: rectangle tags (dots) to demarcate hypoxic and anoxic areas
- Lines 17, 18: circle and text tag to mark cities
- Lines 20-22: circle, rectangle and text tag to mark sampled stations

This new mapping tool provides digital maps for any region on earth in optionally any of the five resolutions offered by RANGS, including the Baltic Sea region as shown in Fig. 8. The created vector graphic is editable with any software application capable of processing vector-based images.

Fig. 8: Blank map of a section of the Baltic Sea (10 ° E to 27 ° E and 52 ° N to 60 ° N; RANGS resolution level 3), resized from 800 px by 800 px.

4. Data basis

4.1 Baltic Monitoring Programme

The basis for each distribution map showing regions of oxygen deficiency is the data collected during the five seasonal monitoring cruises of the IOW. After each cruise, the oxygen and hydrogen sulphide data collected are routinely validated by automatically applied plausibility checks and by expert review.

4.2 Monitoring stations

A fixed set of standard stations from HELCOM's Baltic Monitoring Programme is used to extrapolate the areal extension of oxygen deficiency. The complete list of these stations and their positions are given in the appendix in Table 2 and Fig. 13. All stations from this list are by default included in the representation as long as they were actually sampled. Problems arise if a significant number of stations could not be sampled, as explained in chapter 6. The predefinition of stations improves later comparability between the distribution maps.

A map with an extended set of sampled stations is shown in Fig. 14. The spatial resolution in the eastern Gotland Basin is vastly improved through the additional stations GB_*. The front of the inflow water is clearly extending along the eastern side of the basin. This detail is not resolved in the map with standard stations (Fig. 61). This problem is also further explained in chapter 6.

Until 1980, the stations in the Gdańsk Basin and in the south-western Gotland Basin were regularly sampled by IOW vessels. From 1980 to 1990 and from 2000 on, this task was undertaken by the Polish Institute of Meteorology and Water Management in Gdynia (IMGW).

4.3 Oceanographic Database IOWDB

The oceanographic database of the IOW, the "IOWDB", is used to organize, store and redistribute measurement data and associated metadata. The processed and validated oxygen data for the Baltic Proper from the regular seasonal monitoring cruises since 1969 are available in structured and harmonized form. New cruise data is imported into the IOWDB as soon as the validation process is complete.

Through SQL[12], the database offers multiple options to retrieve, structure and process the data.

4.4 Interchange format

A PHP interface was built to retrieve the relevant hydrochemical data from IOWDB and transcribe it into an interchange format, a so-called level file. This file is manually editable in order to provide a robust tool for checking or correcting questionable data, or including additional data, such as those kindly provided by Polish colleagues.

The level file contains for every surveyed station the depth levels where hypoxia and anoxia were found, as well as the observed values at these depths. The level file offers the option to combine the measurements of two different cruises, for example the winter and summer situations of a given year, for convenient comparison of the seasonal differences. In the example below (Fig. 9), "z(O2‹2)" is the smallest depth where oxygen less than 2 ml/l is found (in any of the cruises), "z(H2S 1)" and "z(H2S 2)", respectively, are the smallest depths where hydrogen sulphide was detected during cruise 1 and 2, and "Btm.O2max", "Btm.H2Smax" are the highest measured near-bottom values (of both cruises) of oxygen and hydrogen sulphide, respectively.

[12] SQL: structured query language, https://de.wikipedia.org/wiki/SQL (accessed June 13th, 2016)

```
H2S&O2, Level File
Version , 1.0
Cruise 1, 11, 2015
Cruise 2,
Stn, Lon,       Lat,       z(O2<2), z(H2S 1), z(H2S 2), Btm.O2max, Btm.H2Smax
001,12.710628,54.696155,999,999,999,6.49,
002,12.450832,54.650433,999,999,999,5.75,
...
271,20.050332,57.320015,80.41,999,999,0.1,
285,20.333120,58.441352,80.38,100.39,999,0.42,1.07
286,19.900188,58.000002,70.38,90.4,999,0.24,1.14
360,10.452572,54.600162,999,999,999,3.37,
361,10.769240,54.658305,999,999,999,5.21,
```

Fig. 9: A section from a level file. The file contains cruise information and column headers at the top, followed by one data row per station.

5. Graphical representation

The blank map created in chapter 3 and the data assembled in chapter 4 build the basis for the lateral distribution map. For each new map, the processing starts in the upper left corner of the map and continues horizontally until the "end of the line", re-starting in the next line below (Fig. 10), analogous to western-style writing. The grid cells of the map and the pixels nested within each cell are processed analogously, each one separately. Only after one grid cell is finished the next one gets processed.

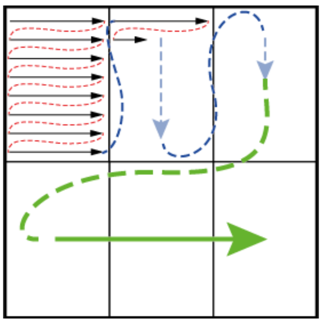

Fig. 10: Processing order

The pixel coordinates are first converted to geographic coordinates depending on the map scale. The digital topography of the Baltic Sea is used to determine whether the geographic position is on land or in water. In the latter case the maximum water depth found within the pixel cell is assigned to these coordinates. Coordinates on land are no further processed.

In the next steps the coordinates are matched to a water column (Fig. 11) horizontally associated with the nearest surveyed station. From that station either the measurement value of oxygen, if less than 2 ml/l, or the hydrogen sulphide value is taken at the maximum depth of the currently processed coordinates.

This is repeated for every pixel of every grid cell of the map, and the result is an array of pixel coordinates with the added information about extrapolated near-bottom oxygen or hydrogen sulphide content at that position. Subsequently, this information is illustrated by a graphic marking (dark dots for hypoxia (SVG: 1 px * 1 px rectangles every three by three pixels), red lines for anoxia (SVG: 1 px * 1 px rectangles every four vertical pixels)). Lines are drawn either zonally or meridionally to distinguish between the oxygen deficiency regions of the two cruises separately.

The result is a top view of hypoxic and anoxic areas in near-bottom layer of the Baltic Sea, isobathically extrapolated from the surveyed stations. The extrapolation from any one station is limited by the regions as defined by FEISTEL et al. (2008) (Fig. 12), such that, for example, values from the eastern Gotland Basin are prevented from influencing the representation of the western Gotland Basin.

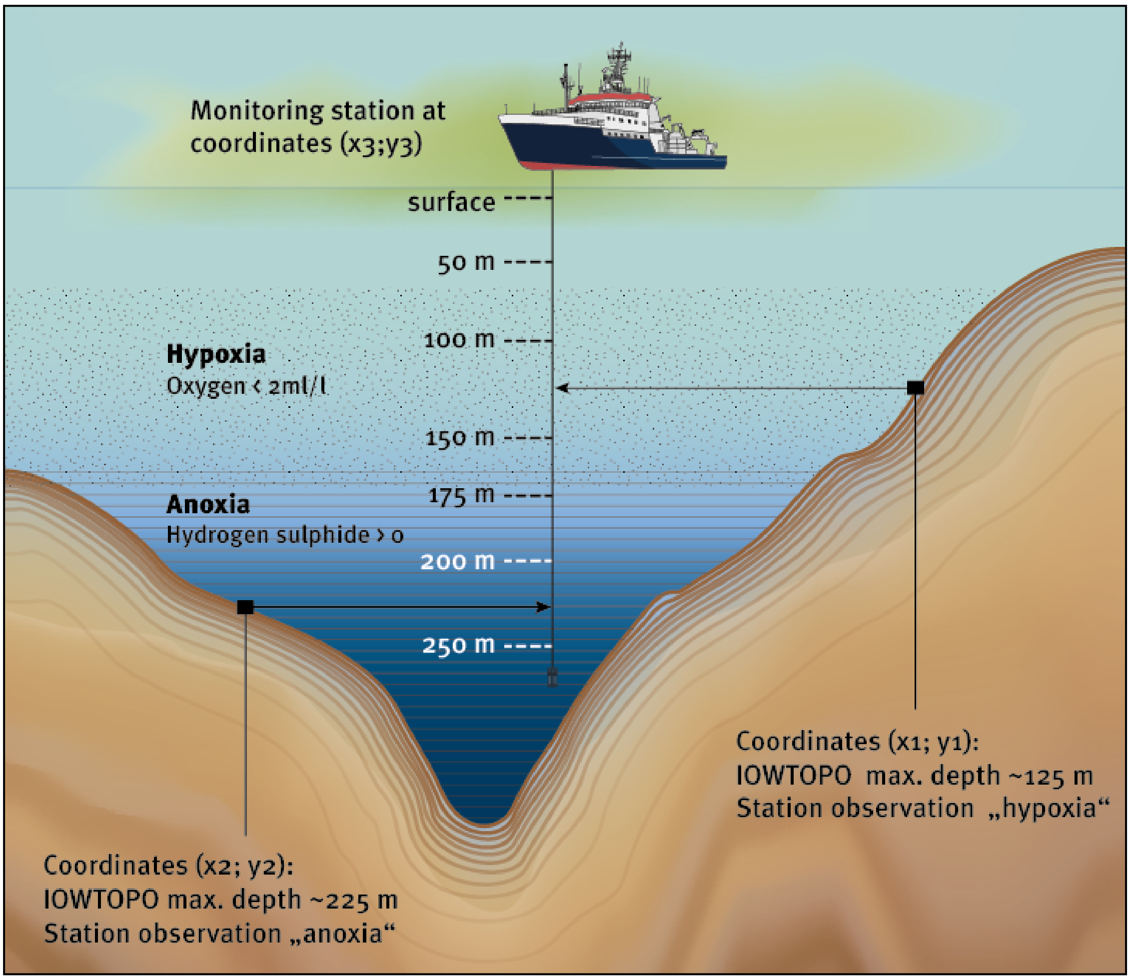

Fig. 11: For the pixel coordinates (x1; y1) the geographical coordinates are calculated. According to IOWTOPO, let the Baltic Sea at these coordinates have a maximum depth of 125 m. For the coordinates (x1;y1) the nearest sampled station is found at the coordinates (x3;y3). The observation from the monitoring station at depth 125 m was, say an oxygen value of less than 2 ml/l (hypoxic conditions). On the other hand, the coordinates at (x2;y2) may correlate with a maximum depth of 225 m, where hydrogen sulphide was observed and anoxic conditions prevail.

Stations included in the analysis are marked with a black circle at their positions. Final steps in processing are the marking of distinct oxygen and hydrogen sulphide values at key stations (213: Bornholm Deep; 133: Gdańsk Deep; 271: Gotland Deep; 284: Landsort Deep; 286: Fårö Deep; 245: Karlsö Deep), the drawing of gridlines, cities and scales as well as the surveyed time frame and copyright information.

6. Known issues and further development

The described mapping method poses a few systematic difficulties, but also opens options for further analyses. A graphic representation like this reduces a 3D-body down to a 2D-surface. Here, the properties (depth, O_2, H_2S) of the near-bottom layer are taken as representatives for the graphical representation of the entire body of water above. The major drawback of this approach is that any stratification details are reduced to just three indicator properties – near-bottom H_2S and O_2 concentration, plus the redoxcline depth, regardless of vertical profiles such as of nutrients, salinity or temperature. Especially during the multiple inflow events between 2013 and 2016, the mapping cannot adequately represent the associated complex processes and structures of relevance. This simplification of actual events will always need additional scientific interpretation of the historical and dynamical context.

The limited spatial sampling resolution and the comparability between different sets of stations pose another problem. The mapping tool was first created to replace a subjective representation of oxygen-deficiency patterns by an objective, repeatable and transparent/traceable method. Subjective, intuitive interpolation of values and distribution areas was substituted by algorithms and clear allocations. There are significant differences between the early hand-drawn maps and the newly generated maps (see Fig. 19, Fig. 20, NEHRING & FRANCKE, 1975). These differences can only be explained by later objective quality control. During early cruises, the sulphuric smell of a sample was noted but not actually measured, and such qualitative observations are not registered as measured values in the database. Thus this subjective information is actually lost.

In an ideal world, the fixed set of stations listed in Table 2 is always completely surveyed, making each map comparable to the other. But especially in autumn and winter cruises it is often the case that stations in the central Baltic Sea are skipped due to bad weather or changes in the cruise planning. An example for such practical difficulties can be seen in 2015 with the cruises of May and November, and the combined map of both. In May all regular stations were processed. The northern Baltic Proper displays a sizable extent of anoxic conditions but limited to depths below 100 m at station 283 and to 120 m at station 285. In contrast, in November the sampling of the entire western Gotland Basin starting with station 283 is missing. In the single-cruise map of November, the values of station 285 are extrapolated to cover the entire northern Gotland Basin. The extrapolation is limited by the area definition around Landsort Deep whereas in May it is limited by the extrapolated values from station 283, south-east of Stockholm. Further south the western Gotland Basin falsly seems oxygenated due to no data being displayed the same way as oxygenated areas. This problem remains to be solved.

The confusing effect of ambiguous extrapolation borders can also be seen in the combined map of spring/autumn 2015 (Fig. 61). The extrapolation of November values is limited by the sampled May station 283, thus suggesting that in November the water column at 283 was oxygenated even though there is no data available and probably high concentrations of H_2S were (unnoticedly) present. This way, combined maps with mutually different missing stations may suggest misleading conclusions to be drawn.

An example for an alternative problem is an extended set of stations – as seen in Fig. 14. Due to several additional survey stations, the front of the inflow water in the eastern Gotland Basin is better resolved than by the standard set of stations.

One of the next aims will be the transfer of these map products into file formats used by geo-information-systems (e.g. Shapefile). It allows the calculation of areas affected by oxygen deficiency and makes them available for broader applications in interaction with other kind of data like fish stocks, distribution of nutrients and so on. Finally the maps can be supplied in a web-mapping-service, updated with results after every ship expedition to support a wide network of users in environmental science, public authorities and NGO's.

Summary

For more than 50 years, scientists at IOW and its predecessor institute have supplied multiple maps per year to substantiate regular, annual and long-term assessments on the status of the Baltic Sea. The Baltic Sea is a complex ecosystem characterized by a strongly fluctuating, fragile balance between high freshwater runoff and saline water inflows, a stable stratification and a topography composed of connected basins.

The sensitivity of the system "Baltic Sea" amplifies climatological fluctuations on the decadal scale. Such changes may be irrelevant in the open ocean but constitute significant indicators in the Baltic Sea. Salt and nutrients in the Baltic Sea remain present there for 20 and more years before being flushed to the Atlantic along with the freshwater export. This long residence time attenuates short-time fluctuations in environmental conditions, but highlights systematic, even small long-term anomalies. The maps in this publication allow a visual evaluation of systematic changes, of inflow events, of the progress of oxygen-consuming processes and of the development of hydrogen sulphide distributions over longer periods of time.

The process of producing these maps is in continuous development. It started as a map drawn manually with oceanographic knowledge of the Baltic Sea and professional experience. The currently used method is a database- and software-based, transparent and reproducible way to represent the distribution of hypoxic and anoxic water in the near-bottom layer of the Baltic Sea. It represents a reasonable estimate of the real situation based on data from about 60 more or less evenly spaced monitoring stations. The algorithms applied perform an intentionally simplified interpolation procedure from these relatively small, systematically under-sampled set of data points. The mutual comparability between different maps depends on comparable data from a defined list of sampling stations (Table 2). Scientific analyses like this require regular sampling with comparable methods at standardized stations, systematically repeated over extended periods of time. Fewer sampled stations in this network would severely impair future comparability.

The datasets of IOWTOPO and RANGS form the framework for all created maps. IOW's oceanographic database IOWDB serves as the standard primary data source and contains validated oxygen and hydrogen sulphide data from the regular seasonal monitoring cruises that have visited the central Baltic Sea since 1969. A numerical interchange format allows editing and extension of the data in-between data compilation from the database, and ultimate graphic representation. Integration of different data sources is possible in the database or in the interchange format. The interface to this data source allows uniform, comparable mapping of harmonized, quality-controlled datasets in retrospect.

The final graphic is created in XML-based format SVG and editable in any text editor. Furthermore SVG is a vector graphic that is editable with any software application capable of

processing vector graphics. For publication in print and web it is subsequently converted to appropriate graphic formats.

The SVG format is available for download at http://www.io-warnemuende.de/msr-2016-0100/.

Acknowledgement

The authors thank ELZBIETA ŁYSIAK-PASTUSZAK at the Maritime Branch of the Polish Institute of Meteorology and Water Management in Gdynia (IMGW) for the continued cooperation in exchanging monitoring data.

References

ALEXANDER, A., 2002: SVG, Scalable Vector Graphics. Franzis Verlag, 2002, ISBN 978-3-7723-6190-6.

DICKSON, R.R., 1971: A recurrent and persistent pressure-anomaly as the principal cause of intermediate-scale hydrographic variations in the European shelf seas. – Dtsch. Hydrogr. Z., **24**, 97-119.

DICKSON, R.R., 1973: The prediction of major Baltic inflows. – Dtsch. Hydrogr. Z., **26**, 97-105.

ELKEN, J., MATTHÄUS, W., 2008: Baltic Sea oceanography. In: Assessment of the Climate Change for the Baltic Sea Basin. Springer-Verlag, Berlin, Heidelberg, 379-386.

FEISTEL, R., 1999: New Shoreline Map-Drawing Data Available. Eos, June 1, 1999, Vol. **80**, No.22, p. 249. Eos, Transactions, American Geophysical Union, Electronic Supplement, June 7, 1999, http://www.io-warnemuende.de/rangs.html, https://www.researchgate.net/publication/248818434_New_shoreline_map-drawing_data_available (accessed June 13th, 2016)

FEISTEL, R., NAUSCH, G., MATTHÄUS, W., HAGEN, E., 2003a: The Baltic inflow of autumn 2001. – Meereswiss. Ber., Warnemünde, **54**, 55-68, doi: 10.12754/msr-2003-0054.

FEISTEL, R., NAUSCH, G., MOHRHOLZ, V., ŁYSIAK-PASTUSZAK, E., SEIFERT, T., MATTHÄUS, W., KRÜGER, S., SEHESTED HANSEN, I., 2003b: Warm Waters of Summer 2002 in the Deep Baltic Proper. Oceanologia, **45(4)**, 571-592.

FEISTEL, R., NAUSCH, G., MATTHÄUS, W., HAGEN, E., 2003c: Temporal and spatial evolution of the Baltic deep water renewal in spring 2003. – Oceanologia, **45**, 623-642, http://www.iopan.gda.pl/oceanologia/454feis2.pdf (accessed June 13th, 2016)

FEISTEL, R., NAUSCH, G., MATTHÄUS, W., ŁYSIAK-PASTUSZAK, E., SEIFERT, T., SEHESTED HANSEN, I., MOHRHOLZ, V., KRÜGER, S., BUCH, E., HAGEN, E., 2004: Background Data to the Exceptionally Warm Inflow into the Baltic Sea in Late Summer of 2002. – Meereswiss. Ber., Warnemünde, **58**, 1-58, doi: 10.12754/msr-2004-0058.

FEISTEL, R., SEIFERT, T., FEISTEL, S., NAUSCH, G., BOGDANSKA, B., BROMAN, B., HANSEN, L., HOLFORT, J., MOHRHOLZ, V., SCHMAGER, G., HAGEN, E., PERLET, I., WASMUND, N., 2008: Digital Supplement. In: FEISTEL, R., NAUSCH, G., WASMUND, N. (eds.): State and Evolution of the Baltic Sea, 1952–2005. John Wiley & Sons, Hoboken, NJ, 625-667.

FISCHER, H., MATTHÄUS, W., 1996: The importance of the Drogden Sill in the Sound for major Baltic inflows. – J. Mar. Res., **9,** 137-157.

FONSELIUS, S. H., 1969: Hydrography of the Baltic deep basins III. – Fishery Board of Sweden, Series Hydrography, Rep. No. **23**, 1-97.

FRANCKE, E., NEHRING, D., 1971: Erste Beobachtungen über einen erneuten Salzwassereinbruch in die Ostsee im Februar 1969. – Beitr. Meereskd., Berlin, **28**, 33-47.

FRANCKE, E., NEHRING, D., 1986: The salt water inflow in autumn 1982 and in winter 1982/83 – the beginning of a renewed change in the marine environment of the Baltic Sea in 1983. Symposium on Ecological Investigations of the Baltic Sea Environment, Riga 16-19 March 1983, 148-160.

HAGEN, E., FEISTEL, R., 2001: Spreading of Baltic Deep Water: A Case Study for the Winter 1997-1998. – Meereswiss. Ber., Warnemünde, **45**, 99-133, doi: 10.12754/msr-2001-0045.

LASS, H. U., SCHWABE, R., 1990: An analysis of the salt water inflow into the Baltic in 1975 to 1976. – Dtsch. Hydrogr. Z., **43**, 97-125.

MATTHÄUS, W., FRANCK, H., 1992: Characteristics of major Baltic inflows - a statistical analysis. – Cont. Shelf Res., **12**, 1375-1400;

MATTHÄUS, W., LASS, H. U., 1995: The recent salt inflow into the Baltic Sea. – J. Phys. Oceanogr., **25**, 280-286.

MATTHÄUS, W., NEHRING, D., LASS, H. U., NAUSCH, G., NAGEL, K., SIEGEL, H., 1996: The Baltic Sea in 1996 – Continuation of stagnation and decreasing phosphate concentrations. – Dtsch. Hydrogr. Z., **48**, 161-174.

MATTHÄUS, W., NEHRING, D., LASS, H. U., NAUSCH, G., NAGEL, K., SIEGEL, H., 1997: Hydrographisch-chemische Zustandseinschätzung der Ostsee 1996. – Meereswiss. Ber., Warnemünde, **24**, 1-49, doi: 10.12754/msr-1997-0024.

MATTHÄUS, W., NAUSCH, G., LASS, H. U., NAGEL, K., SIEGEL, H., 1998a: The Baltic Sea in 1997 – Impacts of the extremely warm summer and of the exceptional Oder flood. – Dtsch. Hydrogr. Z., **50**, 45-67.

MATTHÄUS, W., NAUSCH, G., LASS, H. U., NAGEL, K., SIEGEL, H., 1998b: Hydrographisch-chemische Zustandseinschätzung der Ostsee 1997. – Meereswiss. Ber., Warnemünde, **29**, 1-65, doi: 10.12754/msr-1998-0029.

MATTHÄUS, W., NAUSCH, G., LASS, H. U., NAGEL, K., SIEGEL, H., 1999a: The Baltic Sea in 1998 – Characteristic features of the current stagnation period, nutrient conditions in the surface layer and exceptionally high deep water temperature. – Dtsch. Hydrogr. Z., **51**, 67-84.

MATTHÄUS, W., NAUSCH, G., LASS, H. U., NAGEL, K., SIEGEL, H., 1999b: Hydrographisch-chemische Zustandseinschätzung der Ostsee 1998. – Meereswiss. Ber., Warnemünde, **35**, 1-69, doi: 10.12754/msr-1999-0035.

MATTHÄUS, W., NAUSCH, G., LASS, H. U., NAGEL, K., SIEGEL, H., 2000: Hydrographisch-chemische Zustandseinschätzung der Ostsee 1999. – Meereswiss. Ber., Warnemünde, **39**, 1-73, doi: 10.12754/msr-2000-0039.

MATTHÄUS, W., NAUSCH, G., LASS, H. U., NAGEL, K., SIEGEL, H., 2001a: The Baltic Sea in 1999 – Stabilization of nutrient concentrations in the surface water and increasing extent of oxygen deficiency in the central Baltic deep water. – Meereswiss. Ber., Warnemünde, **45**, 3-25, doi: 10.12754/msr-2001-0045.

MATTHÄUS, W., NAUSCH, G., LASS, H. U., NAGEL, K., SIEGEL, H., 2001b: Hydrographisch-chemische Zustandseinschätzung der Ostsee 2000. – Meereswiss. Ber., Warnemünde, **45**, 27-88, doi: 10.12754/msr-2001-0045.

MATTHÄUS, W., NAUSCH, G., LASS, H. U., NAGEL, K., SIEGEL, H., 2001c: The Baltic Sea in 2000 – Low inflow activity caused an increase in stagnation of the central Baltic deep water. – Meereswiss. Ber., Warnemünde, **45**, 89-97, doi: 10.12754/msr-2001-0045.

MATTHÄUS, W., 2006: The history of investigation of salt water inflows into the Baltic Sea – from the early beginning to recent results. – Meereswiss. Ber., Warnemünde, **65**, 1-73, doi: 10.12754/msr-2006-0065.

MATTHÄUS, W., NEHRING, D., FEISTEL, R., NAUSCH, G., MOHRHOLZ, V., LASS, H.U., 2008: The inflow of highly saline water into the Baltic Sea. – In: FEISTEL, R., NAUSCH, G., WASMUND, N. (Eds.) State and Evolution of the Baltic Sea, 1952-2005. John Wiley & Sons, Inc. Hoboken, New Jersey, 265-309.

MOHRHOLZ, V., NAUMANN, M., NAUSCH, G., KRÜGER, S., GRÄWE, U., 2015: Fresh oxygen for the Baltic Sea – An exceptional saline inflow after a decade of stagnation. – J. Mar. Syst. **148**, 152-166, doi: 10.1016/j.jmarsys.2015.03.005.

NAUMANN, M., NAUSCH, G., 2015: Salzwassereinstrom 2014 – Die Ostsee atmet auf (english title: The Baltic Sea is breathing on – Salt Water Inlet 2014). – Chem. unserer Zeit, **49** **(1)**, 76-80.

NAUMANN, M.; NAUSCH, G.; SCHULZ-VOGT, H.; DONATH, J.; FEISTEL, S.; GOGINA, M.; MOHRHOLZ, V.; PRIEN, R.; SCHMIDT, M.; UMLAUF, L.; WANIEK, J.J.; WASMUND, N.; SCHULZ-BULL, D. (in review): A major oxygenation event in the Baltic Sea. – Sci. Rep.

NAUMANN, M.; NAUSCH, G.; MOHRHOLZ, V.; GRÄWE, U.; SCHMIDT, M.; PRIEN, R.; ROEDER, W.; WASMUND, N. (in prep.): Intensified inflow activity of the winter season 2015/2016 – an ongoing ventilation after the one in hundred years event of 2014 in the Baltic Sea? – Estuar. Coast. Shelf Sci.

NAUSCH, G., FEISTEL, R., LASS, H. U., NAGEL, K., SIEGEL, H., 2002: Hydrographisch-chemische Zustandseinschätzung der Ostsee 2001. – Meereswiss. Ber., Warnemünde, **49**, 2-77, doi: 10.12754/msr-2002-0049.

NAUSCH, G., FEISTEL, R., LASS, H.-U., NAGEL, K., SIEGEL, H., 2003a: Hydrographisch-chemische Zustandseinschätzung der Ostsee 2002. – Meereswiss. Ber., Warnemünde **55**, 1-71, doi: 10.12754/msr-2003-0055.

NAUSCH, G., MATTHÄUS, W., FEISTEL, R., 2003b: Hydrographic and hydrochemical conditions in the Gotland Deep area between 1992 and 2003, Oceanologia **45(4)**, 557-569, http://www.iopan.gda.pl/oceanologia/454nausc.pdf (accessed June 13th, 2016)

NAUSCH, G., FEISTEL, R., LASS, H.-U., NAGEL, K., SIEGEL, H., 2004: Hydrographisch-chemische Zustandseinschätzung der Ostsee 2003. – Meereswiss. Ber., Warnemünde **59**, 1-80, doi: 10.12754/msr-2004-0059.

NAUSCH, G., FEISTEL, R., LASS, H.U., NAGEL, K., SIEGEL, H., 2005: Hydrographisch-chemische Zustandseinschätzung der Ostsee 2004. – Meereswiss. Ber., Warnemünde **62**, 1-78, doi: 10.12754/msr-2005-0062.

NAUSCH, G., FEISTEL, R., LASS, H.U., NAGEL, K., SIEGEL, H., 2006: Hydrographisch-chemische Zustandseinschätzung der Ostsee 2005. – Meereswiss. Ber., Warnemünde **66**, 1-82, doi: 10.12754/msr-2006-0066.

NAUSCH, G., FEISTEL, R., LASS, H.U., NAGEL, K., SIEGEL, H., 2007: Hydrographisch-chemische Zustandseinschätzung der Ostsee 2006. – Meereswiss. Ber., Warnemünde **70**, 1-91, doi: 10.12754/msr-2007-0070.

NAUSCH, G., FEISTEL, R., LASS, H.U., NAGEL, K., SIEGEL, H., 2008: Hydrographisch-chemische Zustandseinschätzung der Ostsee 2007. – Meereswiss. Ber., Warnemünde **72**, 1-93, doi: 10.12754/msr-2008-0072.

NAUSCH, G., FEISTEL, R., UMLAUF, L., NAGEL. K., SIEGEL, H., 2009: Hydrographisch-chemische Zustandseinschätzung der Ostsee 2008. – Meereswiss. Ber., Warnemünde **77**, 1-93, doi: 10.12754/msr-2009-0077.

NAUSCH, G., FEISTEL, R., UMLAUF, L., NAGEL. K., SIEGEL, H., 2010: Hydrographisch-chemische Zustandseinschätzung der Ostsee 2009. – Meereswiss. Ber., Warnemünde **80**, 1-107, doi: 10.12754/msr-2010-0080.

NAUSCH, G., FEISTEL, R., UMLAUF, L., SIEGEL, H., 2011: Hydrographisch-chemische Zustandseinschätzung der Ostsee 2010. – Meereswiss. Ber., Warnemünde, **84**, 1-99, doi: 10.12754/msr-2011-0084.

NAUSCH, G., FEISTEL, R., UMLAUF, L., MOHRHOLZ, V., NAGEL, K., SIEGEL, H., 2012: Hydrographisch-hydrochemische Zustandseinschätzung der Ostsee 2011. – Meereswiss. Ber., Warnemünde, **86**, 1-121, doi: 10.12754/msr-2012-0086.

NAUSCH, G., FEISTEL, R., UMLAUF, L., MOHRHOLZ, V., SIEGEL, H., 2013: Hydrographisch-hydrochemische Zustandseinschätzung der Ostsee 2012. – Meereswiss. Ber., Warnemünde, **91**, 1-109, doi: 10.12754/msr-2013-0091.

NAUSCH, G., NAUMANN, M., UMLAUF, L., MOHRHOLZ, V., SIEGEL, H., 2014: Hydrographisch-hydrochemische Zustandseinschätzung der Ostsee 2013. – Meereswiss. Ber., Warnemünde, **93**, 1-104, doi: 10.12754/msr-2014-0093.

NAUSCH, G., NAUMANN, M., UMLAUF, L., MOHRHOLZ, V., SIEGEL, H., 2015: Hydrographic-hydrochemical assessment of the Baltic Sea 2014. – Meereswiss. Ber., Warnemünde, **96**, 1-93, doi: 10.12754/msr-2015-0096.

NAUSCH, G., NAUMANN, M., UMLAUF, L., MOHRHOLZ, V., SIEGEL, H., 2016: Hydrographic-hydrochemical assessment of the Baltic Sea 2015. – Meereswiss. Ber., Warnemünde, **101**, in prep, doi: 10.12754/msr-2016-0101.

NEHRING, D., FRANCKE, E., 1971: Hydrographisch-chemische Veränderungen in der Ostsee seit Beginn dieses Jahrhunderts und während des Internationalen Ostseejahres 1969/70. – Fischerei-Forschung, **9(1)**, 35-42.

NEHRING, D., FRANCKE, E., 1973a: Zusammenfassende Darstellung der hydrografisch-chemischen Veränderungen in der Ostsee 1969/1970. – Fischerei-Forschung, **11(1)**, 31-43.

NEHRING, D., FRANCKE, E., 1973b: Hydrographisch-chemische Veränderungen in der Ostsee im Jahre 1971. – Fischerei-Forschung, **11(1)**, 45-42.

NEHRING, D., FRANCKE, E., 1974: Hydrographisch-chemische Veränderungen in der Ostsee im Jahr 1972 unter besonderer Berücksichtigung des Salzwassereinbruchs im März/April 1972. – Fischerei-Forschung, **12(1)**, 23-33.

NEHRING, D., FRANCKE, E., 1975: Hydrographisch-chemische Veränderungen in der Ostsee im Jahr 1973. – Fischerei-Forschung, **13(1)**, 7-14.

NEHRING, D., FRANCKE, E., 1976a: Hydrographisch-chemische Veränderungen in der Ostsee im Jahr 1974. – Fischerei-Forschung, **14(1)**, 19-27.

NEHRING, D., FRANCKE, E., 1976b: Hydrographisch-chemische Veränderungen in der Ostsee im Jahr 1975. – Fischerei-Forschung, **14(1)**, 65-75.

NEHRING, D., FRANCKE, E., 1978: Die Erneuerung des Tiefenwassers und andere hydrographisch-chemische Veränderungen in der Ostsee im Jahr 1976. – Fischerei-Forschung, **16(2)**, 15-24.

NEHRING, D., FRANCKE, E., 1980a: Hydrographisch-chemische Veränderungen in der Ostsee im Jahr 1977. – Fischerei-Forschung, **18(1)**, 51-59.

NEHRING, D., FRANCKE, E., 1980b: Hydrographisch-chemische Veränderungen in der Ostsee im Jahr 1978. – Fischerei-Forschung, **18(1)**, 61-70.

NEHRING, D., FRANCKE, E., 1981: Hydrographisch-chemische Veränderungen in der Ostsee nach dem extremen Eiswinter 1978/79. – Fischerei-Forschung, **19(1)**, 7-14.

NEHRING, D., FRANCKE, E., 1982: Die hydrographisch-chemischen Bedingungen in der Ostsee im Jahr 1980. – Fischerei-Forschung, **20(2)**, 69-77.

NEHRING, D., FRANCKE, E., 1983a: Die hydrographisch-chemischen Bedingungen in der Ostsee im Jahr 1981. – Fischerei-Forschung, **21(4)**, 45-55.

NEHRING, D., FRANCKE, E., 1983b: Die hydrographisch-chemischen Bedingungen in der Ostsee im Jahr 1982. – Fischerei-Forschung, **21(4)**, 56-65.

NEHRING, D., FRANCKE, E., 1985a: Die hydrographisch-chemischen Bedingungen in der westlichen und zentralen Ostsee im Jahr 1983. – Fischerei-Forschung, **23(4)**, 7-17.

NEHRING, D., FRANCKE, E., 1985b: Die hydrographisch-chemischen Bedingungen in der westlichen und zentralen Ostsee im Jahr 1984. – Fischerei-Forschung, **23(4)**, 18-27.

NEHRING, D., FRANCKE, E., 1987a: Die hydrographisch-chemischen Bedingungen in der westlichen und zentralen Ostsee im Jahr 1985. – Fischerei-Forschung, **25(2)**, 7-16.

NEHRING, D., FRANCKE, E., 1987b: Die hydrographisch-chemischen Bedingungen in der westlichen und zentralen Ostsee im Jahr 1986. – Fischerei-Forschung, **25(4)**, 68-79.

NEHRING, D., FRANCKE, E., 1988: Die hydrographisch-chemische Bedingungen in der westlichen und zentralen Ostsee im Jahr 1987. – Fischerei-Forschung, **26(3)**, 43-52.

NEHRING, D., FRANCKE, E., 1990a: Die hydrographisch-chemischen Bedingungen in der westlichen und zentralen Ostsee im Jahr 1988. – Fischerei-Forschung, **28(2)**, 7-17.

NEHRING, D., FRANCKE, E., 1990b: Die hydrographisch-chemischen Bedingungen in der westlichen und zentralen Ostsee im Jahr 1989. – Fischerei-Forschung, **28(3)**, 35-45.

NEHRING, D., 1991: Die hydrographisch-chemischen Bedingungen in der westlichen und zentralen Ostsee im Jahr 1990. – Fischerei-Forschung, **29(2)**, 5-15.

NEHRING, D., MATTHÄUS, W., 1991/92: Die hydrographisch-chemischen Bedingungen in der westlichen und zentralen Ostsee im Jahre 1991. – Dtsch. Hydrogr. Z., **44**, 217-238.

NEHRING, D., MATTHÄUS, W., LASS, H.U., 1993: Die hydrographisch-chemischen Bedingungen in der westlichen und zentralen Ostsee im Jahre 1992. – Dtsch. Hydrogr. Z., **45**, 281-312.

NEHRING, D., MATTHÄUS, W., LASS, H. U., NAUSCH, G., 1994a: Hydrographisch-chemische Zustandseinschätzung der Ostsee 1993. – Meereswiss. Ber., Warnemünde, **7**, 1-68, doi: 10.12754/msr-1994-0007

NEHRING, D., MATTHÄUS, W., LASS, H. U., NAUSCH, G., 1994b: Die hydrographisch-chemischen Bedingungen in der westlichen und zentralen Ostsee im Jahre 1993. – Dtsch. Hydrogr. Z., **46**, 151-162.

NEHRING, D., MATTHÄUS, W., LASS, H. U., NAUSCH, G., NAGEL, K., 1995a: Hydrographisch-chemische Zustandseinschätzung der Ostsee 1994. – Meereswiss. Ber., Warnemünde, **9**, 1-71, doi: 10.12754/msr-1995-0009.

NEHRING, D., MATTHÄUS, W., LASS, H. U., NAUSCH, G., NAGEL, K., 1995b: The Baltic Sea 1994 – Consequences of the hot summer and inflow events. – Dtsch. Hydrogr. Z., **47**, 131-144.

NEHRING, D., MATTHÄUS, W., LASS, H. U., NAUSCH, G., NAGEL, K., 1995c: The Baltic Sea in 1995 – Beginning of a new stagnation period in its central deep waters and decreasing nutrient load in its surface layer. – Dtsch. Hydrogr. Z., **47**, 319-327.

NEHRING, D., MATTHÄUS, W., LASS, H. U., NAUSCH, G., NAGEL, K., 1996: Hydrographisch-chemische Zustandseinschätzung der Ostsee 1995. – Meereswiss. Ber., Warnemünde, **16**, 1-43, doi: 10.12754/msr-1996-0016.

PIECHURA, J., BESZCZYNSKA-MÖLLER, A., 2004: Inflow waters in the deep regions of the southern Baltic Sea - transport and transformations. – Oceanologia, **46**, 113–141. http://www.iopan.gda.pl/oceanologia/454piech.pdf (accessed June 13th, 2016)

SCHINKE, H., MATTHÄUS, W., 1998: On the causes of major Baltic inflows – an analysis of long time series. – Cont. Shelf Res., **18**, 67-97.

SEIFERT, T., KAYSER, B., 1995: A high resolution spherical grid topography of the Baltic Sea. – Meereswiss. Ber., Warnemünde, **9**, 72-88, doi: 10.12754/msr-1995-0009.

SEIFERT, T., TAUBER, F., KAYSER, B., 2001: A high resolution spherical grid topography of the Baltic Sea - 2nd edition. Baltic Sea Science Congress, Stockholm 25-29. November 2001, Poster #147, http://www.io-warnemuende.de/iowtopo

WESSEL, P., SMITH, W. H. F., 1996: A Global Self-consistent, Hierarchical, High-resolution Shoreline Database. – J. Geophys. Res. B, Vol. **101**, No. B4, 8741-8743

WYRTKI, K., 1953: Die Dynamik der Wasserbewegungen im Fehmarnbelt I. – Kiel. Meeresforsch., **9**, 155-170.

WYRTKI, K., 1954: Der große Salzeinbruch in die Ostsee im November und Dezember 1951. – Kiel. Meeresforsch., **10**, 19-25.

Appendix

Map of Baltic Sea regions

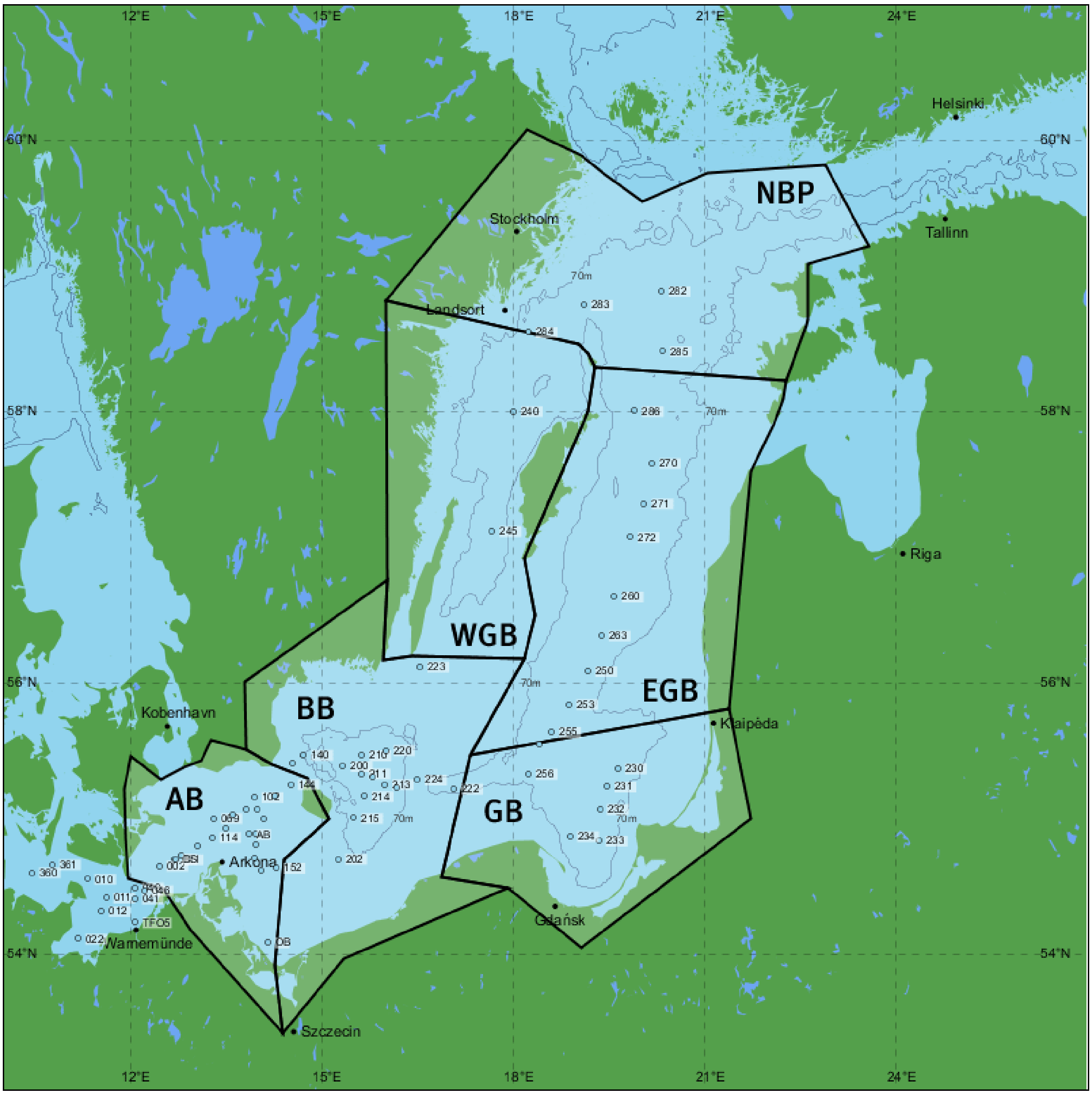

Fig. 12: Regions of the Baltic Sea as defined in FEISTEL et al. (2008). The closed polygons were used to limit interpolation across basins. Clearly separated are Arkona Basin (AB), Bornholm Basin (BB), Gdańsk Basin (GB), western and eastern Gotland Basins (WGB, EGB) and the northern Baltic Proper (NBP).

Map of included monitoring stations

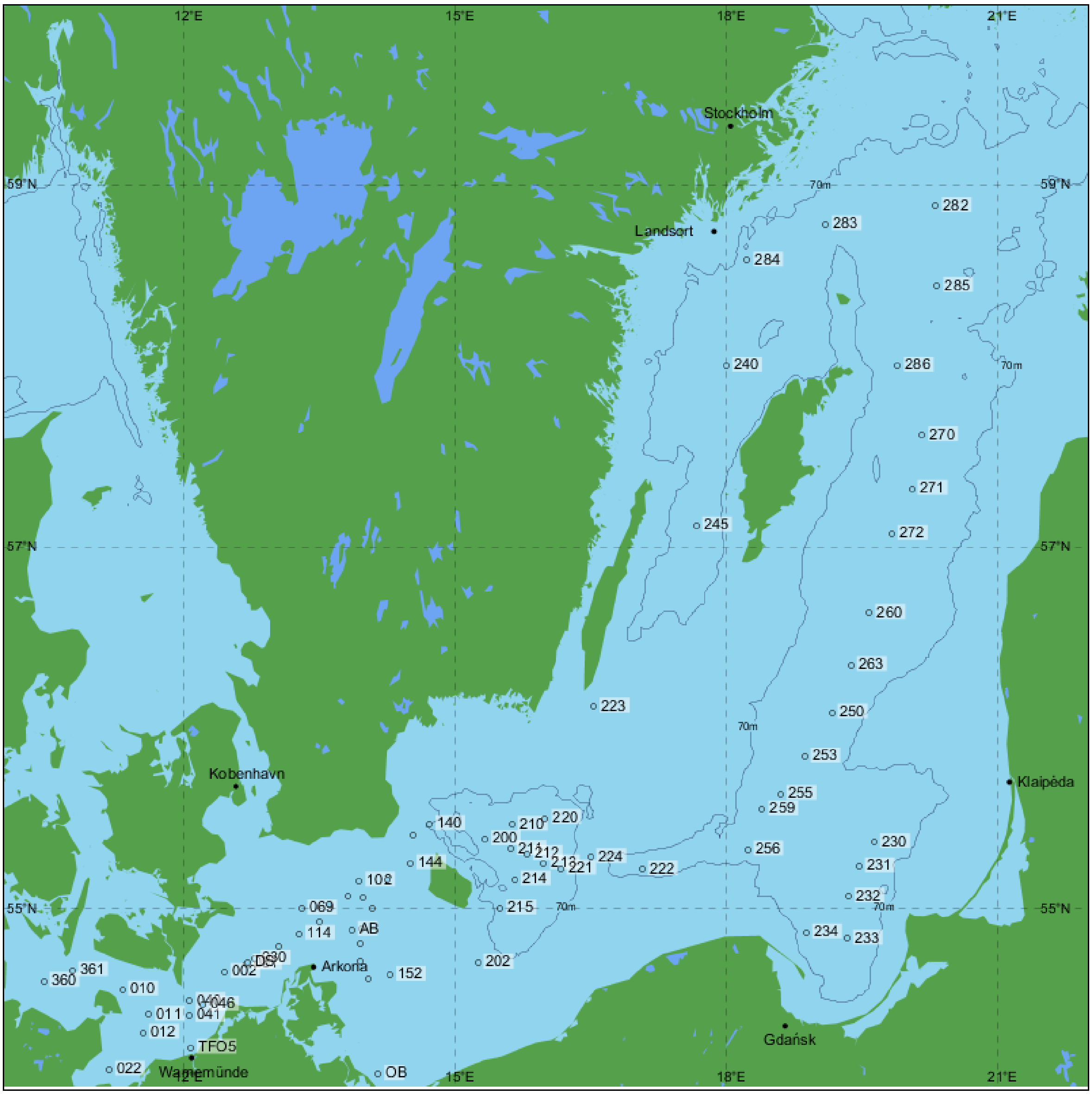

Fig. 13: Map of permanent monitoring stations included by default in the representation as long as they were sampled.

List of included monitoring stations

Table 2: List of the fixed set of monitoring stations included to create a distribution map. The stations are ordered by area.

	Name	Longitude	Latitude
Arkona Buoy	AB	13.86	54.88
Darss Sill	DS	12.70	54.70
Oder Bank	OB	14.15	54.08
Western Baltic	001	12.69	54.70
	002	12.45	54.65
	010	11.32	54.55
	011	11.62	54.41
	012	11.55	54.31
	022	11.18	54.11
	030	12.78	54.72
	040	12.07	54.49
	041	12.06	54.41
	046	12.22	54.47
	360	10.45	54.60
	361	10.77	54.66
	O5	12.08	54.23
Arkona Basin	069	13.30	55.00
	102	13.94	55.16
	103	13.99	55.06
	104	13.81	55.07
	105	13.61	55.02
	109	14.08	55.00
	111	13.97	54.89
	112	13.96	54.80
	113	13.50	54.92
	114	13.28	54.86
	115	13.06	54.79
	121	13.95	54.71
	140	14.72	55.47
	142	14.54	55.40
	144	14.51	55.25
	145	14.26	55.16
	150	14.04	54.61
	152	14.28	54.63

	Name	Longitude	Latitude
Bornholm Basin	200	15.33	55.38
	202	15.25	54.70
	210	15.63	55.46
	211	15.61	55.33
	212	15.79	55.30
	213	15.98	55.25
	214	15.66	55.16
	215	15.50	55.00
	220	16.00	55.50
	221	16.17	55.22
	223	16.53	56.12
Słupsk Furrow	222	17.07	55.22
	224	16.50	55.28
Gdańsk Basin	230	19.63	55.37
	231	19.47	55.23
	232	19.35	55.07
	233	19.33	54.83
	234	18.88	54.87
western Gotland Basin	240	18.00	58.00
	245	17.67	57.12
	284	18.23	58.58
eastern Gotland Basin	250	19.17	56.08
	253	18.87	55.84
	255	18.60	55.63
	256	18.24	55.33
	259	18.40	55.55
	260	19.58	56.63
	263	19.38	56.35
	270	20.17	57.62
	271	20.05	57.32
	272	19.83	57.07
	286	19.90	58.00
northern Baltic Proper	282	20.32	58.88
	283	19.10	58.78
	285	20.33	58.44

Distribution map of August 2015 with extended set of stations

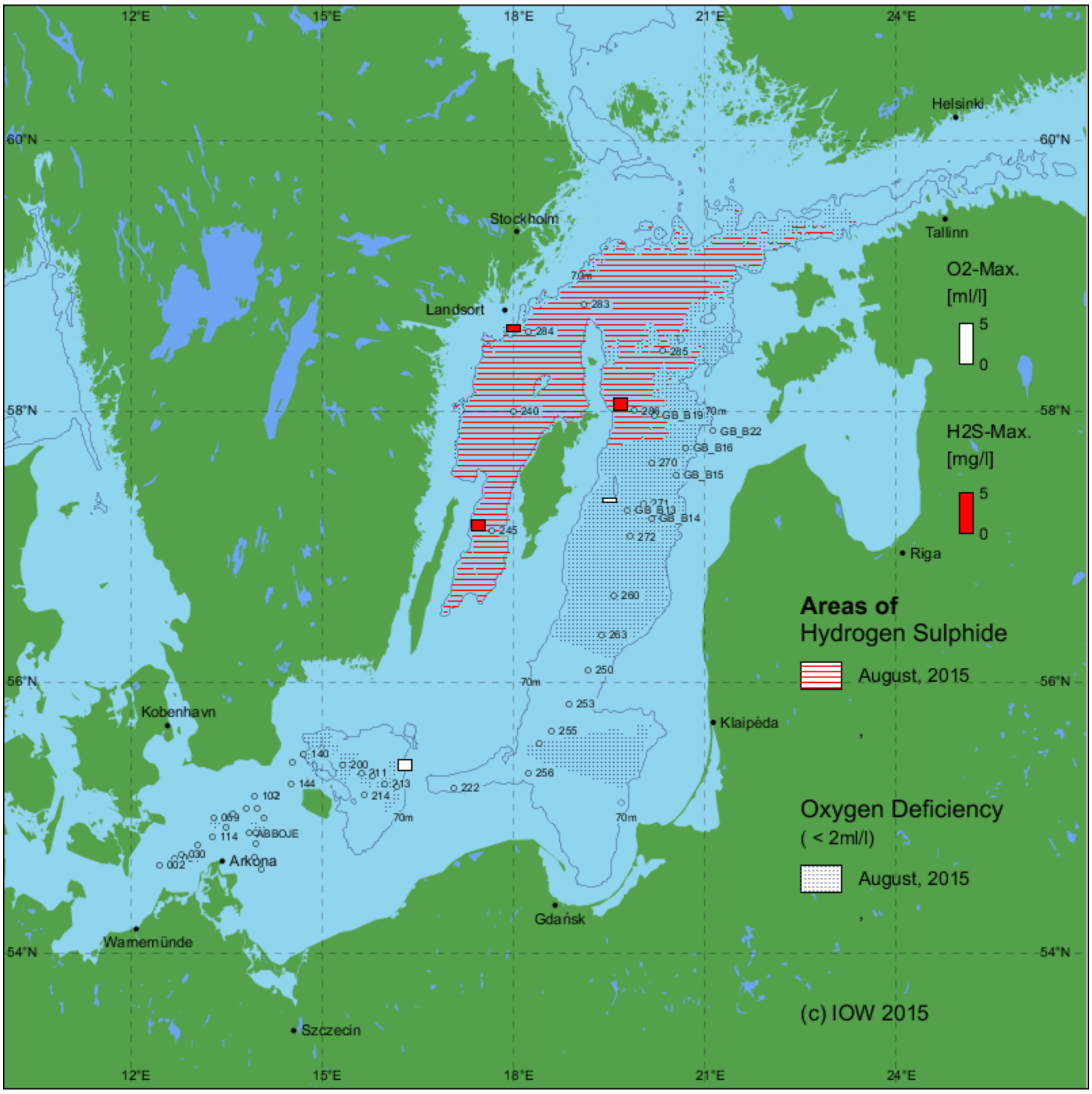

Fig. 14: Distribution map of August 2015 interpolated with an extended set of stations (GB_B13 GB_B14, GB_B15, GB_B16, GB_B19, GB_B22). The front of the inflow water from December 2014 is better resolved than with only standard stations (Fig. 61).

Hypoxic and anoxic regions in the Baltic Sea deep waters, 1969 - 2015

In the following section, maps of the hypoxic (<2 ml/l oxygen) and anoxic regions are shown. They are based on the seasonal monitoring cruises ("Terminfahrten") performed regularly since 1969, firstly by the Institute of Marine Research of the German Academy of Sciences (IfMW) and since 1992 by the Leibniz Institute for Baltic Sea Research Warnemünde (IOW). The upper row displays the results of January/February and March/April of the respective year, followed by May and July/August in the middle row. The lower row shows on the left the autumn cruise in October/November whereas on the right hand side an annual summary map is given.

From 1969 to 1979 and from 1991 until 2000, the Gdańsk Deep was sampled regularly during the monitoring cruises, and data are included in all maps. In the 1980s and from 2000 onwards, we have got the data for the Gdańsk Deep from ELZBIETA ŁYSIAK-PASTUSZAK at the Maritime Branch of the Polish Institute of Meteorology and Water Management in Gdynia. The Polish data were used only for the annual summary map. Maps display the location of the stations and areas of oxygen deficiency and hydrogen sulphide concentrations in the near bottom layer of the Baltic Sea. Bars show the maximum oxygen and hydrogen sulphide concentrations of this layer for selected stations. Additionally, the maps contain the 70 m depth line. For each year, a comprehensive summary is given below the maps together with the respective references. Within these summaries, hydrogen sulphide concentrations are given for better comparison as negative oxygen equivalents (FEISTEL et al., 2008).

The detailed annual assessments can be found at

http://www.io-warnemuende.de/state-of-the-baltic-sea.html.

All maps given in this publication can be found at

http://www.io-warnemuende.de/suboxic-and-anoxic-regions-in-the-baltic-sea-deep-waters.html

Annual updates of the maps and short summaries will be available at

http://www.io-warnemuende.de/msr-2016-0100/

1969

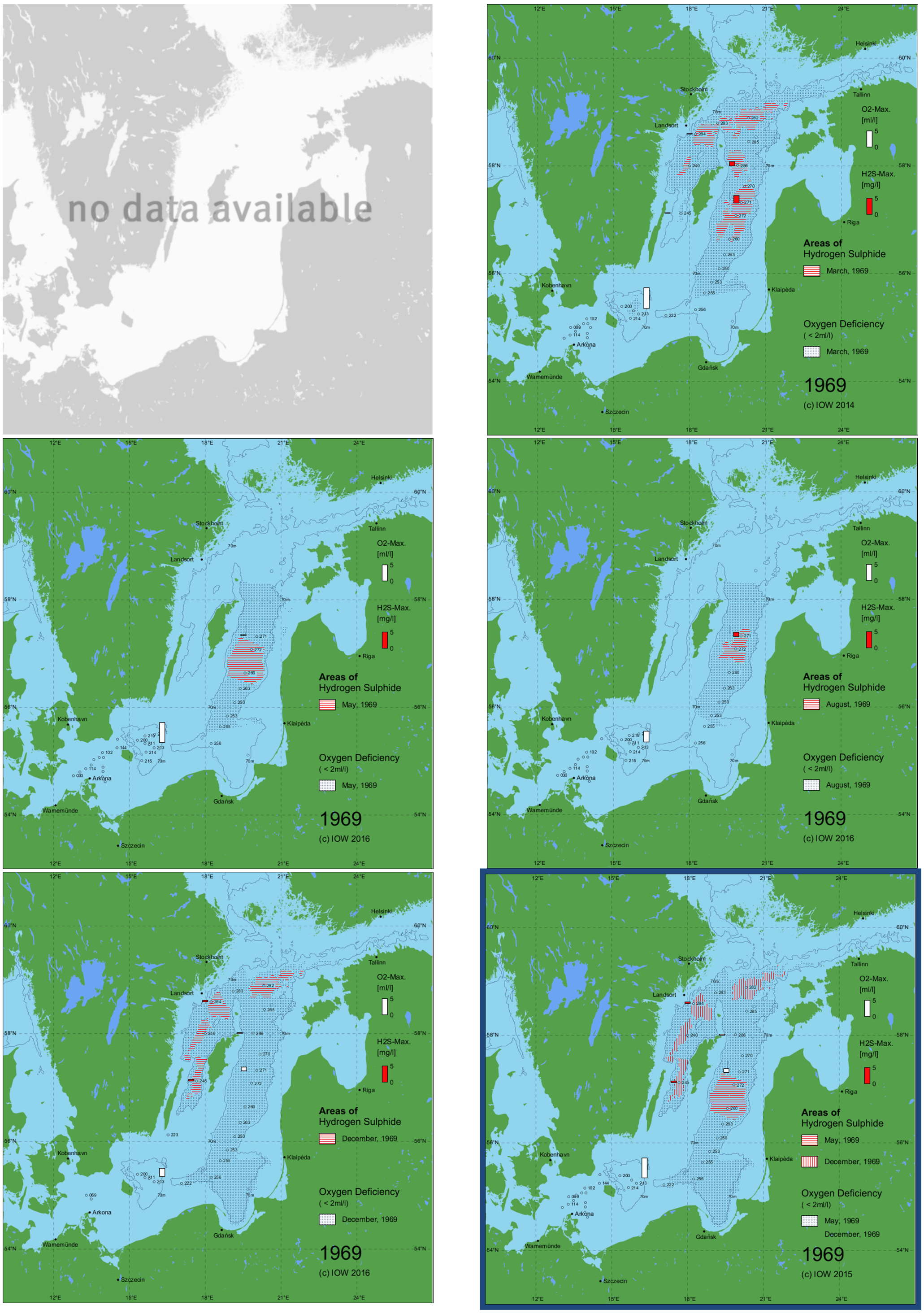

Fig. 15: Distribution maps for 1969. The oceanographical conditions were influenced by the moderate MBI in February 1969 which terminated the stagnation period lasting since 1965. The deep water in the Bornholm and the Gdańsk Basins was supplied with oxygen beginning in Feb./March. In the eastern Gotland Basin, H_2S was replaced by O_2 in the bottom water step by step. First signs of the inflowing water were observed in March. In Oct. an intermediate layer containing H_2S was found. The basin was free of H_2S in Nov./Dec., whereas anoxic conditions were observed in the northern and western Gotland Basin during the whole year (NEHRING & FRANCKE, 1973a).

1970

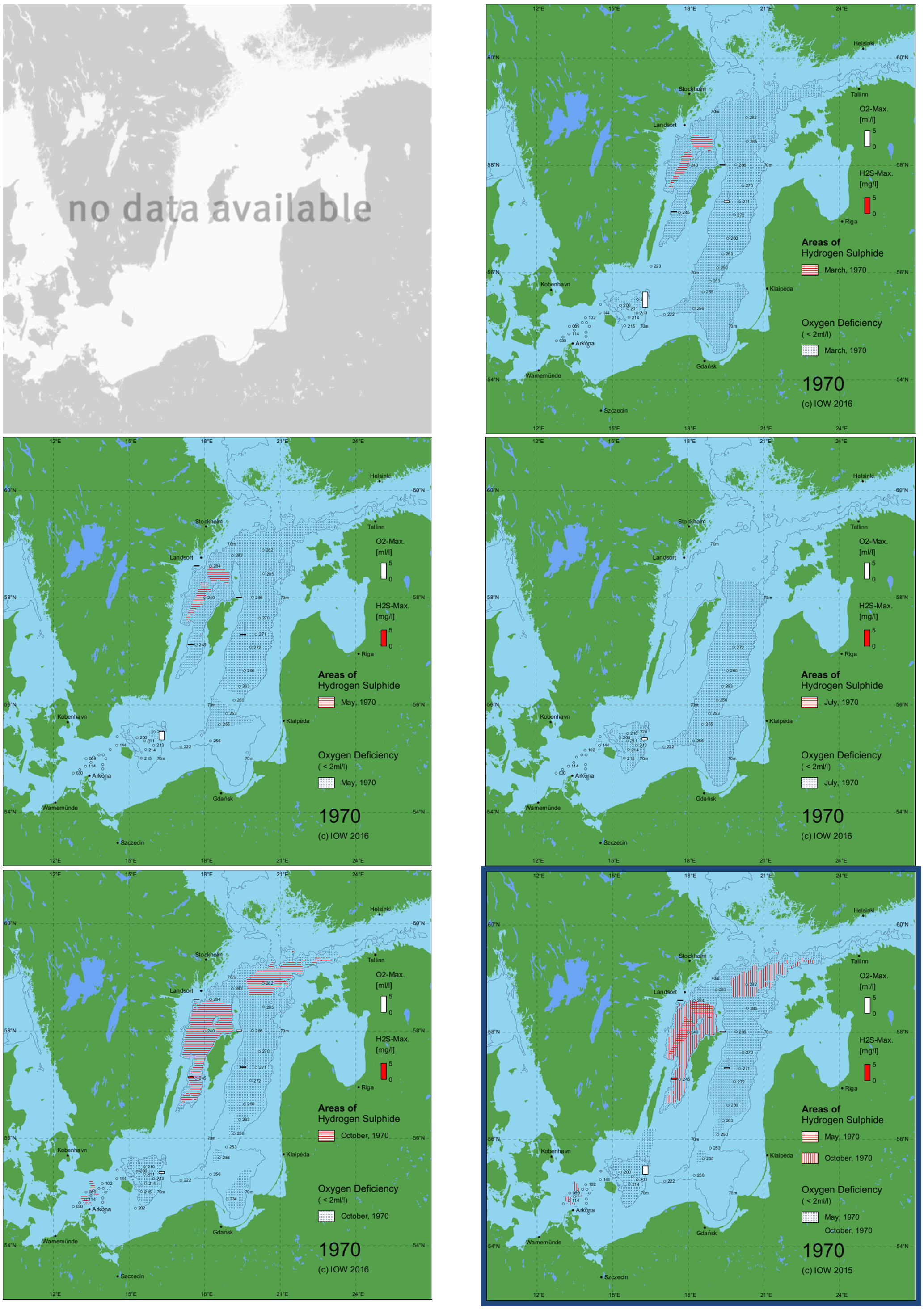

Fig. 16: Distribution maps for 1970. The strong MBI in autumn 1970 increased the effects of the moderate MBI at the beginning of the year. Oxygen conditions improved in the bottom water in most of the central Baltic basins. In March, May and Oct./Nov. 1970 H_2S was only observed in the western Gotland Basin (NEHRING & FRANCKE, 1971, 1973a).

1971

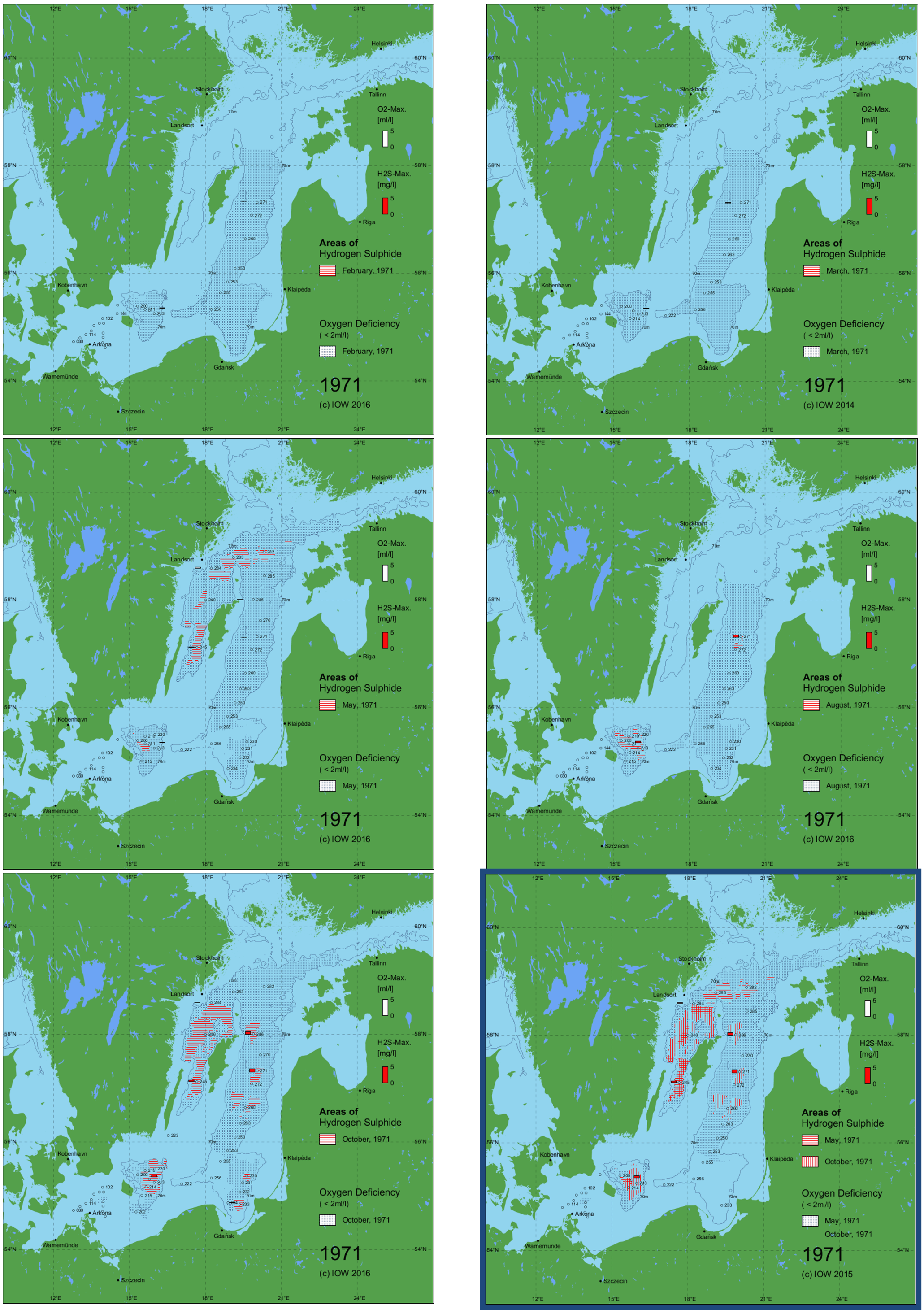

Fig. 17: Distribution maps for 1971. Oxygen has been observed in the bottom water of the Bornholm, the Gdańsk and the eastern Gotland Basins in February and March 1971. In May, H_2S was measured in the bottom water of the Bornholm and the western Gotland Basins. In August, H_2S occurred in the eastern Gotland Basin. H_2S was observed in the bottom water of all stations in the Baltic Proper in Sep./Oct. This indicates the beginning of a new stagnation period in 1971 (NEHRING & FRANCKE, 1973b).

1972

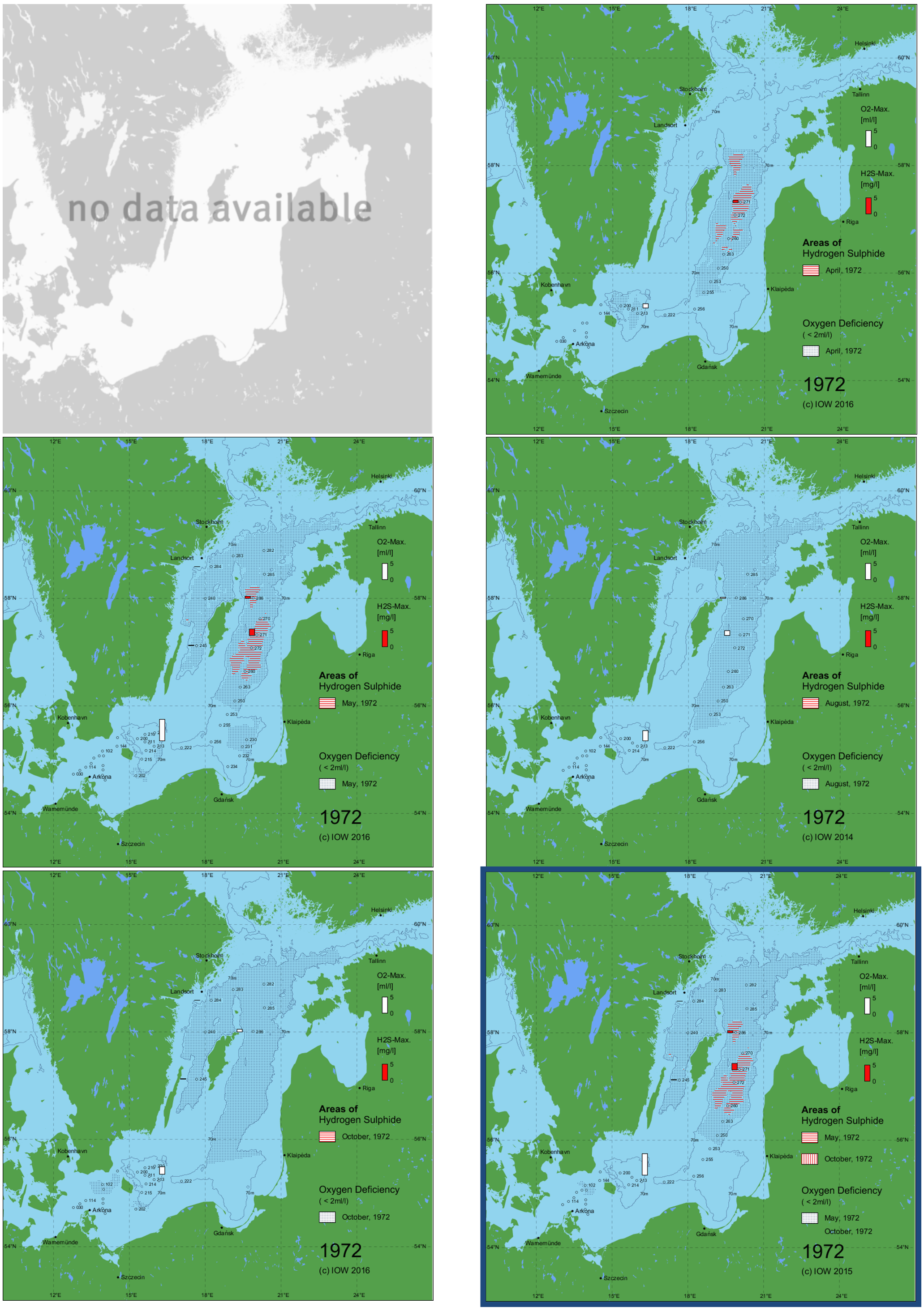

Fig. 18: Distribution maps for 1972. Inflow events of moderate and weak intensity occurred between October and December 1971, causing the deep water renewal of the Bornholm and the Gdańsk Basins in April and May 1972. In August, the bottom water of the eastern Gotland Basin was renewed lifting up H_2S into the intermediate layers. Anoxic conditions were observed in parts of the eastern Gotland Basin as well as in the northern and western Gotland Basins in Oct./Nov.1972 (Nehring & Francke, 1974).

1973

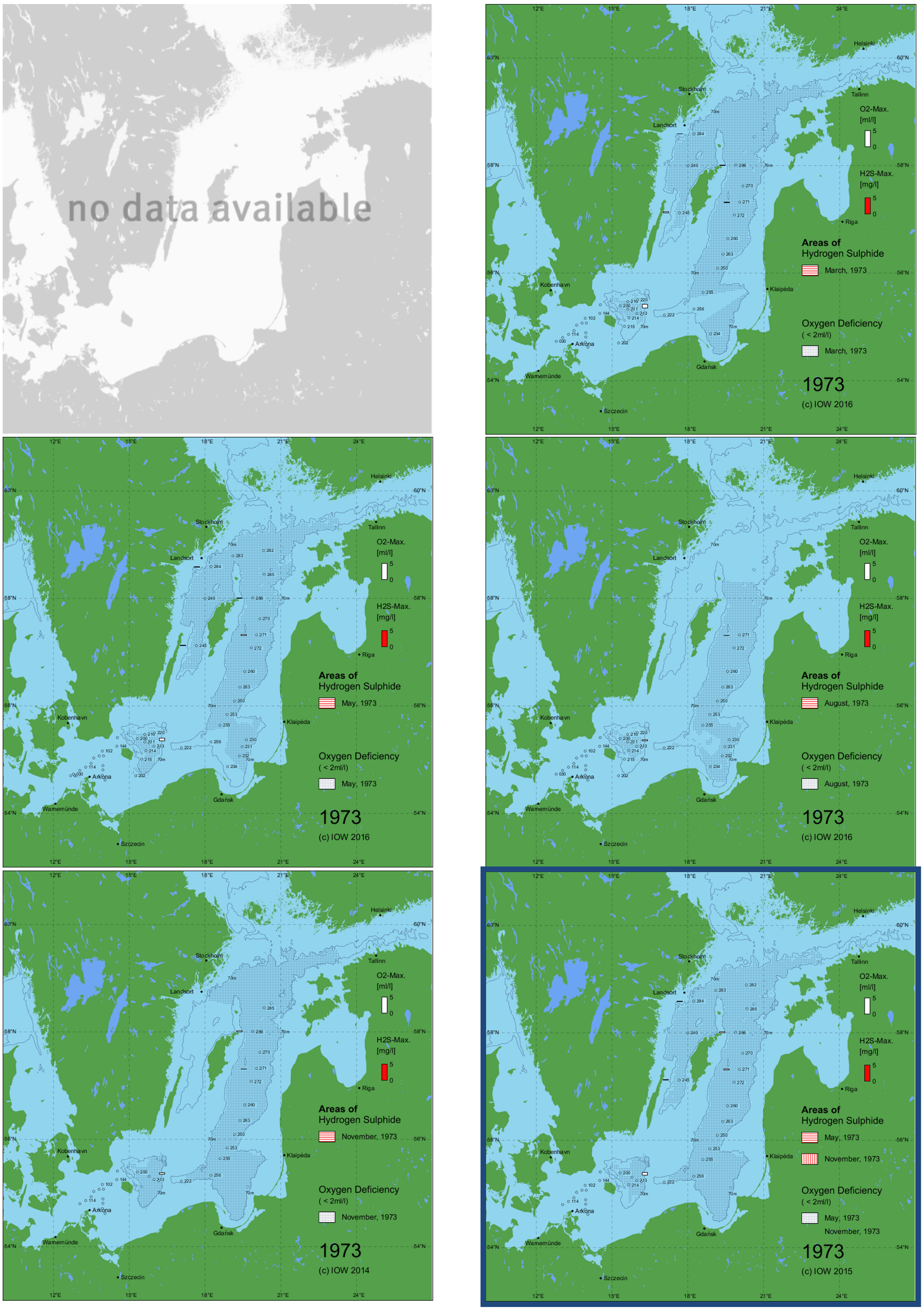

Fig. 19: Distribution maps for 1973. In March/April 1973, H_2S was only present in the western Gotland Basin, whereas in the bottom water of the other basins oxygen was measured. Oxygen conditions deteriorated in May/June. H_2S was observed in the bottom water of the Fårö Deep and in the northern and western Gotland Basins. In August, the southern part of the eastern Basin was free H_2S. In November anoxic conditions had developed in the eastern and northern Gotland Basins (NEHRING & FRANCKE, 1975). Discrepancies between the maps and the explaining text are explained in chapter 6, p. 21.

1974

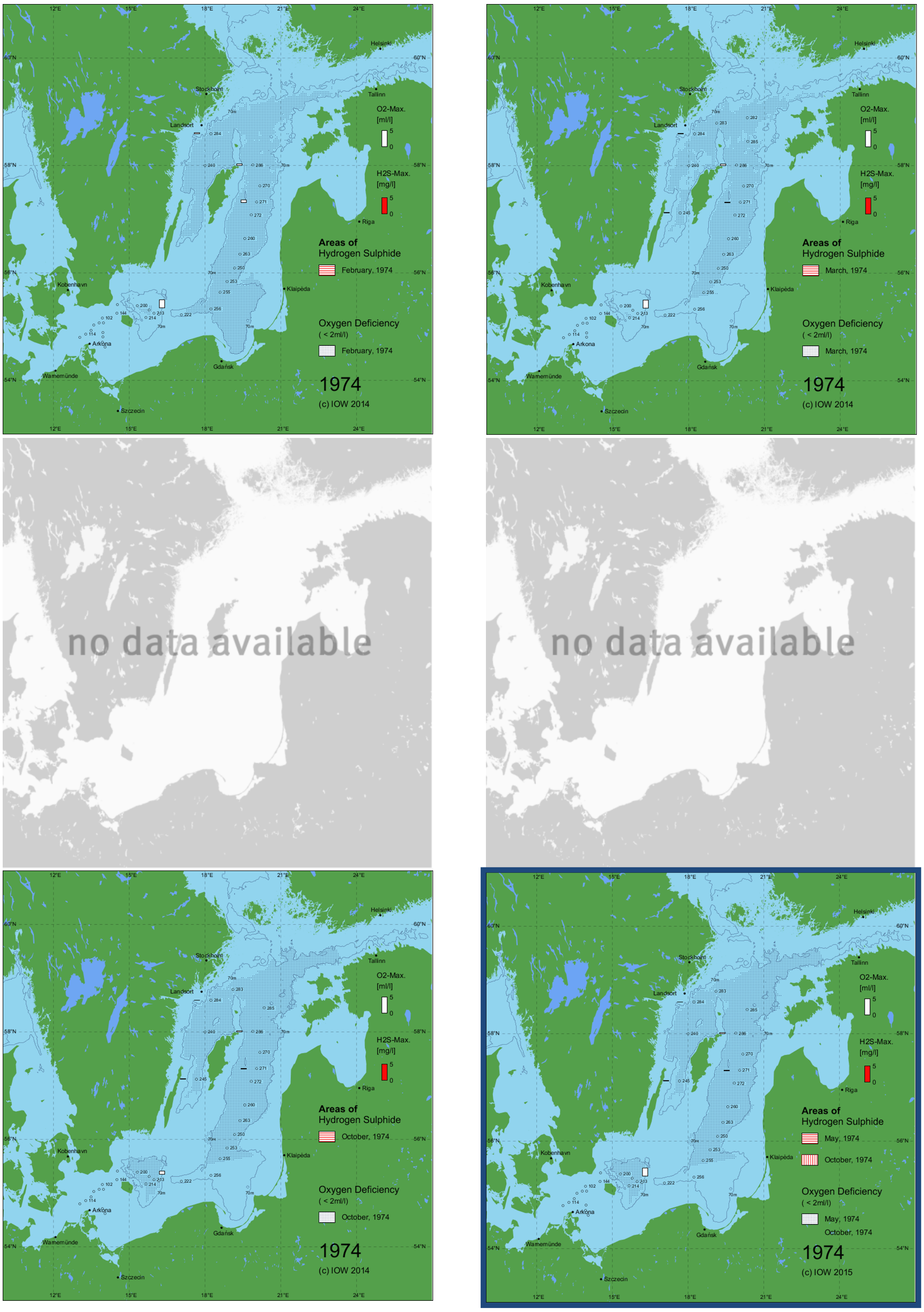

Fig. 20: Distribution maps for 1974. The strong MBI in November 1973 supplied the bottom water of the Bornholm and Gdańsk Basins with oxygen during 1974. Although the H_2S concentrations were reduced, the anoxic bottom water was not completely renewed in the eastern Gotland Basin as well as in the northern and western Gotland Basins in Oct./Nov. 1974. The oxic conditions in the Landsort Deep station are an exception (NEHRING & FRANCKE, 1976a). Discrepancies between the maps and the explaining text are explained in chapter 6, p. 21.

1975

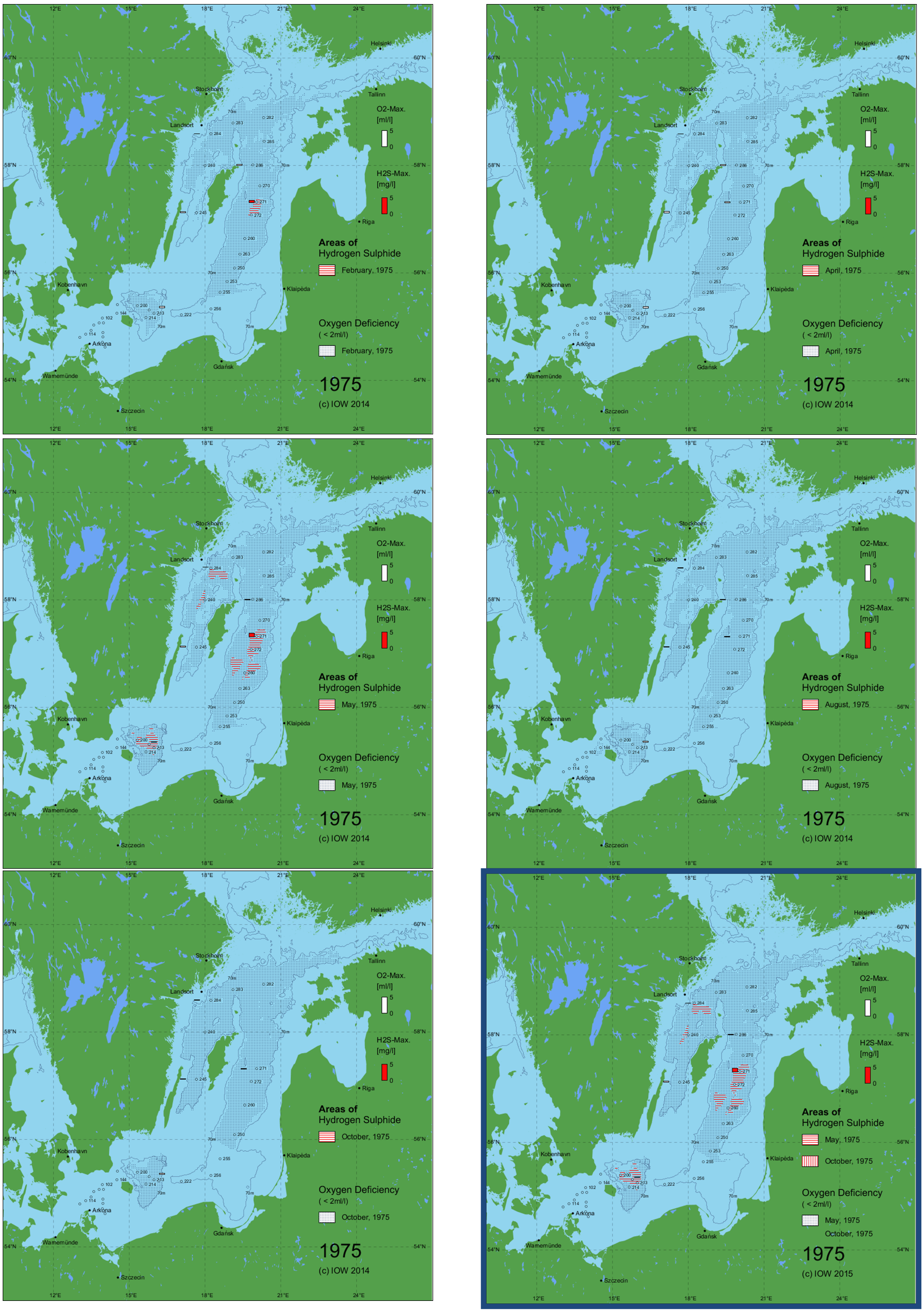

Fig. 21: Distribution maps for 1975. The continuation of the stagnation period caused the deterioration of the oxygen conditions in central Baltic deep waters in 1975. H_2S was observed in the Bornholm and Gdańsk Basins in May, August and Oct./Nov. In the eastern Gotland Basin anoxic conditions prevailed in all seasons. With the exception of the Landsort Deep station, H_2S had developed in the northern and western Basins in August and Oct./Nov. 1975 (NEHRING & FRANCKE, 1976b).

1976

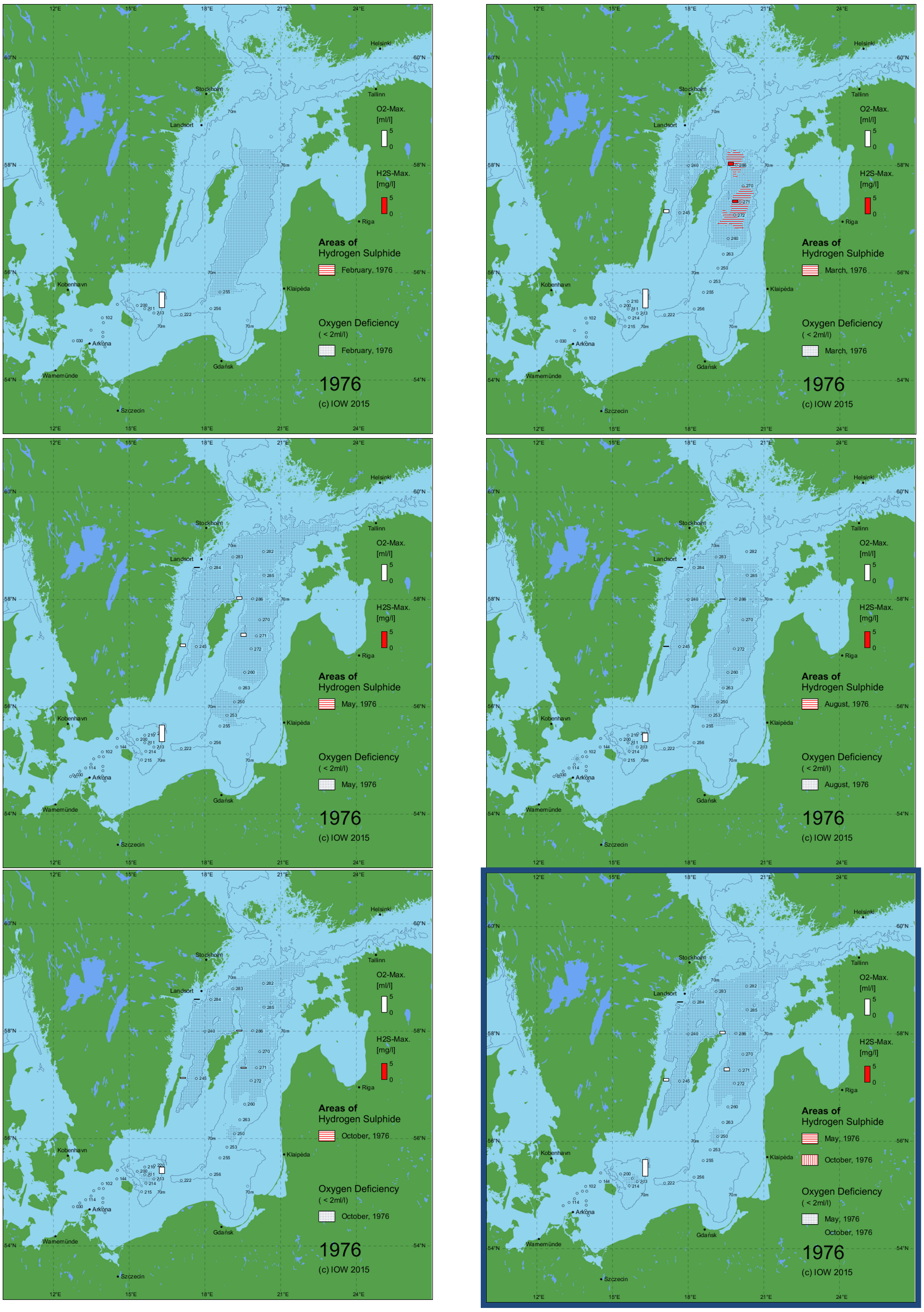

Fig. 22: Distribution maps for 1976. The strong MBI in Dec./Jan. 1975/76, terminated the short stagnation period in central Baltic deep waters. Studies in Jan. 1976 indicated O_2 concentrations up to 6 ml/l in the bottom water of the Bornholm Basin. Due to its high salinity, the inflowing water penetrated quickly into the central Baltic basins lifting up the anoxic bottom water in the eastern Gotland Basin in April/May. Only low H_2S concentrations were found here in Aug. and Nov. No anoxic conditions were observed in the bottom water of the Gdańsk and western Gotland Basins in 1976 (NEHRING & FRANCKE, 1978).

1977

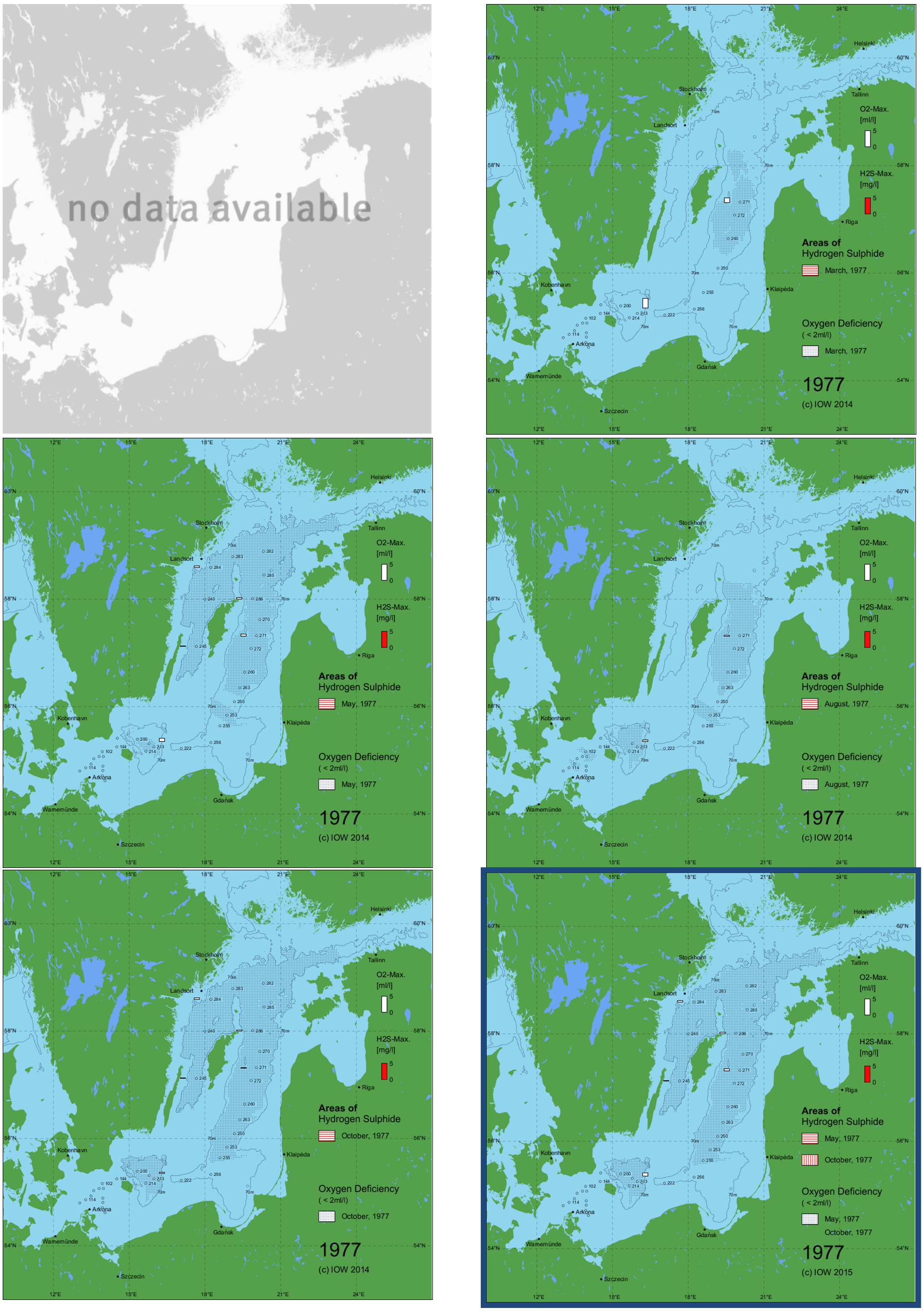

Fig. 23: Distribution maps for 1977. Oxic conditions were observed in the bottom water of the Baltic Proper at all seasons in 1977. Exceptions are single stations in the northern and western Gotland Basins in November. The favourable oxygen conditions in 1977 are the consequence of the deep water renewal in 1976 (NEHRING & FRANCKE, 1980a).

1978

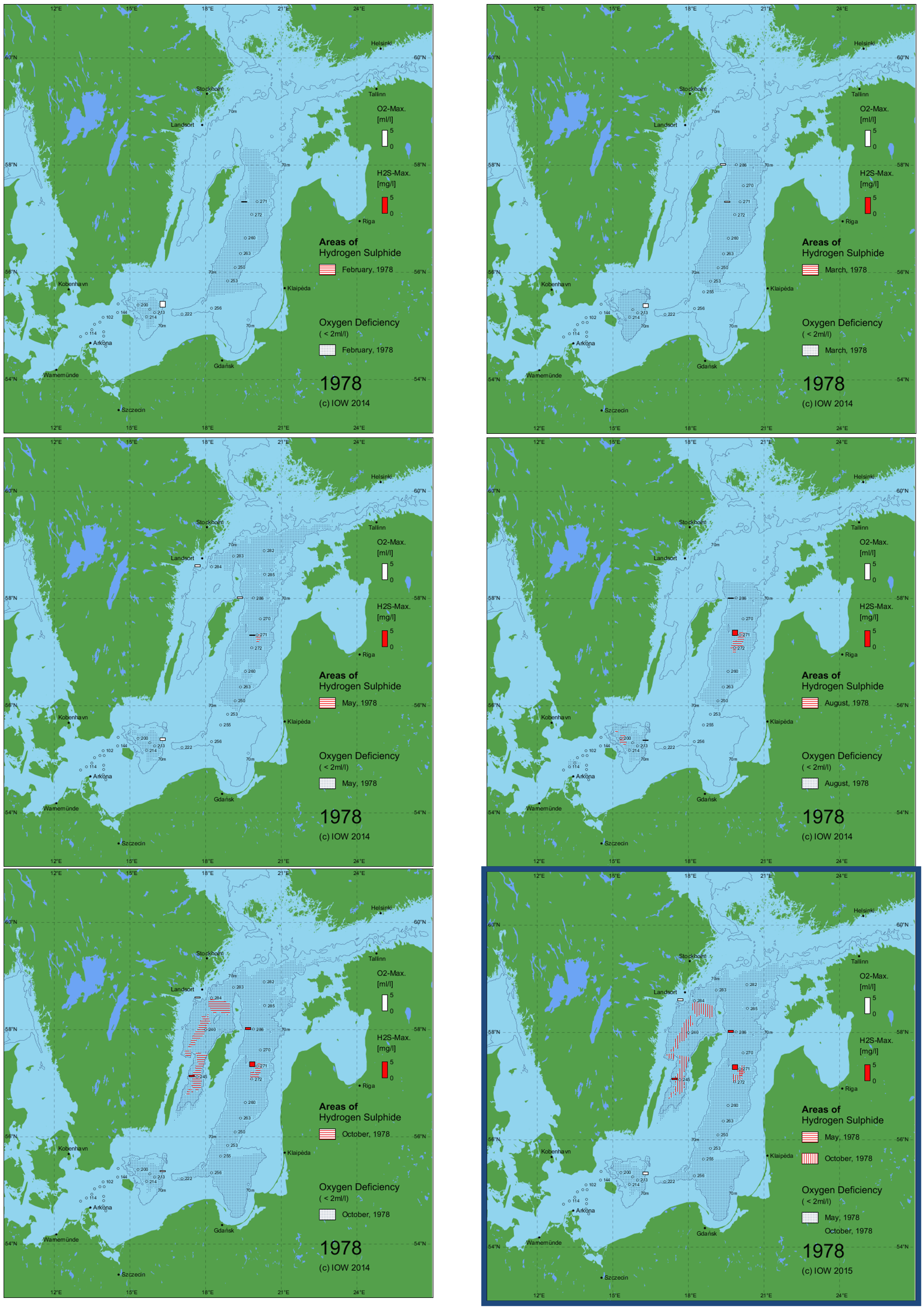

Fig. 24: Distribution maps for 1978. The development of H_2S in the Gotland Deep in May 1978 indicated the beginning of a new stagnation period in the Baltic Proper. Anoxic conditions extended in the eastern Gotland Basin in August and November but were also observed in the western Gotland Basin in November. Low concentrations of H_2S were measured in the Bornholm Basin in August. Oxic conditions prevailed in the Gdańsk Basin in 1978 (NEHRING & FRANCKE, 1980b).

1979

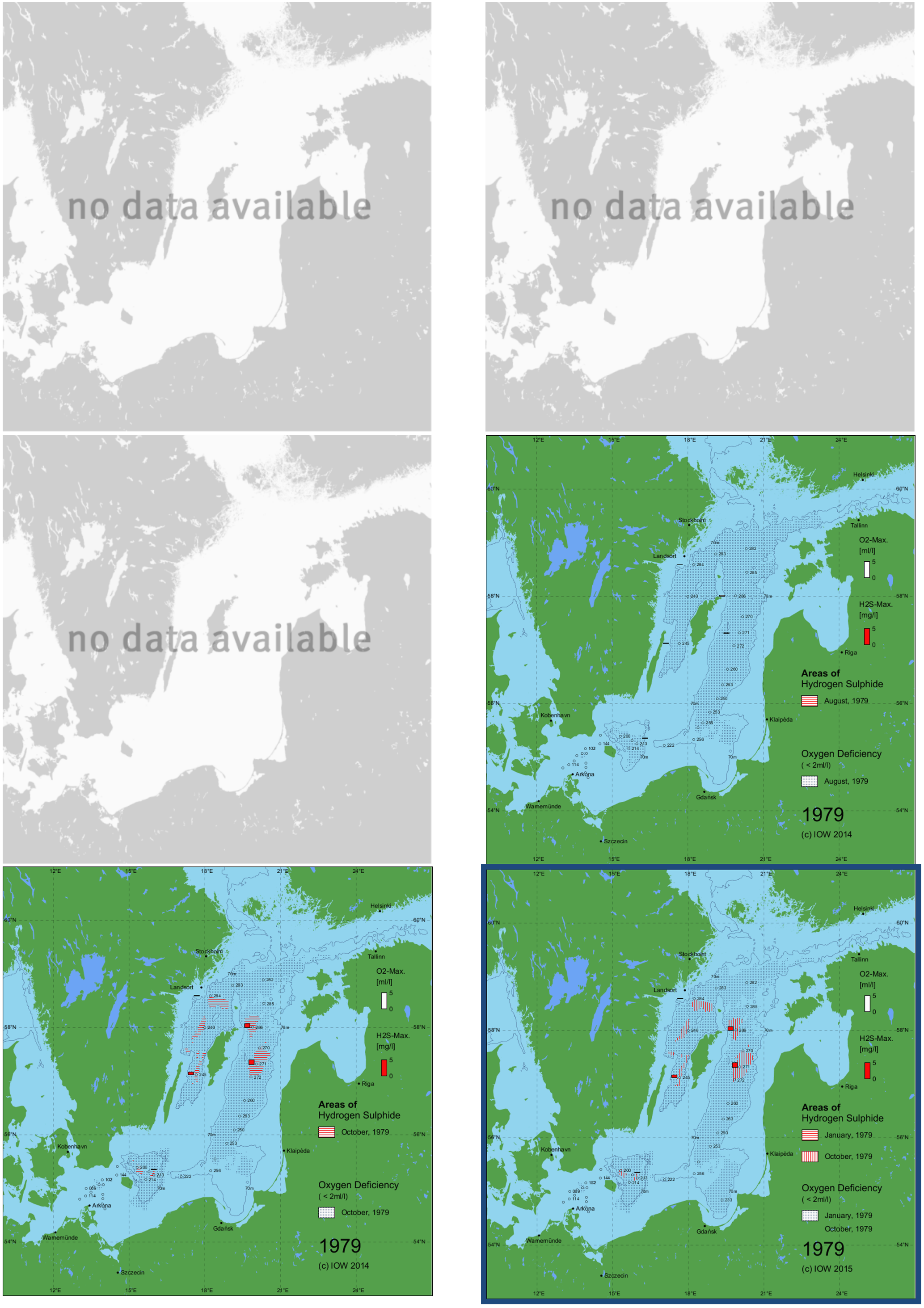

Fig. 25: Distribution maps for 1979. Due to the very strong winter 1978/79 covering huge areas of the Baltic Proper with ice, only data of two monitoring cruises could be collected in 1979. In continuation of the stagnation period, H_2S was observed in the bottom water of the Gdańsk Basin in August and Oct./Nov. as well as in all central basins in August and Oct./Nov, except in the Landsort Deep station. H_2S had developed in the bottom water of the Bornholm Basin in November 1979 (NEHRING & FRANCKE, 1981).

1980

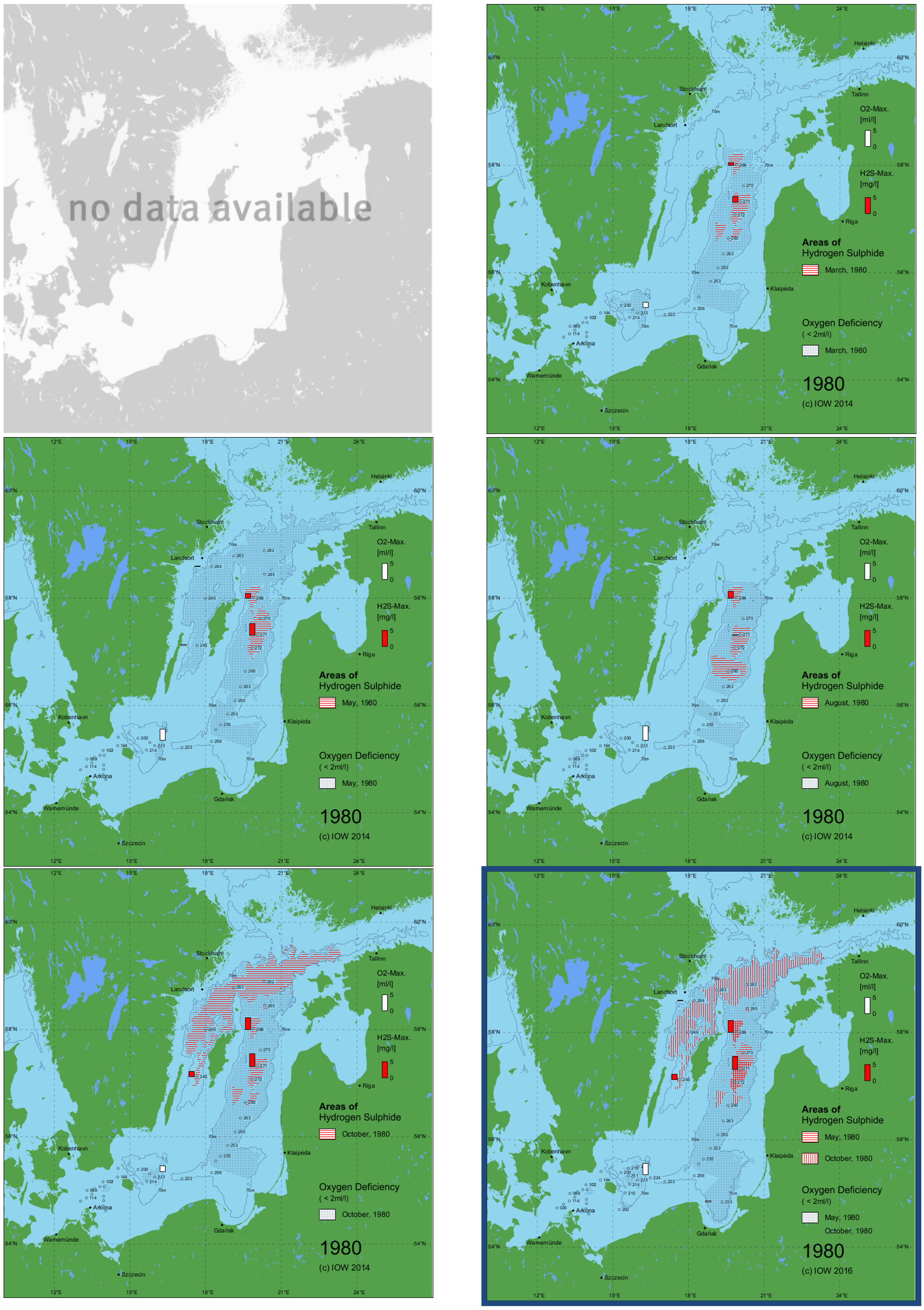

Fig. 26: Distribution maps for 1980. A MBI of low intensity in Nov./Dec. 1979 caused deep water renewal and oxic conditions in the Bornholm and Gdańsk Basins during all seasons. H_2S was observed in the eastern Gotland Basin during the whole year. In August, oxygen containing water lifted up the anoxic bottom water as a consequence of the MBI. H_2S was measured in the bottom water of the northern basin in May and Oct./Nov. and in the western basin (NEHRING & FRANCKE, 1982).

1981

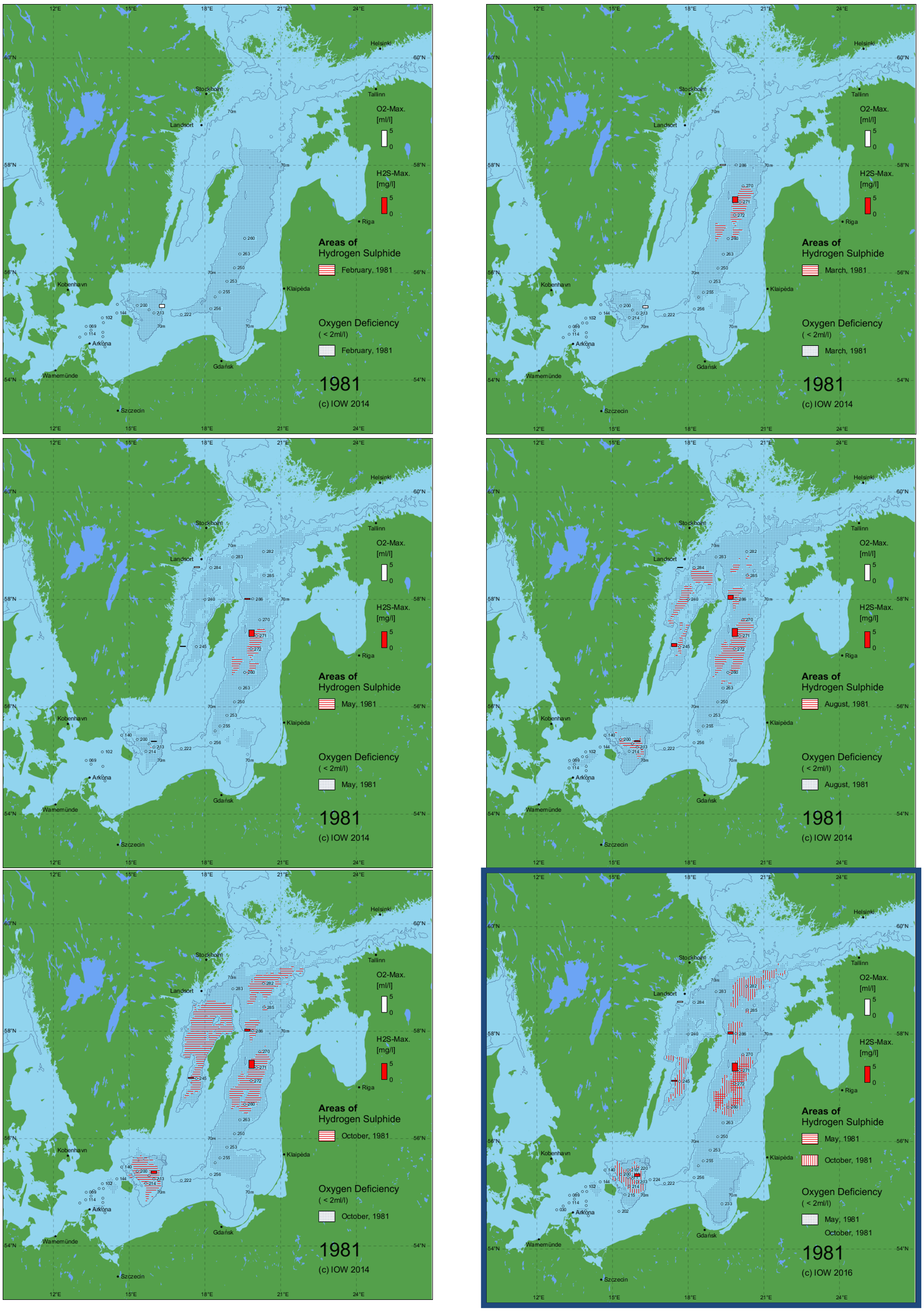

Fig. 27: Distribution maps for 1981. After the water renewal in 1980, stagnating conditions caused the formation of H_2S in the deep water of all central basins in 1981, except in the western Gotland Basin. H_2S also developed in bottom water of the Bornholm Basin in August and in the Gdańsk Basin in November 1981 (NEHRING & FRANCKE, 1983a).

1982

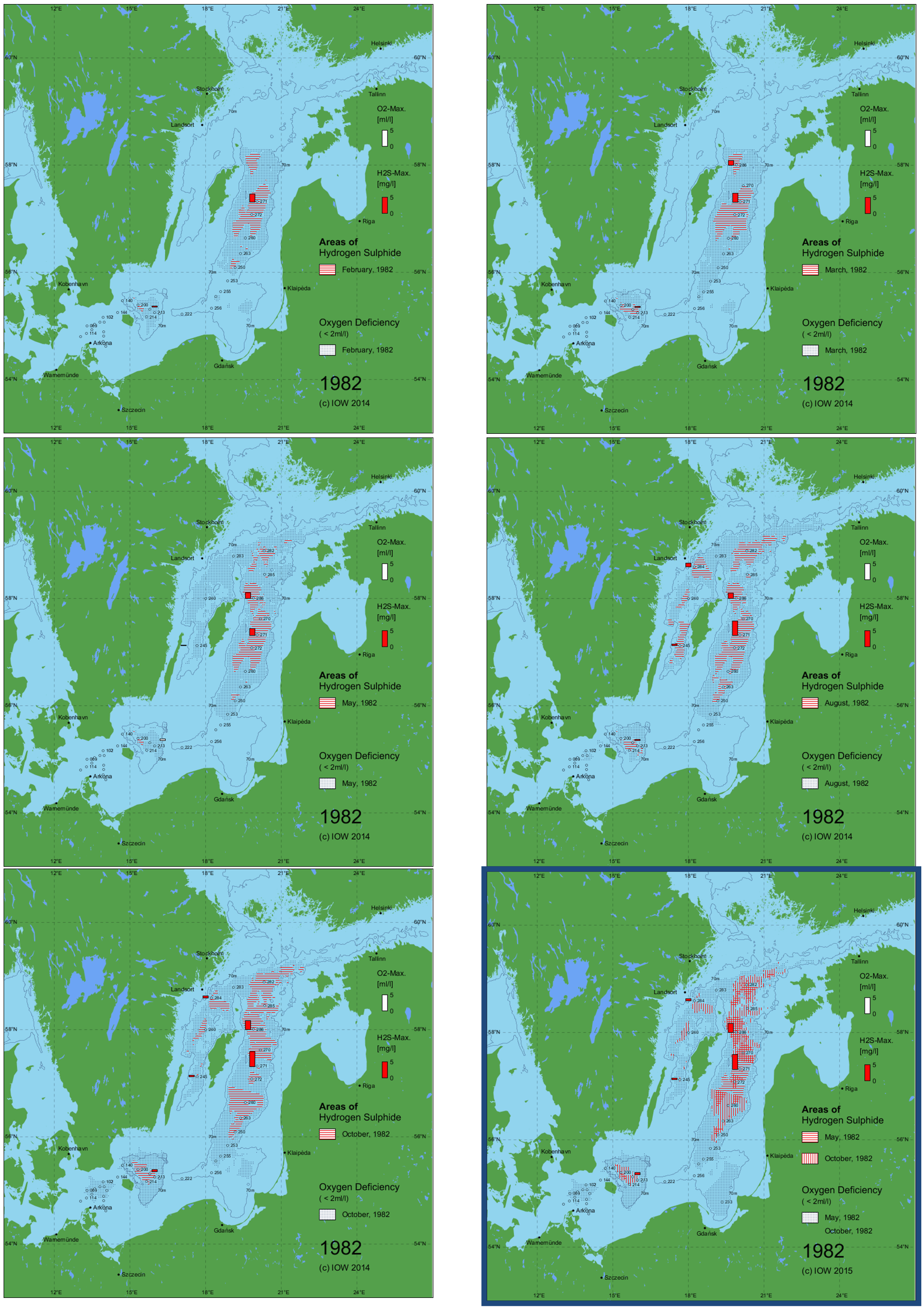

Fig. 28: Distribution maps for 1982. Stagnant conditions continued in all basins of the Baltic Proper in 1982, producing high concentrations of hydrogen sulphide in the deep water (NEHRING & FRANCKE, 1983b).

1983

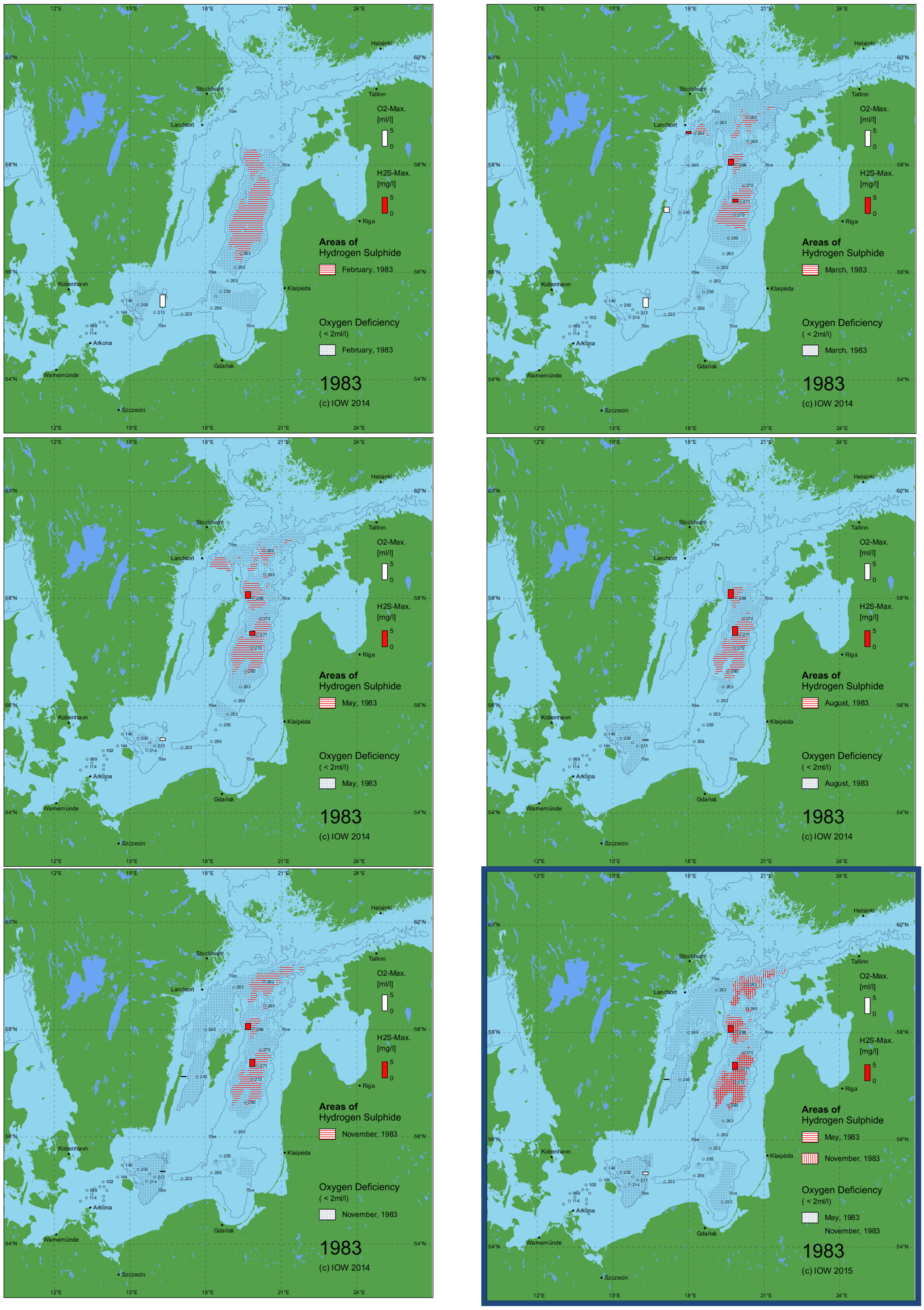

Fig. 29: Distribution maps for 1983. The moderate MBIs in December 1982 and January 1983 supplied the deep water of the Bornholm and Gdańsk Basins with oxygen. In March/April, the inflow of water containing oxygen was observed in the eastern Gotland Basin lifting up the stagnant bottom water in the Gotland Deep and forming an intermediate layer with H_2S. Anoxic conditions remained in the deep water of all other central basins during 1983 (NEHRING & FRANCKE, 1985a).

1984

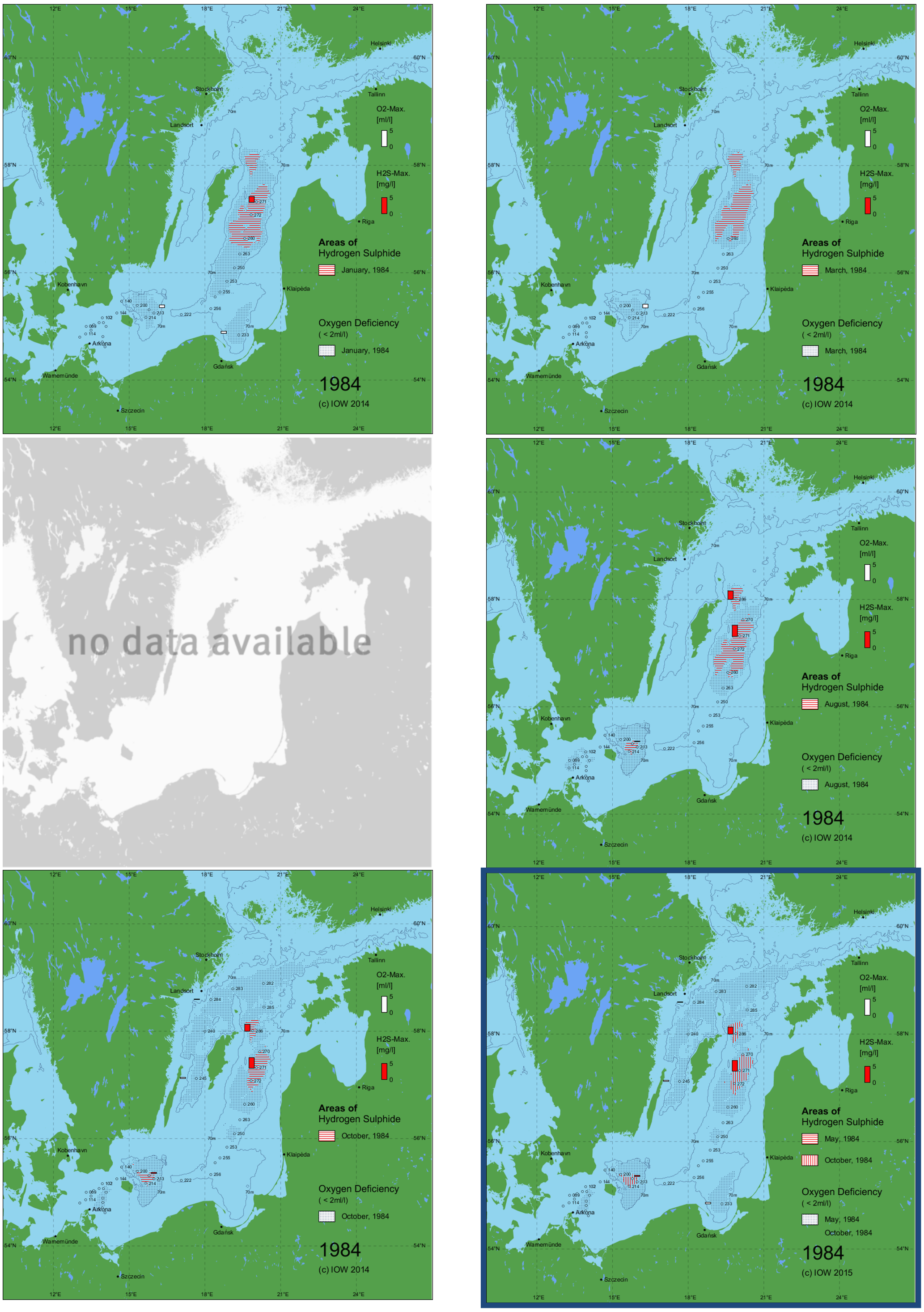

Fig. 30: Distribution maps for 1984. Although no MBI occured in winter 1983/84, the oxygen conditions improved in the bottom water of the Bornholm and Gdańsk Basins as well as in the northern and western Gotland Basins in 1984. The stagnation period continued in the eastern Gotland Basin, reaching high concentrations of H_2S below the halocline (NEHRING & FRANCKE, 1985b).

1985

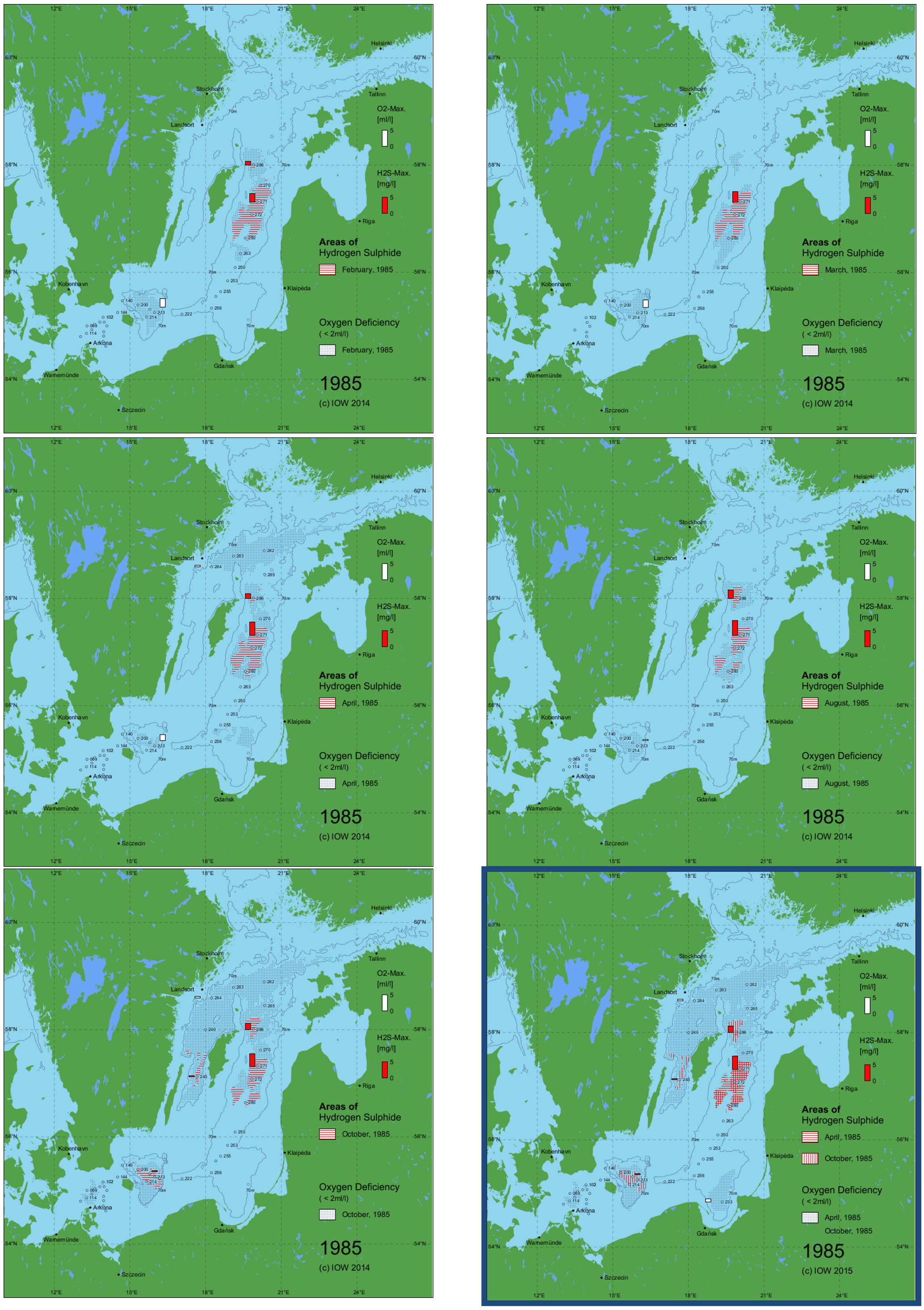

Fig. 31: Distribution maps for 1985. Except November 1985, oxygen was measured in the deep water of the Bornholm and the Gdańsk Basins during the whole year. In the eastern Gotland Basin, H_2S was present below the halocline in all seasons. As in 1984, oxygen was observed in the deep water of the other central basins. No anoxic conditions were detected in the bottom water of the Karlsö Deep in October 1985 (NEHRING & FRANCKE, 1987a).

1986

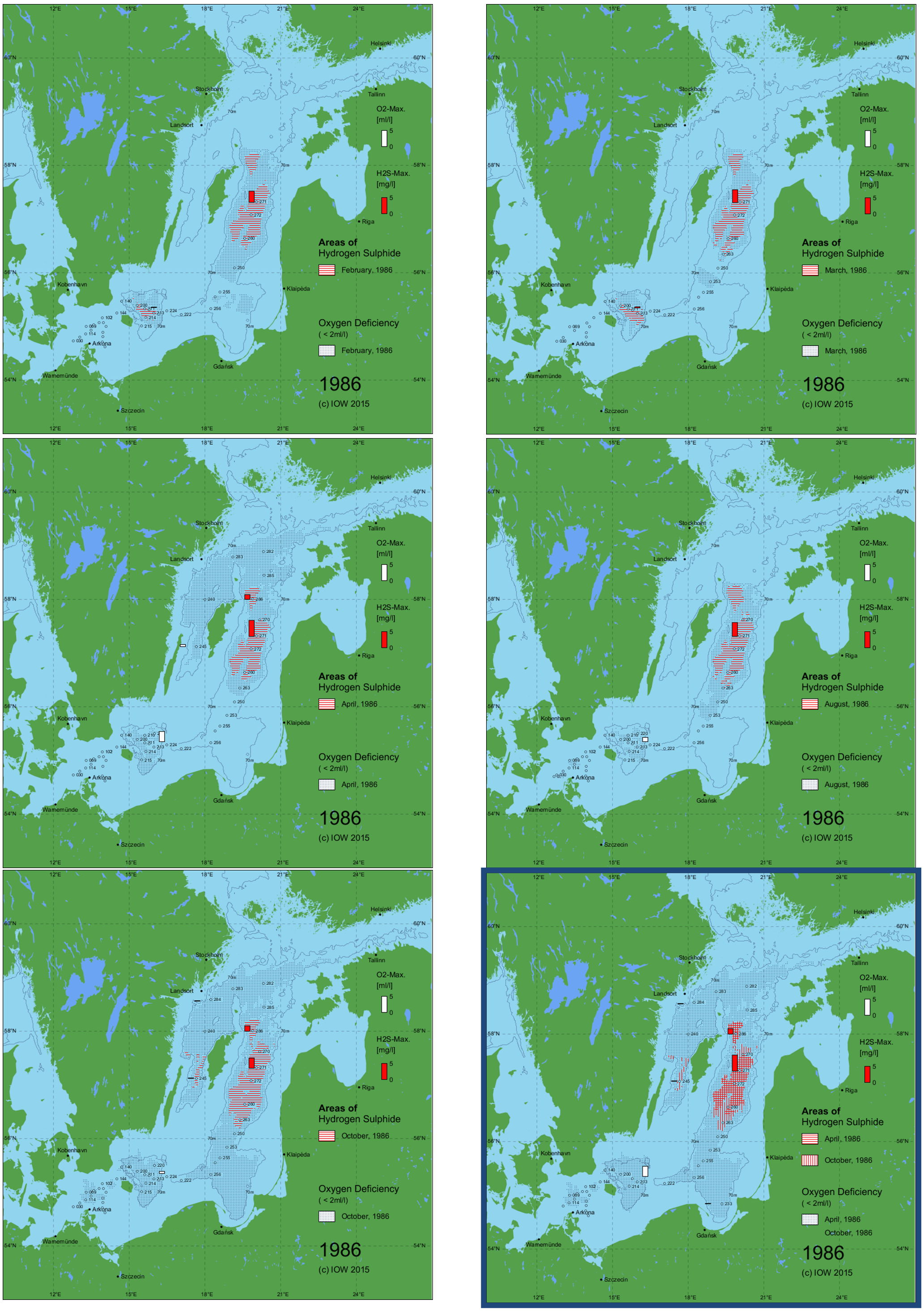

Fig. 32: Distribution maps for 1986. In February/March, H_2S was present in the deep water of the Bornholm Basin. Inflow events, not reaching the intensity of MBIs, supplied this basin with oxygen in April/May. Oxic conditions were observed in the Gdańsk Basin during the whole year. H_2S was present in the deep water of the eastern Gotland Basin during 1986. Oxic conditions prevailed below the halocline in the northern and western basins, except in the Karlsö Deep with anoxic conditions near the bottom in November 1986 (NEHRING & FRANCKE, 1987b).

1987

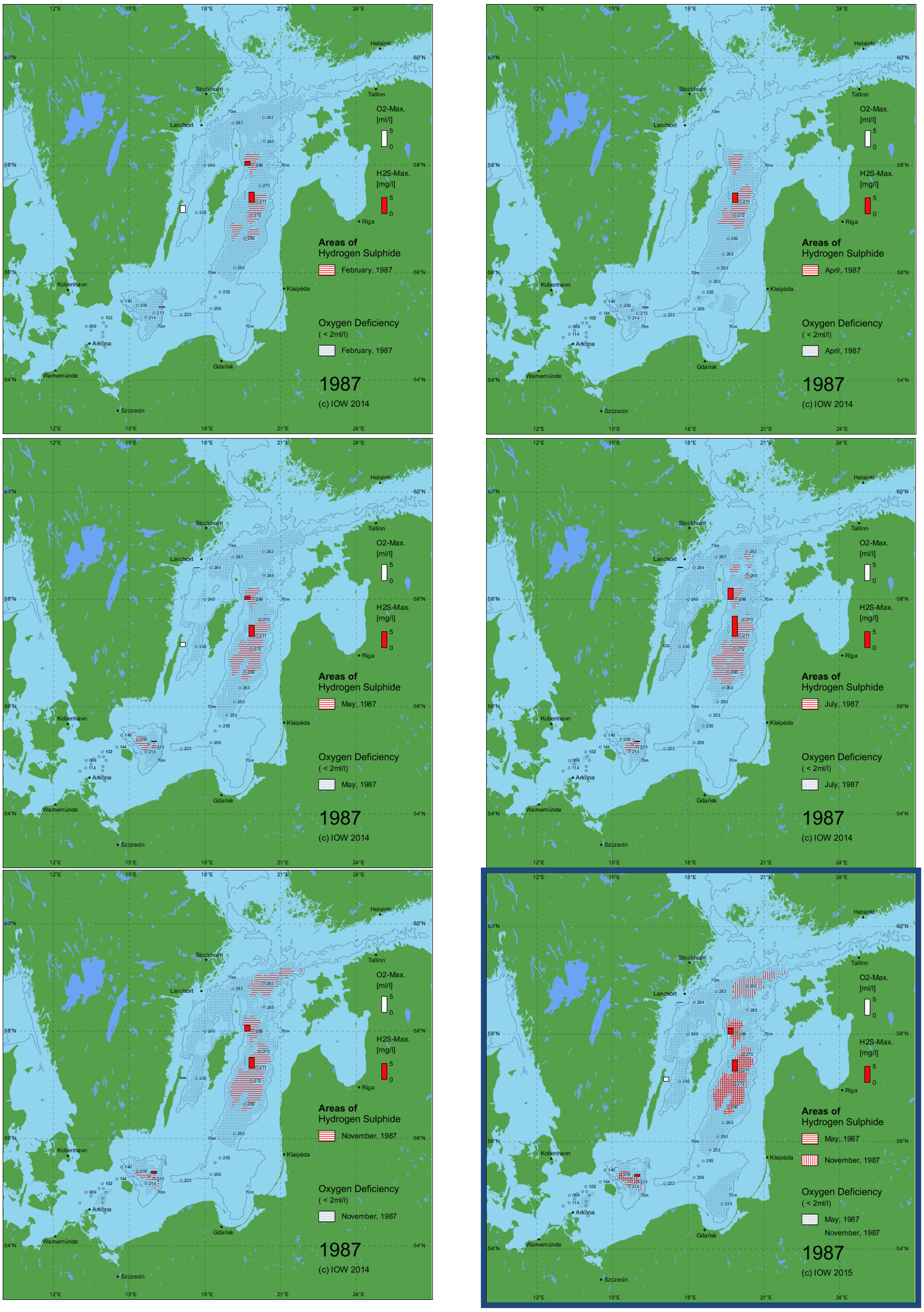

Fig. 33: Distribution maps for 1987. The renewal of the deep water in the western and northern Gotland Basins caused improvements in the oxygen conditions in May and July 1987. In November, H_2S was observed again in the bottom water of the northern basin. In the deep water of the eastern Gotland Basin, the stagnation period continued, characterized by high concentrations of H_2S. H_2S was observed since April in the bottom water of the Bornholm Basin and since July in the Gdańsk Basin (NEHRING & FRANCKE, 1988).

1988

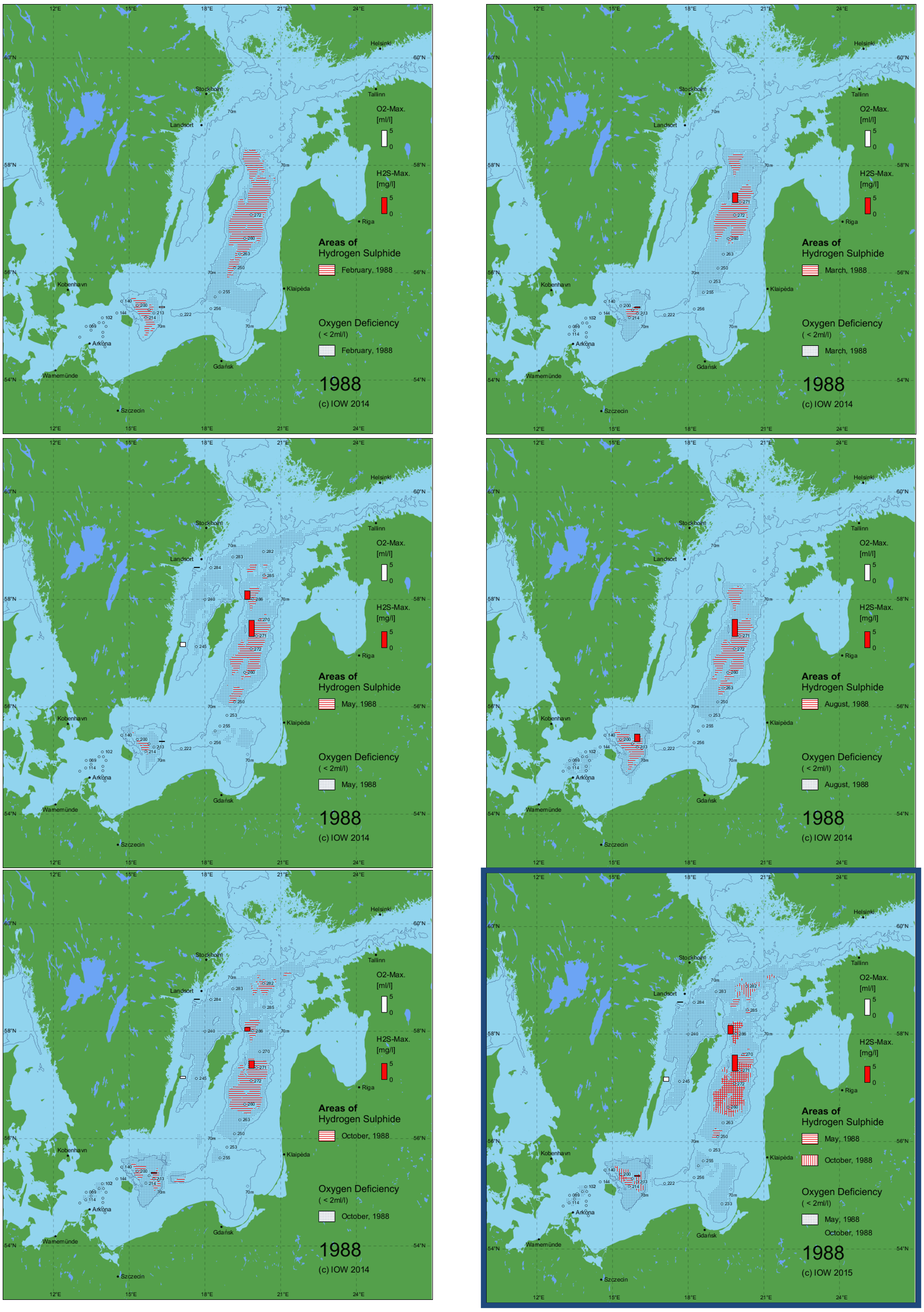

Fig. 34: Distribution maps for 1988. Anoxic conditions with partly high concentrations of H_2S dominated the deep water in the Bornholm and Gdańsk Basins as well as in the eastern Gotland Basin in 1988. In contrast to these basins, oxygen was measured in the bottom water of the northern and western Gotland Basins in May and November (NEHRING & FRANCKE, 1990a).

1989

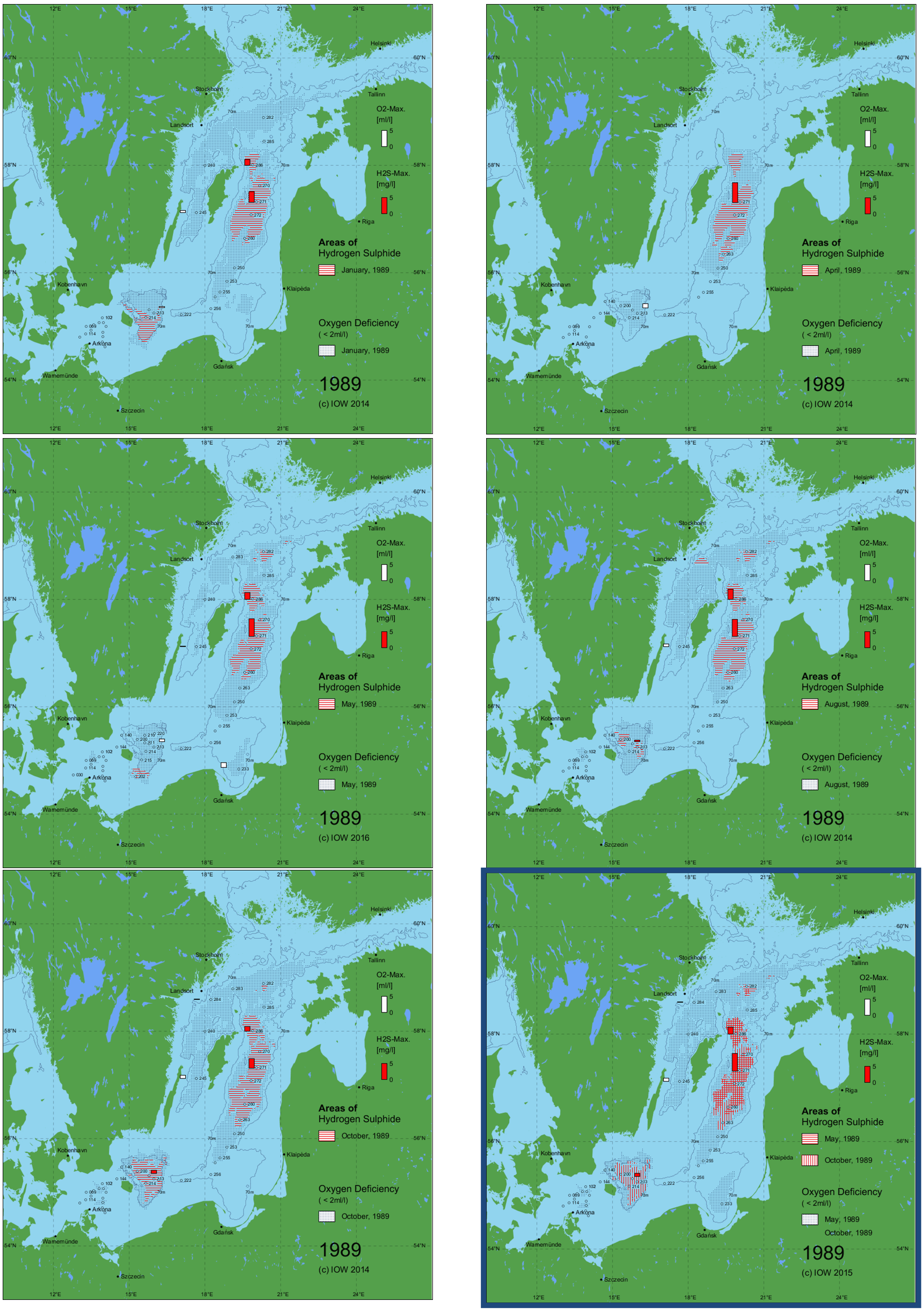

Fig. 35: Distribution maps for 1989. Oxygen was present in the bottom water of the Bornholm Basin until May 1989. Later on, H_2S developed. In the Gdańsk Basin, no H_2S was detected during the whole year. Due to the ongoing stagnation, H_2S was measured below the halocline at all investigations in the eastern Gotland Basin in high concentrations. Whereas no anoxic conditions were observed in the western Gotland Basin, low concentrations of H_2S were measured in the northern Basin in May, April, and November 1989 (NEHRING & FRANCKE, 1990b).

1990

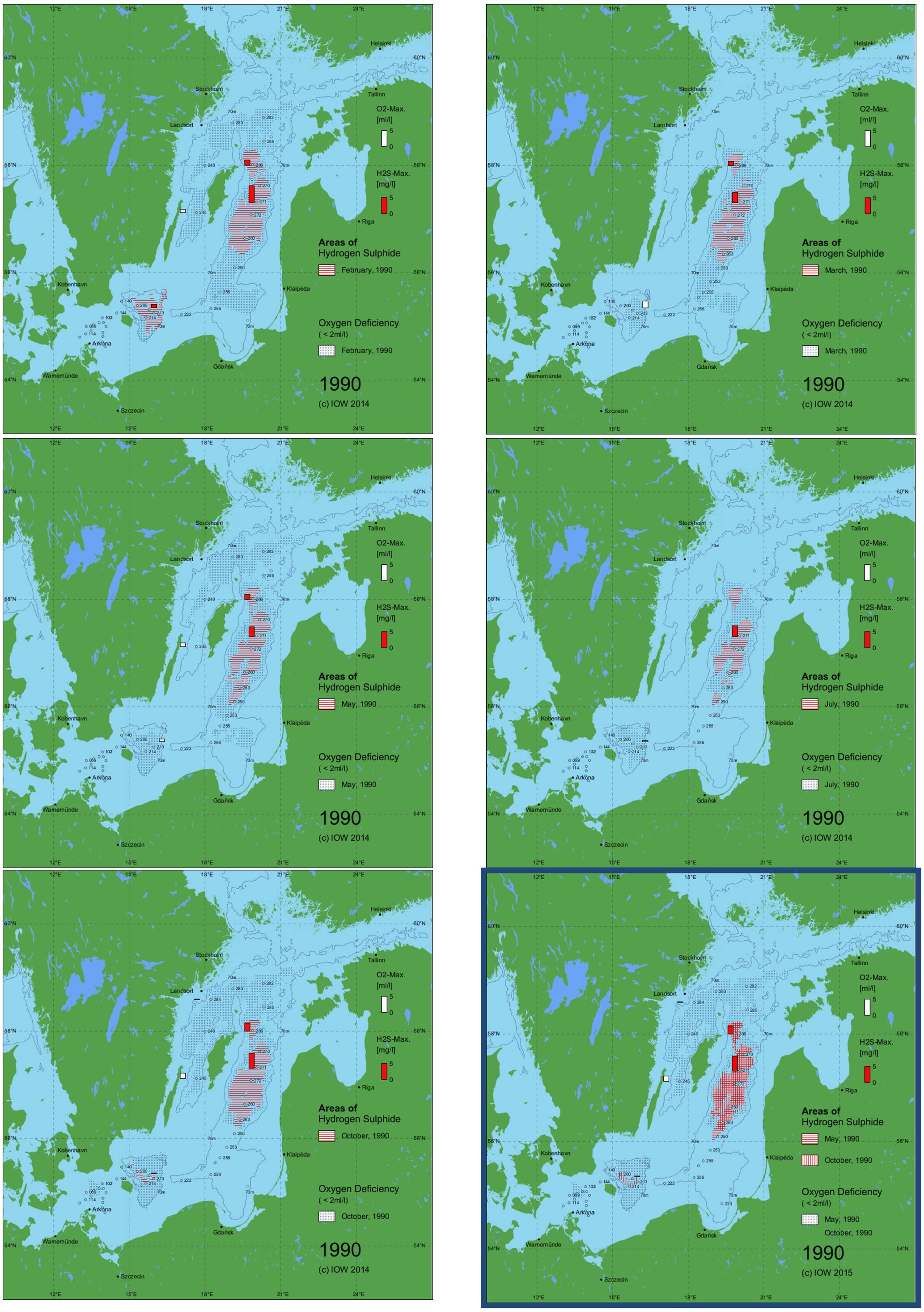

Fig. 36: Distribution maps for 1990. Inflows into the Baltic Proper, not reaching the intensity of MBIs pushed away the anoxic deep water in the Bornholm and Gdańsk Basins and supplied them with oxygen in March. In November, anoxic conditions returned in the Bornholm Basin, but not in the Gdańsk Basin. The eastern Gotland Basin was characterized by stagnant conditions with very high concentrations of H_2S (cf. Fig. 3). Oxygen was present in the deep water of the northern and western Gotland Basins during the whole year (NEHRING, 1991).

1991

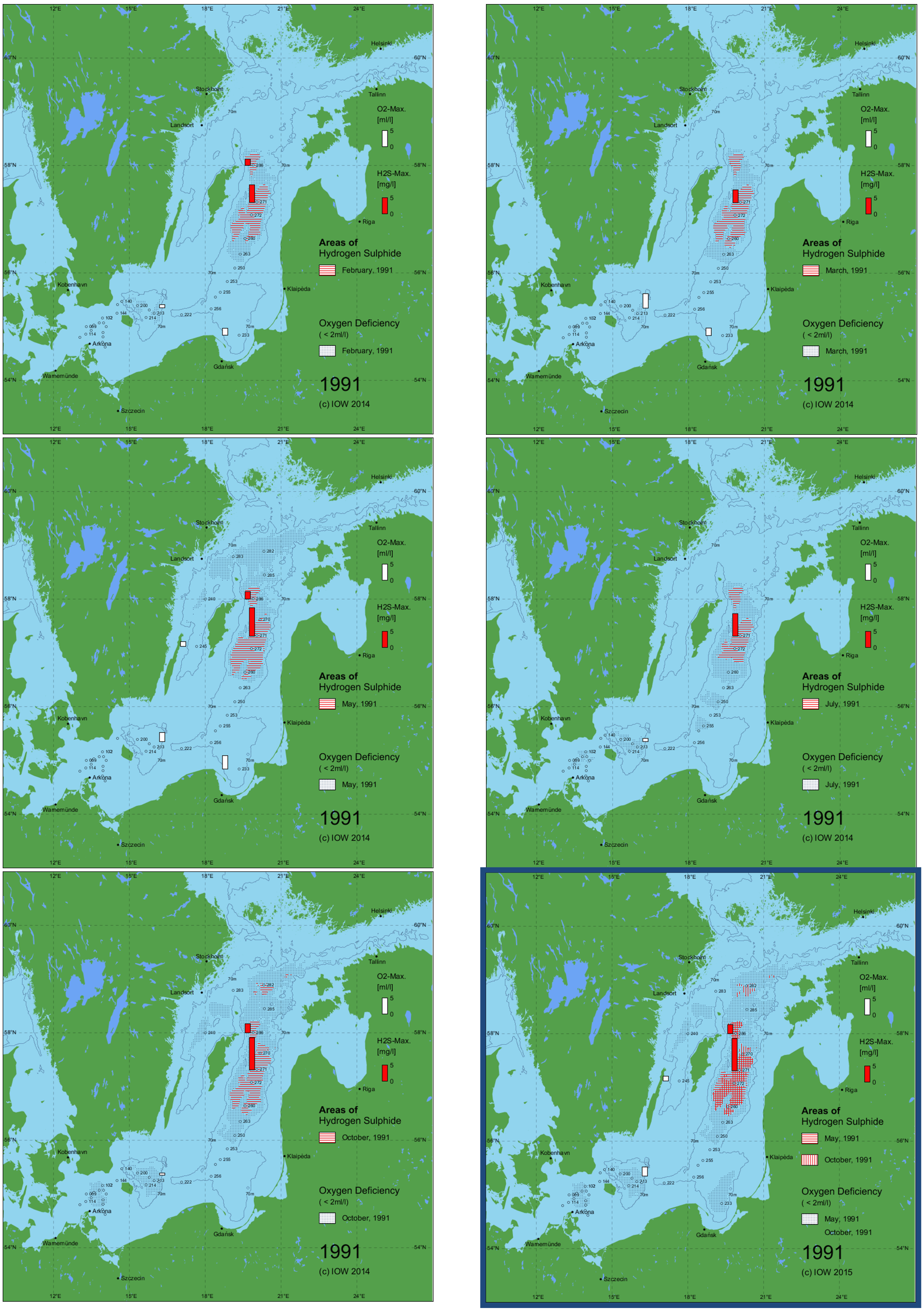

Fig. 37: Distribution maps for 1991. The inflow of deep water, not meeting the criteria of a MBI, supplied the Bornholm and the Gdańsk Basins with oxygen in February and March 1991. This inflow affected the distribution of oxygen in the shallow parts of the eastern Gotland Basin as well. However, H_2S was observed in the deep water of the Gotland and Fårö Deeps in very high concentrations during the whole year. In May/June, oxygen concentrations above 1 ml/l were observed in the bottom water of the western Gotland Basin (NEHRING & MATTHÄUS, 1991/92).

1992

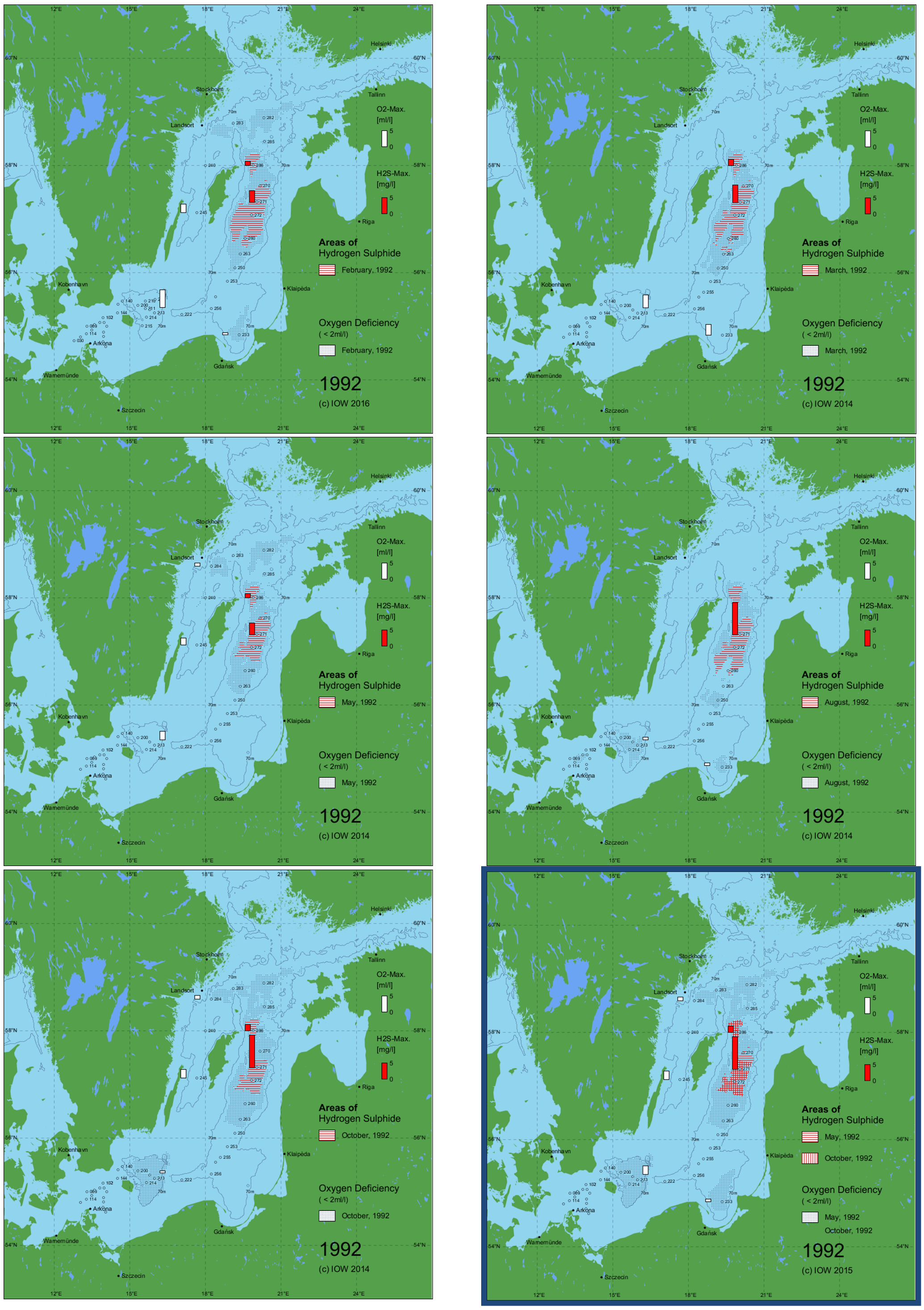

Fig. 38: Distribution maps for 1992. As in 1991, week inflows into the Baltic Proper supplied the deep water of the Bornholm Basin with oxygen in February and April 1992. Effects of this event were also observed in the eastern Gotland Basin. However, this inflow could not replace the anoxic deep water below 125 m to 150 m, which was characterized by extremely high concentrations of H_2S. No data were available from the Gdańsk Basin and the northern and western Gotland Basin in 1992 (NEHRING et al., 1993).

1993

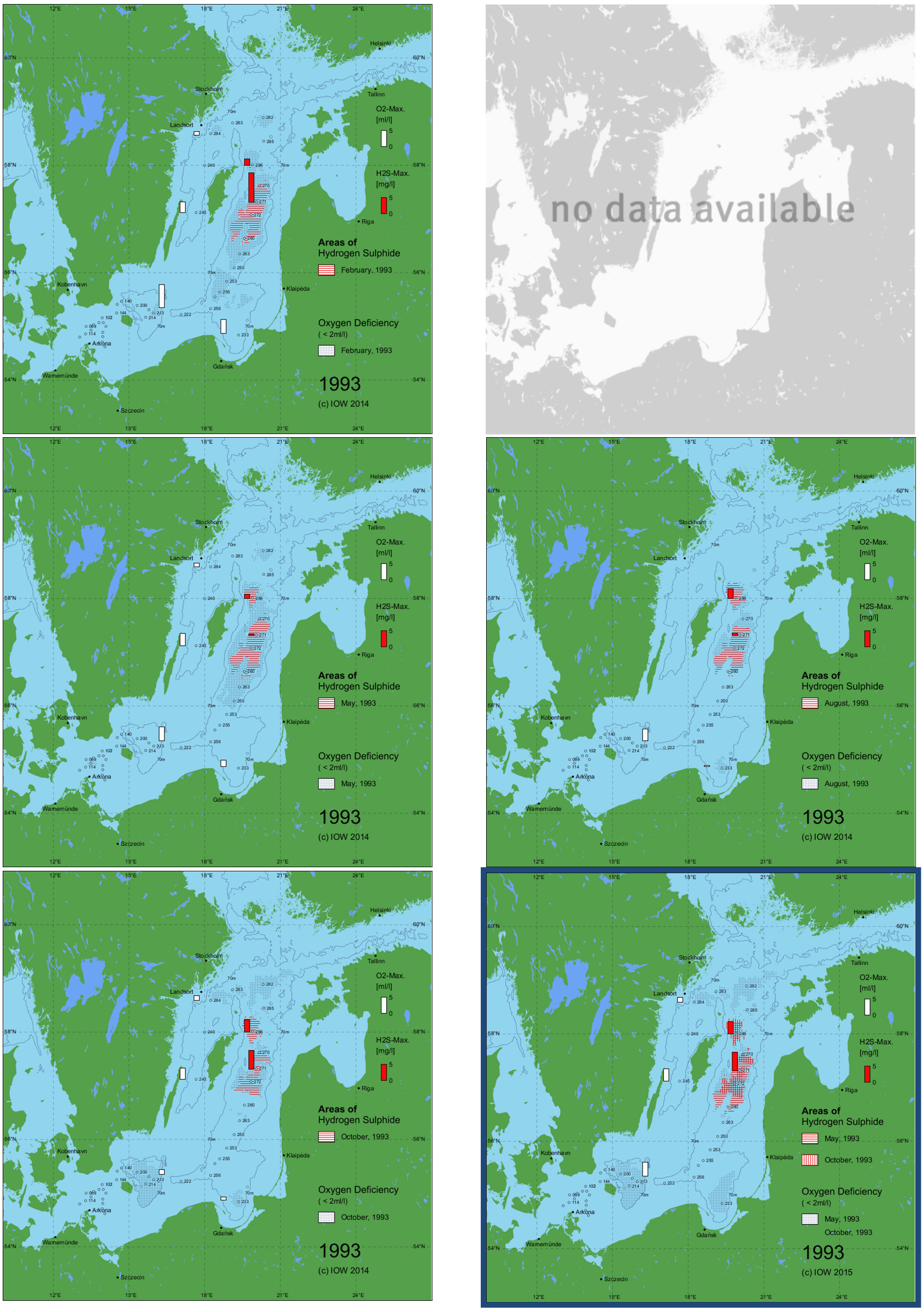

Fig. 39: Distribution maps for 1993. In January 1993, a very strong MBI occurred (see Table 1) which was of great importance for the oxygen conditions in the whole central Baltic deep water. The event caused an increase in oxygen concentrations in the deep water of the Bornholm and Gdańsk Basins. Favoured by pulsations of the inflow through the Słupsk Furrow short-term fluctuations between oxic and anoxic conditions occurred during the deep water renewal in the eastern Gotland Basin (NEHRING et al., 1994a, 1994b).

1994

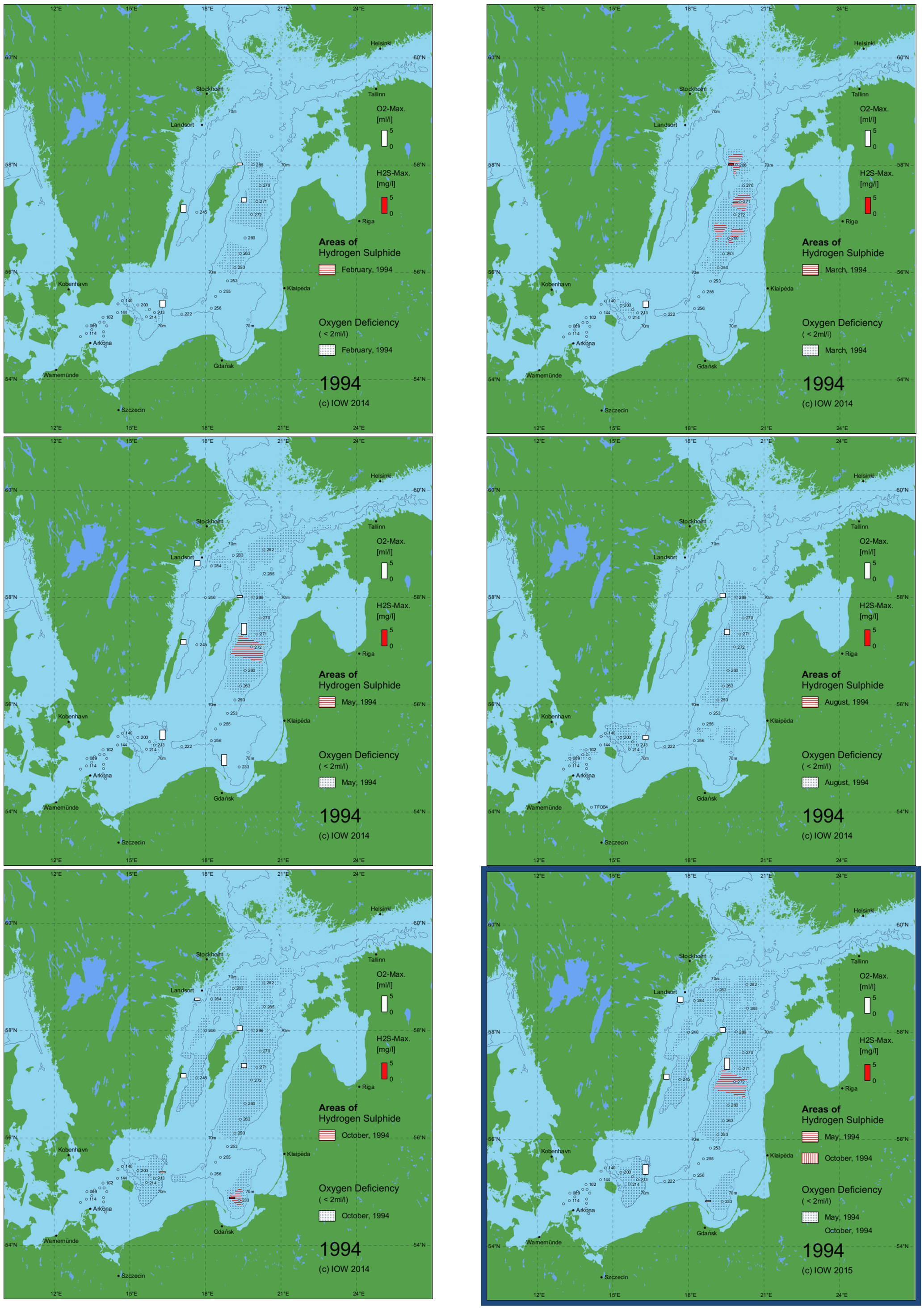

Fig. 40: Distribution maps for 1994. Small inflows in December 1993 and March 1994 in combination with the very strong MBI in January 1993 terminated the 16-year stagnation in the central Baltic. The inflows caused a significant improvement of the oxygen conditions in the eastern Gotland Basin deep water and led to the highest oxygen concentrations since the 1930s (Fig. 3). The favourable oxygen conditions continued until the end of the year (NEHRING et al., 1995a, 1995b).

1995

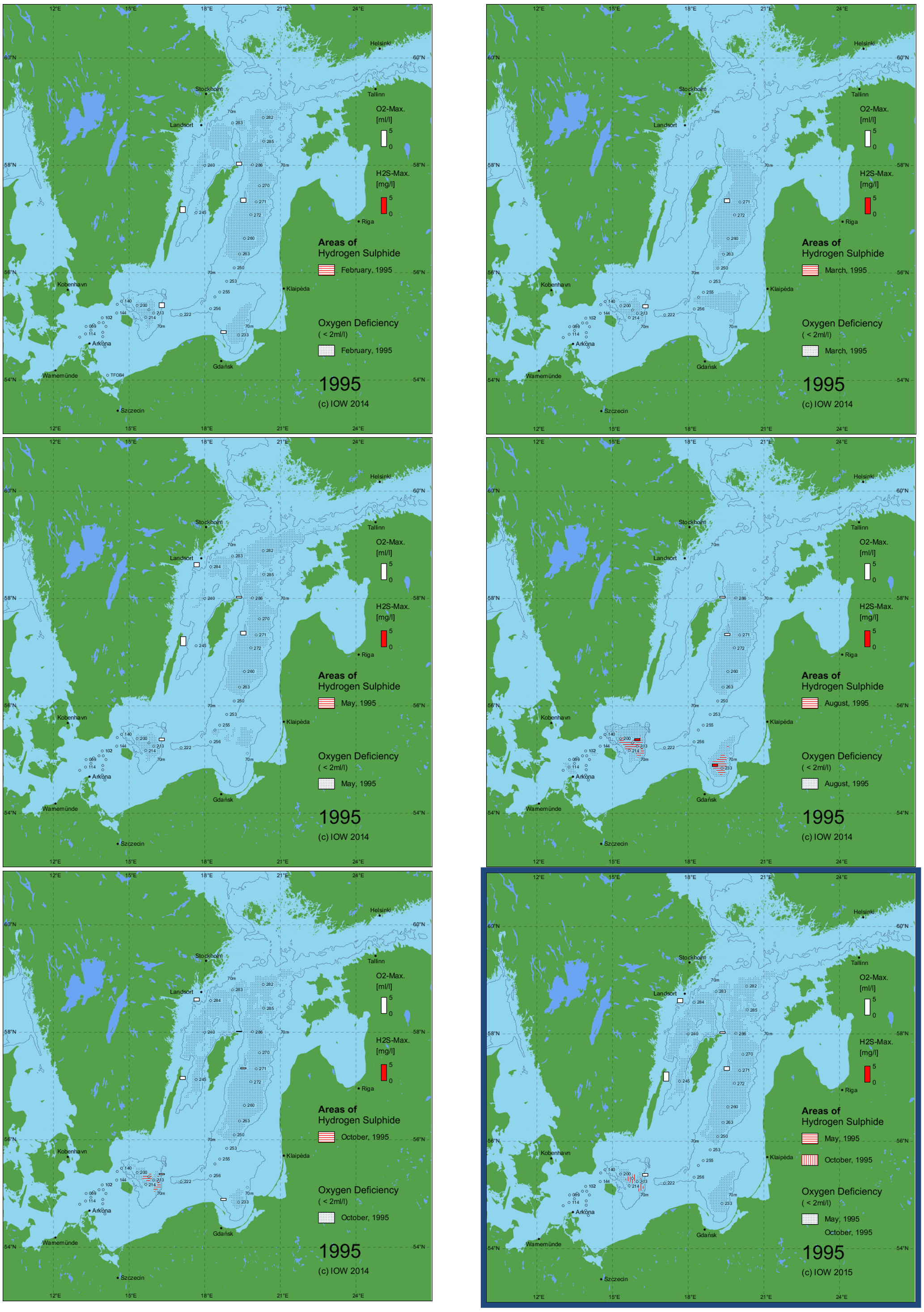

Fig. 41: Distribution maps for 1995. Small inflow events below the MBI level in November and December 1994 and in spring 1995 only increased the oxygen concentration in the Bornholm Basin deep water. The central Baltic deep water was free of hydrogen sulphide. The weak inflow intensity in 1995 favoured the beginning of a new stagnation in the central Baltic. Oxygen conditions generally deteriorated in the eastern Gotland Basin. Hydrogen sulphide was found as early as May in the Gdańsk Basin and in the Bornholm Basin from August 1995 onwards (NEHRING et al., 1995c, 1996).

1996

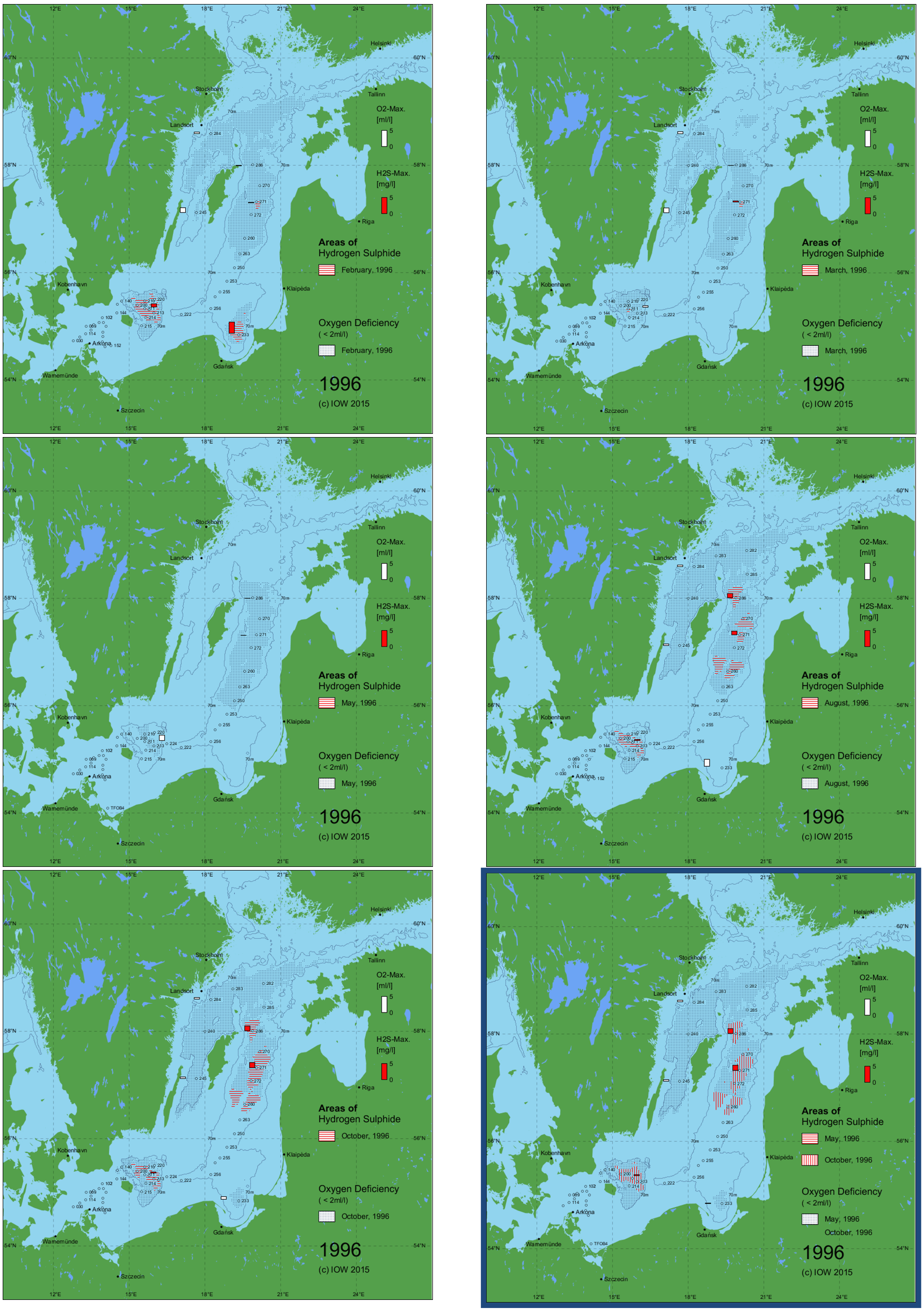

Fig. 42: Distribution maps for 1996. Advective processes linked with minor inflow events in March and June 1996 supplied the deep water of the Bornholm and Gdańsk Deeps with small amounts of oxygen. Conditions in the central Baltic deep water deteriorated due to the continued stagnation. H_2S was observed in the Gotland and Fårö Deeps for the first time since 1994. An intensive inflow in the beginning of November, which just failed the criteria for a MBI, transported water with salinities of 26 and 20 g/kg across the Drogden and Darss Sills respectively (MATTHÄUS et al., 1996, 1997).

1997

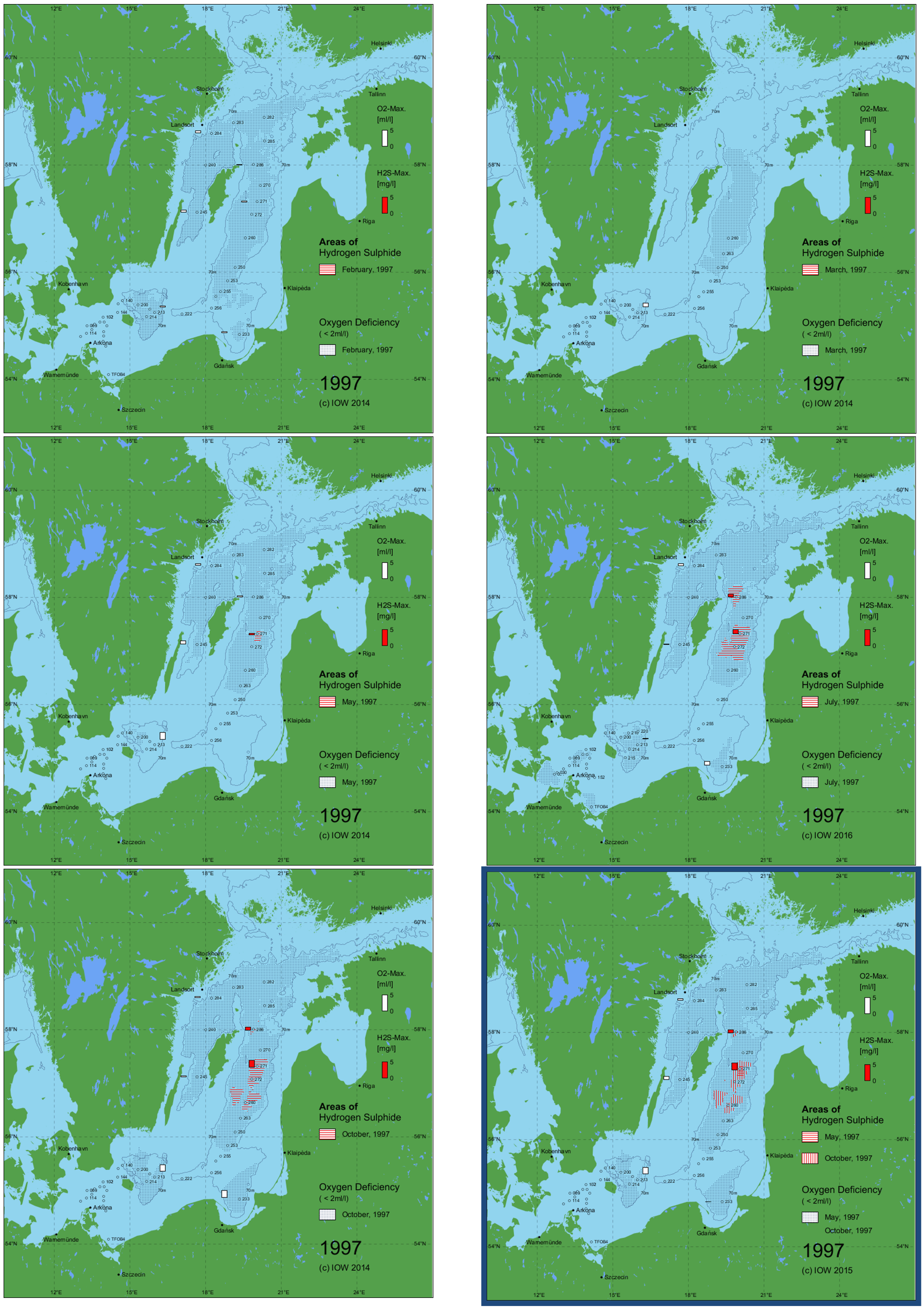

Fig. 43: Distribution maps for 1997. Because of the November 1996 inflow, the central Baltic deep water became oxic until May. From August onwards, the layer below 150 m in the eastern Gotland Basin again became anoxic. The western Gotland Basin deep water continues to be oxic. In September, an inflow of exceptionally warm, saline and oxygenated water occurred, later identified as a moderate MBI (MATTHÄUS, 2006). At the end of October, the oxygen-rich water crossed the Słupsk Furrow into the central Baltic Sea (MATTHÄUS et al., 1998a, 1998b).

1998

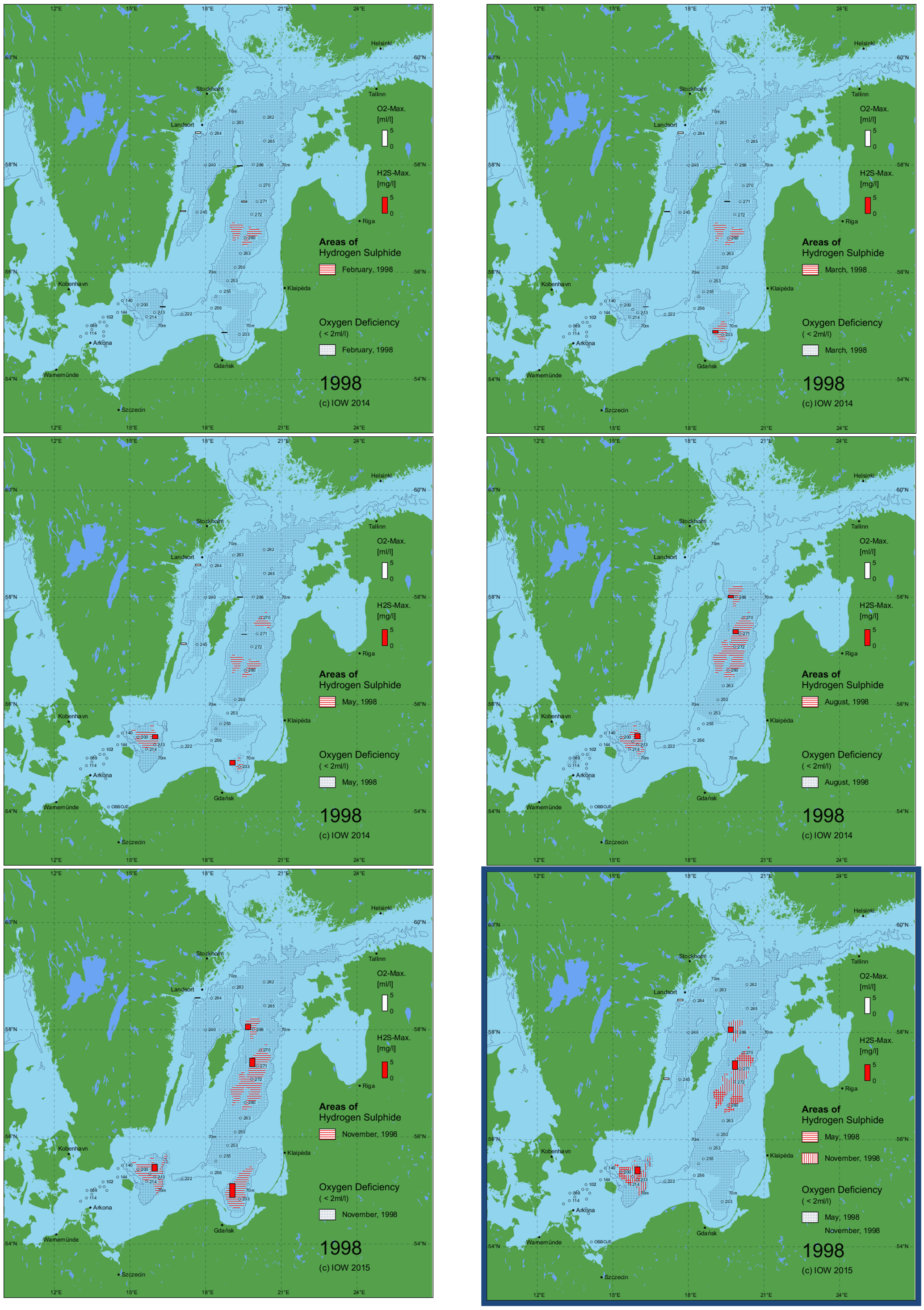

Fig. 44: Distribution maps for 1998. The inflow of saline and oxygen-rich, but unusually warm water into the Baltic Sea in autumn 1997 (HAGEN & FEISTEL, 2001) temporarily interrupted the anoxic conditions in the eastern Gotland Basin between January and April 1998. From May onwards, hydrogen sulphide was again measured in the Bornholm Basin and partly in the Gdańsk Deep and, beginning in June, in the eastern Gotland Basin. Oxygen depletion continued in the deep water of the western Gotland Basin (MATTHÄUS et al., 1999a, 1999b).

1999

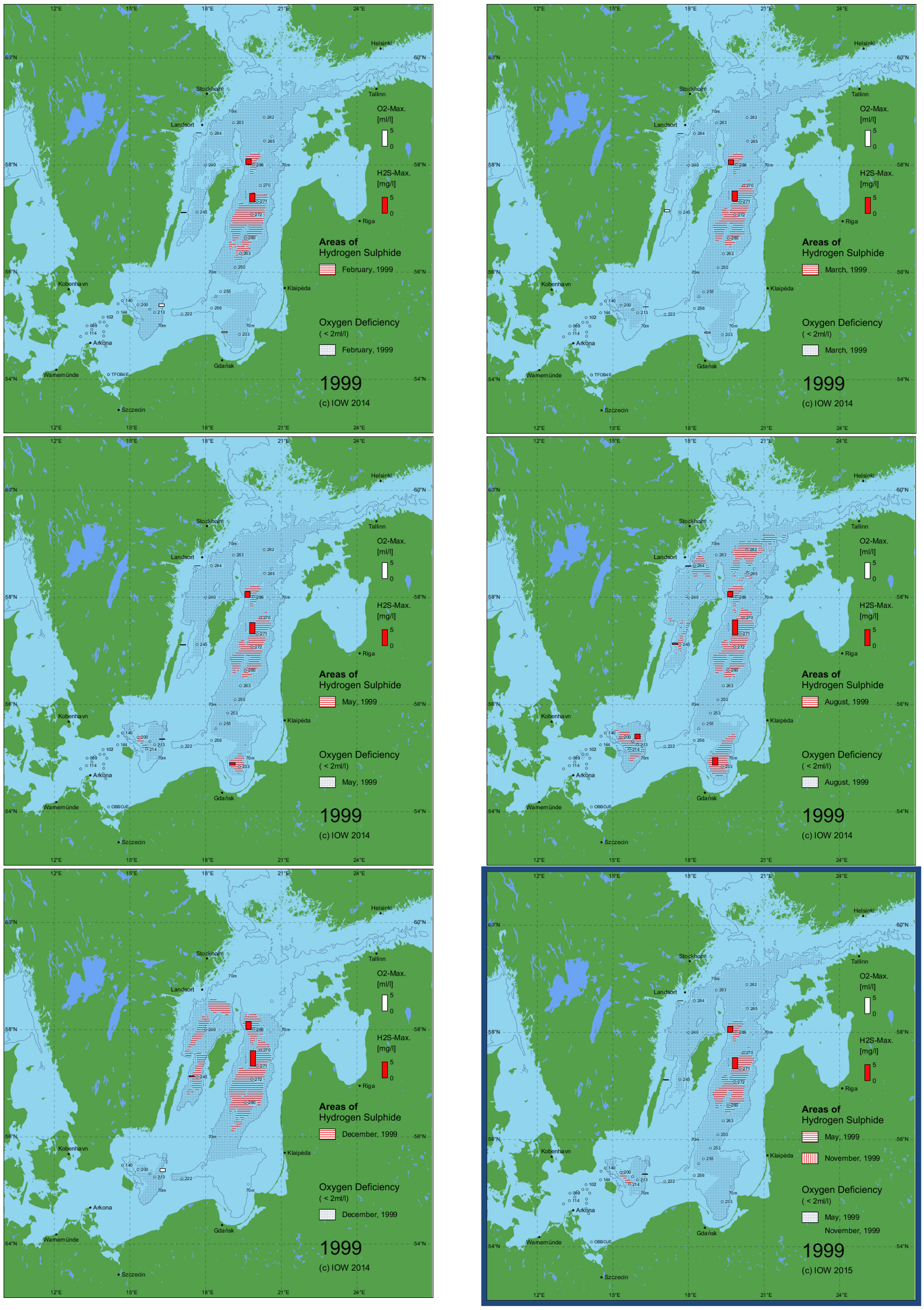

Fig. 45: Distribution maps for 1999. Inflows in October and late December 1998 led to the renewing of the Bornholm Basin deep water in spring 1999. From May onwards, hydrogen sulphide was measured in that basin up to the end of November when other small inflows led again to oxic conditions. In the eastern Gotland Basin, the anoxic water covered the layer between bottom and about 130 m depth all the year round. In the deep water of the western Gotland Basin, oxygen depletion has continued and H_2S formation started in August (MATTHÄUS et al., 2000, 2001a).

2000

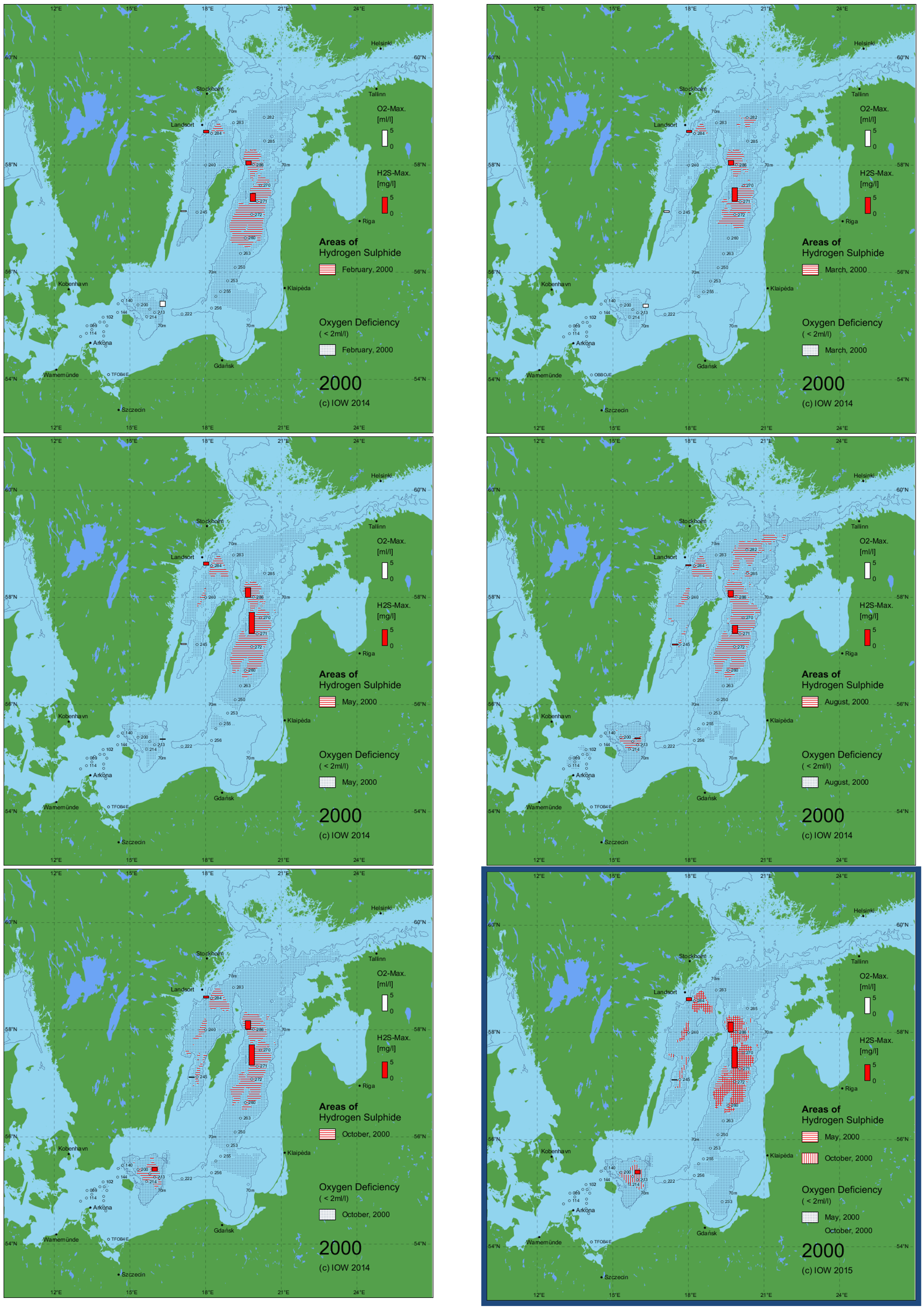

Fig. 46: Distribution maps for 2000. Weak inflows in December 1999 and February 2000 led to the renewal of the Bornholm Basin deep water in spring. From August onwards, hydrogen sulphide was measured in that basin up to mid-November. In the eastern Gotland Basin, anoxic water covered the layer between bottom and 120 – 125 m all the year round. In the deep water of the western Gotland Basin, oxygen depletion has continued since 1993. Since August 1999, hydrogen sulphide has been partly present in the western basin deep water (MATTHÄUS et al., 2001b, 2001c).

2001

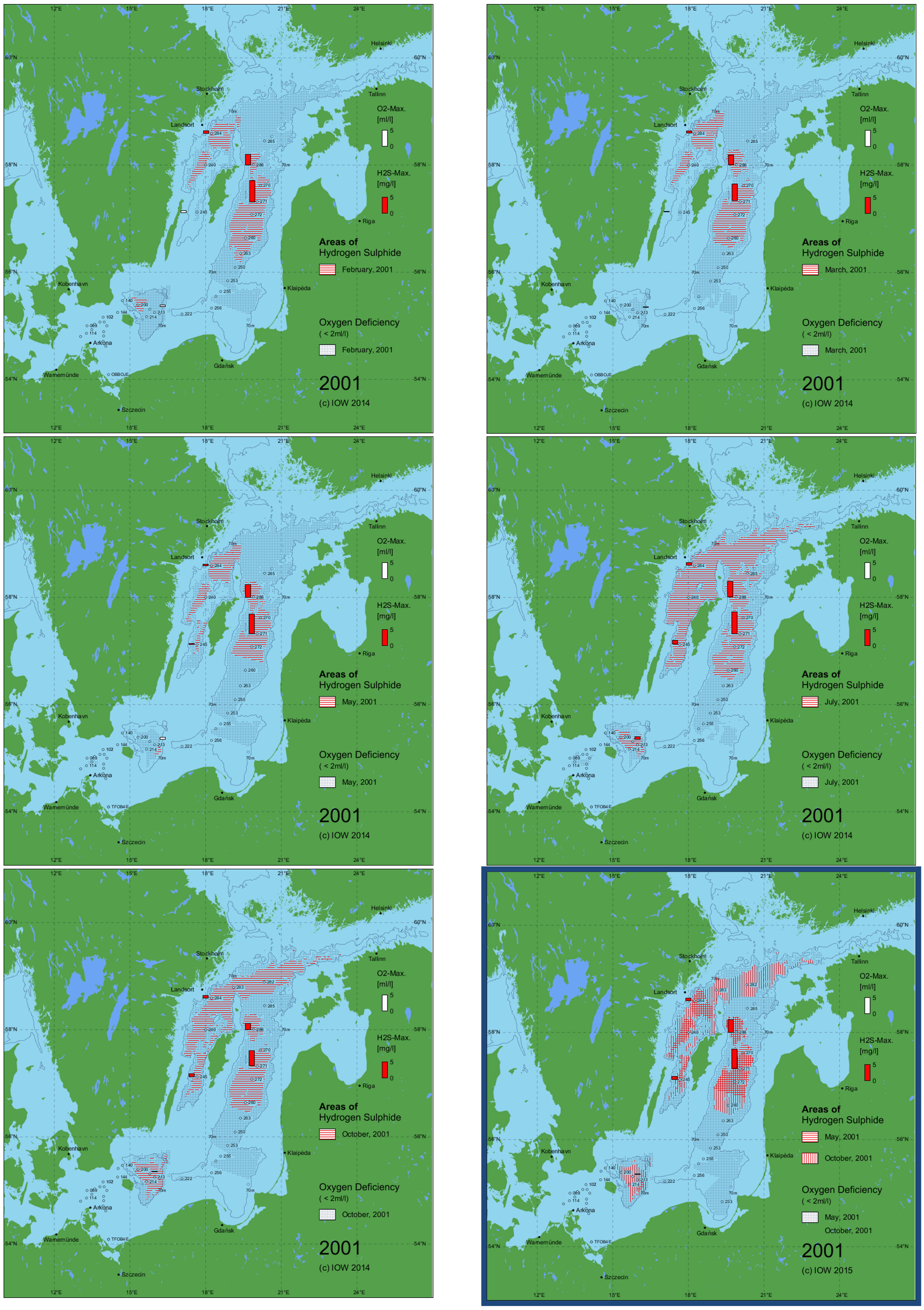

Fig. 47: Distribution maps for 2001. 2001 was characterized by low inflow activity. Only in Oct./Nov. a stronger inflow event occurred (FEISTEL et al., 2003a) causing a rapid increase of the O_2 content in the deep water of the Bornholm Basin up to 4.68 ml/l in December. The stagnation lasting since 1995 continued in all deep basins of the central Baltic Sea. In the eastern Gotland Basin, the anoxic water covered the layer between 125 m and the bottom whereby the H_2S concentrations near the bottom layer were comparable to that measured at the end of the long lasting stagnation period in 1992 (NAUSCH et al., 2002).

2002

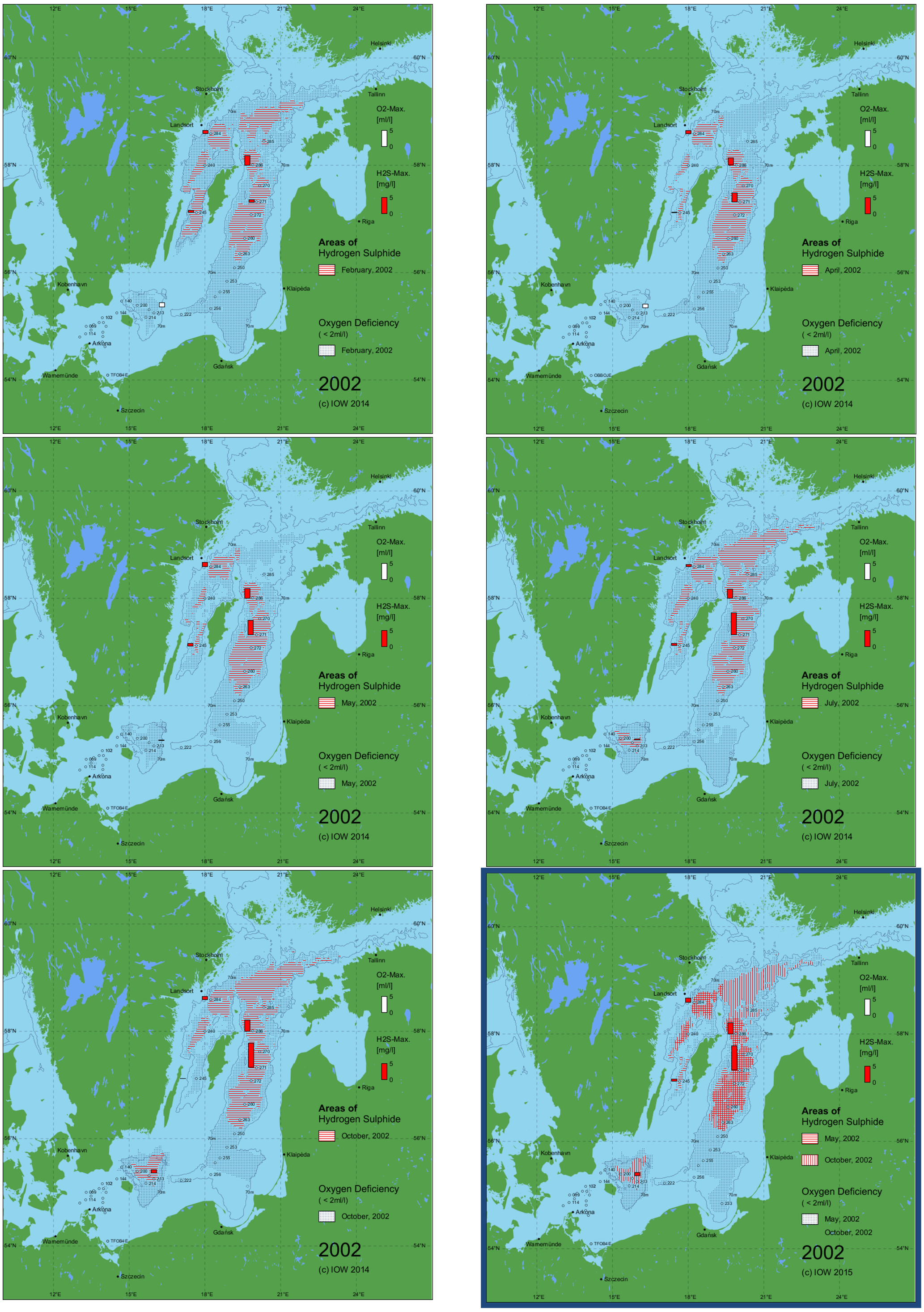

Fig. 48: Distribution maps for 2002. In Aug./Sept. 2002, the Darss Sill mast recorded inflowing water (FEISTEL et al., 2003b, 2004) in a thick bottom layer with high salinity and O_2 content between 4 and 1 ml/l, which carried exceptionally warm water into the adjacent basins. In Oct./Nov. 2002, an additional small inflow occurred, which added even more warm water and caused a ventilation of the Gdańsk Basin by November. Warm water later propagated further towards the eastern Gotland Basin and improved the stagnation conditions slightly without terminating it (NAUSCH et al., 2003a).

2003

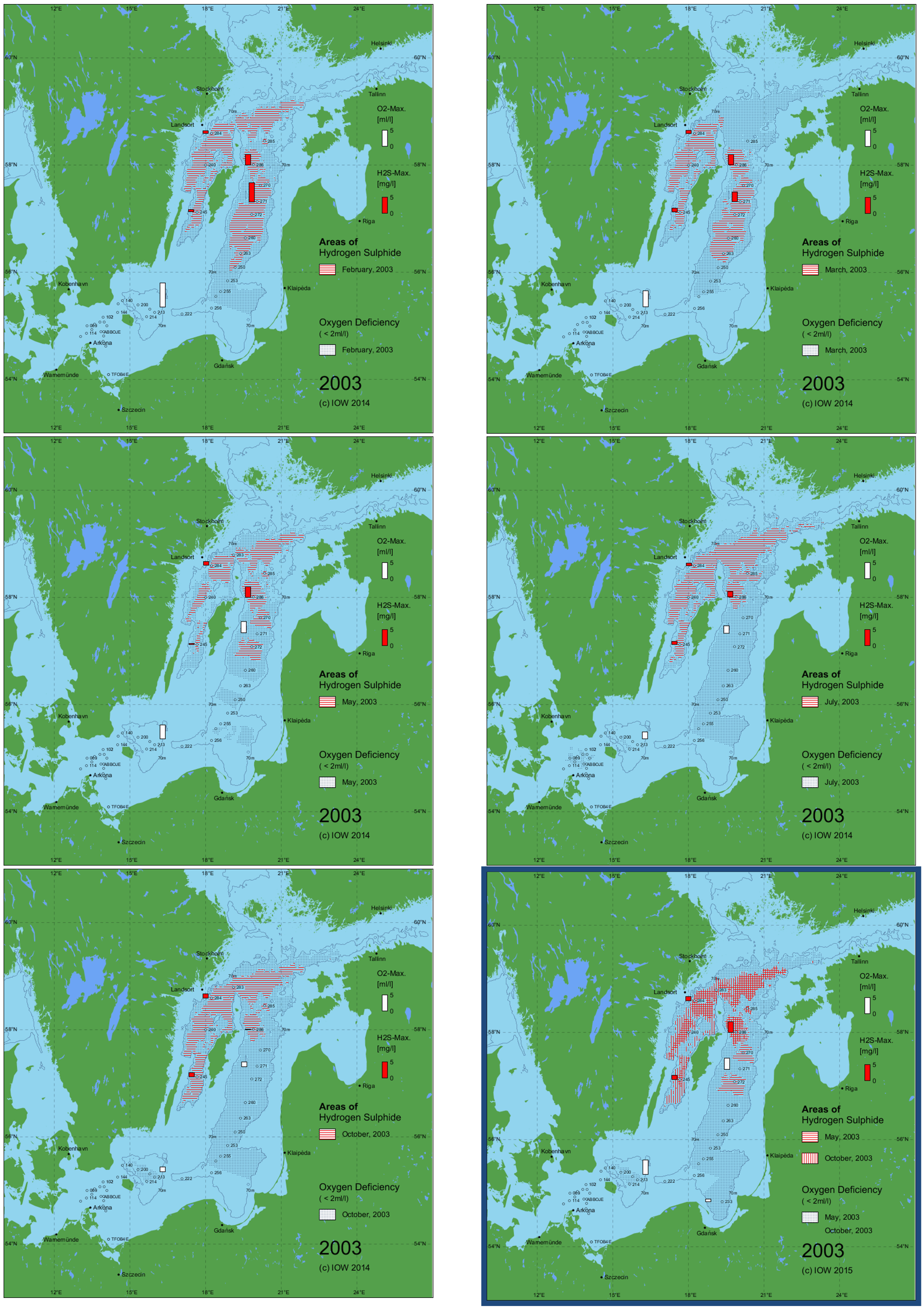

Fig. 49: Distribution maps for 2003. The most important event for the Baltic Sea in 2003 was the intensive, cold and oxygen-rich inflow of Kattegat water in January terminating the stagnation period lasting since 1995 (FEISTEL et al., 2003c; NAUSCH et al., 2003b; PIECHURA & BESZCZYNSKA-MÖLLER, 2004). However, only half the amount of water and salt was transported during this MBI compared to 1993. The inflow had grasped the Bornholm Basin in February whereas the ventilation of the eastern Gotland Basin was recorded at the end of April. In May an O_2 content of 3.96 ml/l could be measured near the bottom in the Gotland Deep (cf. Fig. 3) (NAUSCH et al., 2004).

2004

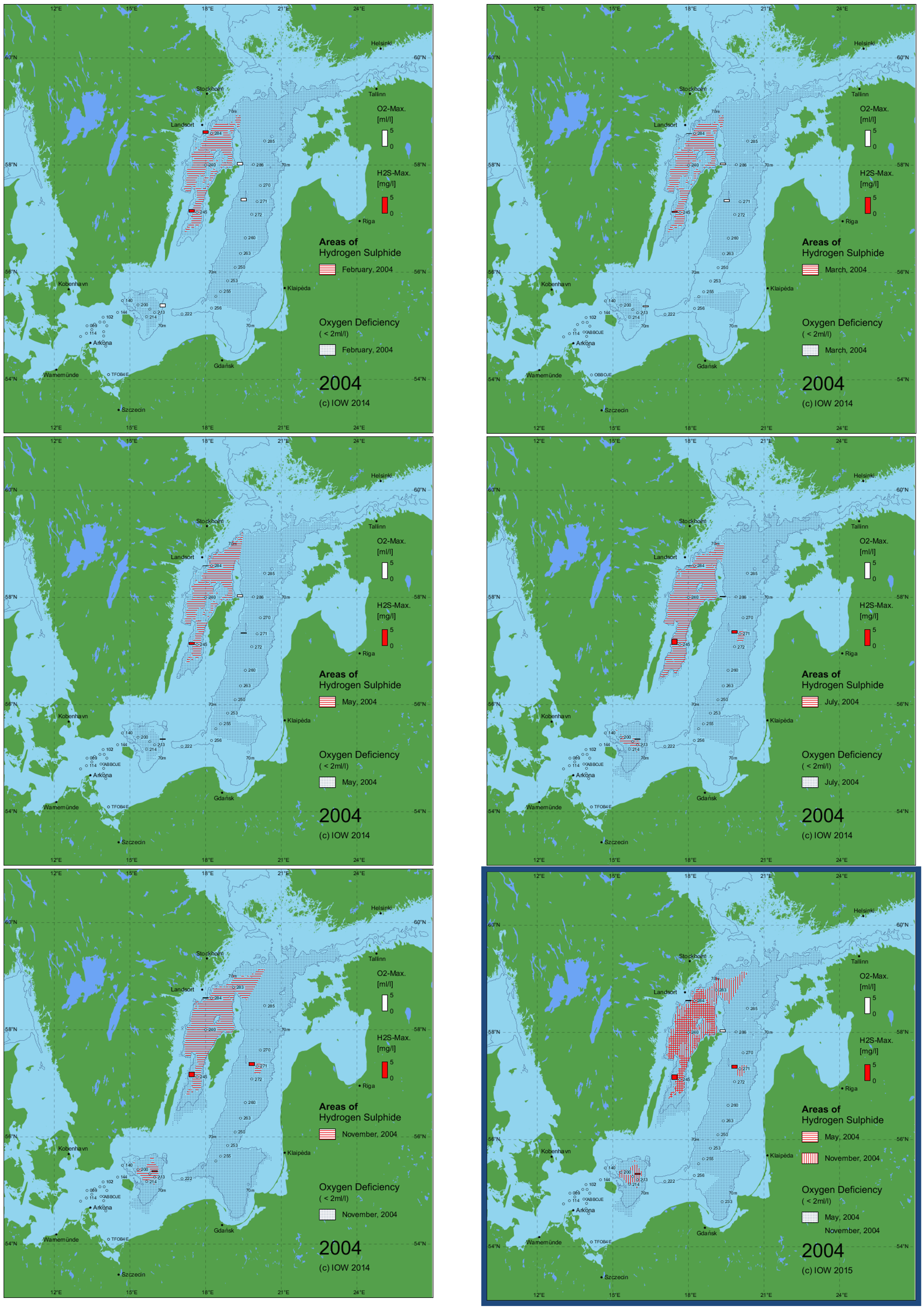

Fig. 50: Distribution maps for 2004. Main focus was on the lingering effects of the MBI of January 2003 in the deep water of the different basins. During the course of 2004, the oxygen content in the Bornholm and eastern Gotland Basins decreased continuously due to mineralisation processes. In the Gotland Deep, again anoxic conditions have restored below 200 m water depth indicating the beginning of a new stagnation period. In the Landsort Deep, traces of oxygen were found only shortly and the Karlsö Deep remained anoxic throughout the whole year (Nausch et al., 2005).

2005

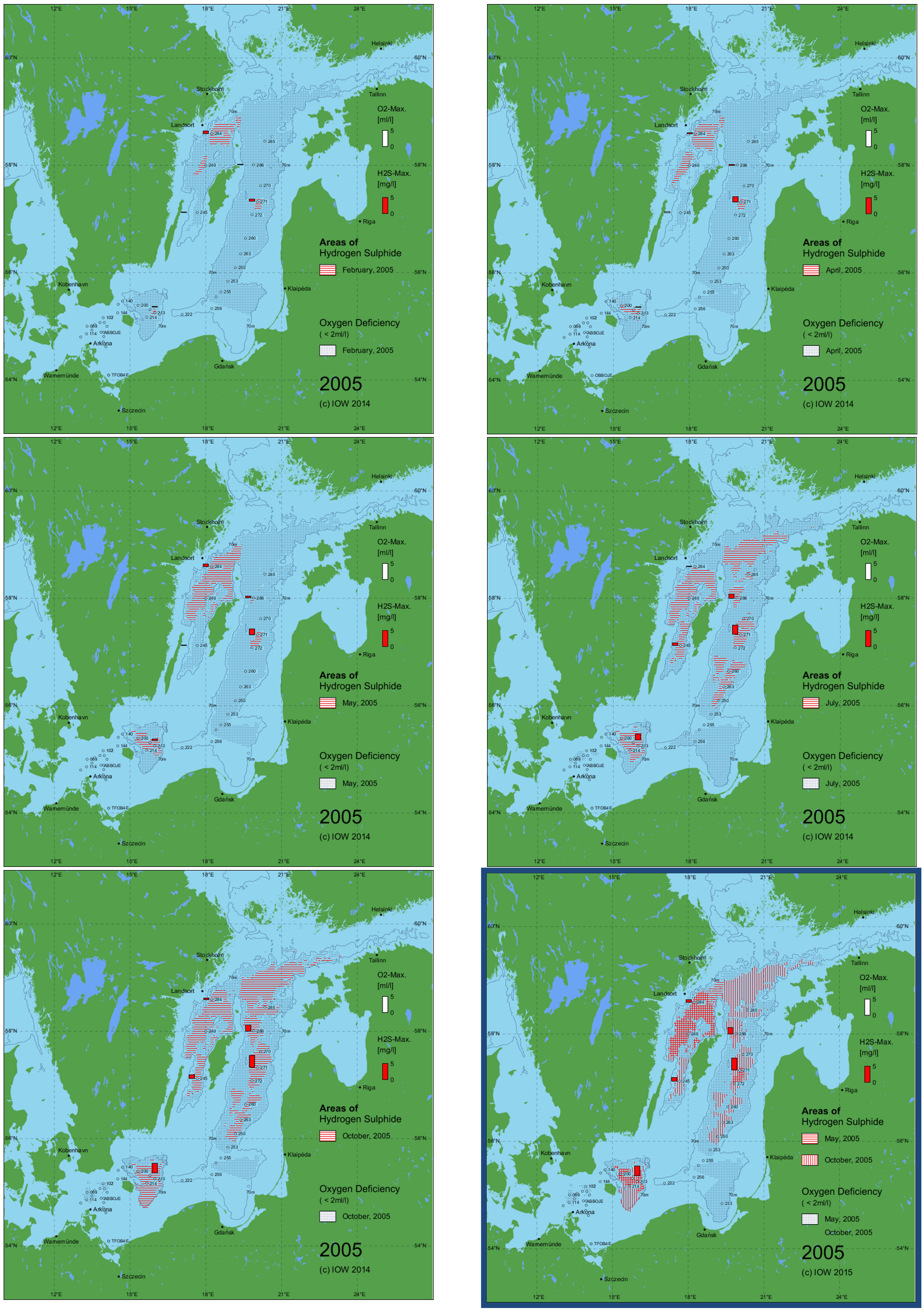

Fig. 51: Distribution maps for 2005. The conditions in the deep basins were still coined of the aftereffects of the MBI in January 2003. However, the start of a new stagnation period could be stated. The deep water of the Bornholm Basin became anoxic with -3.12 ml/l H_2S, highest ever observed (cf. Fig. 3). In the eastern Gotland Basin, the whole water column between 150 m and the bottom was anoxic. In the western Gotland Basin, no definite improvement of the situation could be stated (NAUSCH et al., 2006).

2006

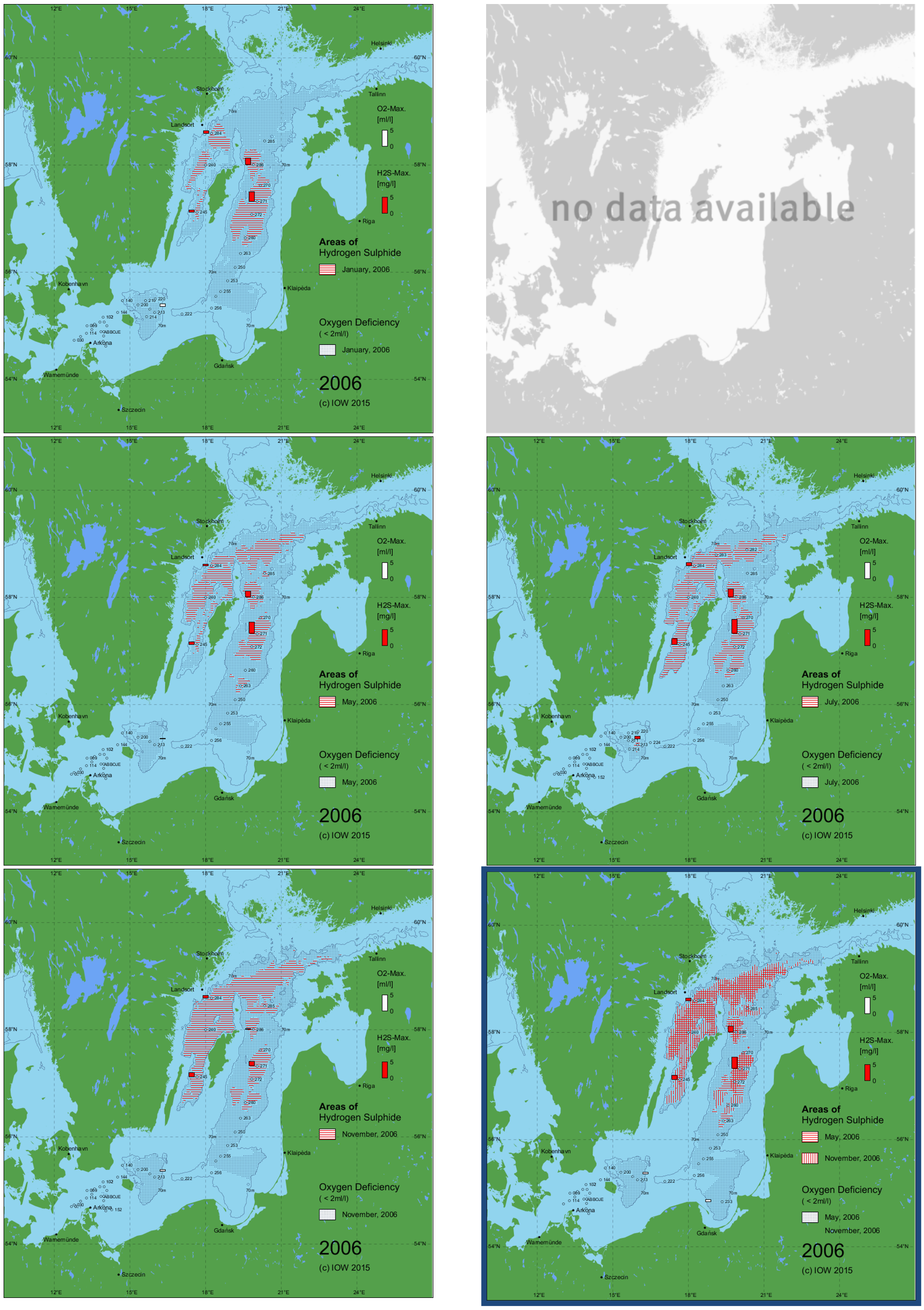

Fig. 52: Distribution maps for 2006. The year 2006 was characterized by the stagnation period which started in 2005. However, two baroclinic inflow events caused a certain improvement of the oxygen conditions in the Bornholm Basin esp. in the first half of the year. In the eastern Gotland Basin, the whole water column between 140 m depth and the bottom was free of oxygen. The annual mean for the 200 m level decreased from 0.80 ml/l (2004) over -0.23 ml/l (2005) to -1.58 ml/l in 2006. Also in the northern and western Gotland Basin, the stagnation was intensified (Nausch et al., 2007).

2007

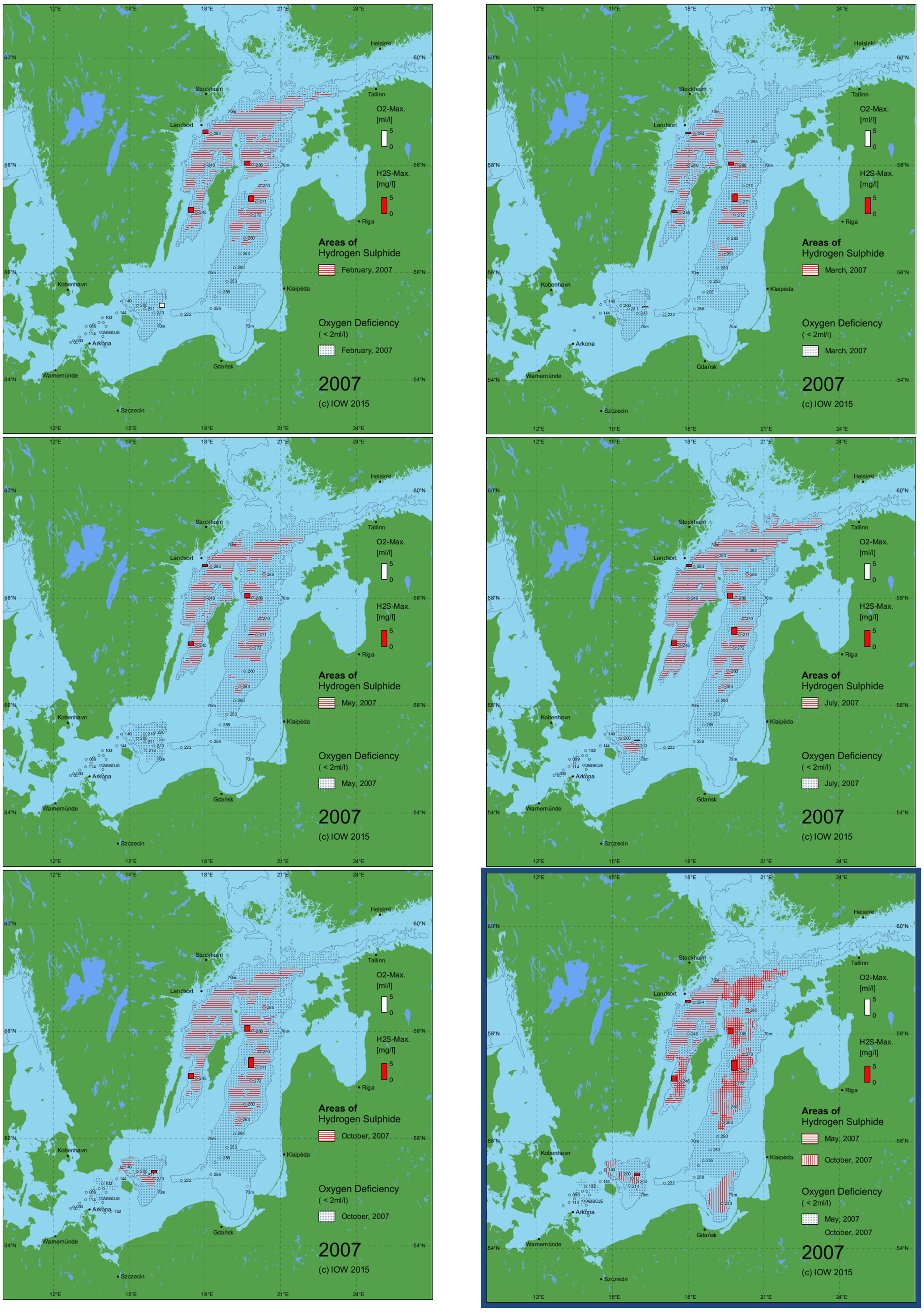

Fig. 53: Distribution maps for 2007. In 2007, five barotropic inflow events could be observed. Esp. the near-bottom layer from the Bornholm Basin to the Gdańsk Deep was ventilated repeatedly. These inflows could only shortly improve the oxygen situation in the eastern Gotland Basin with traces of oxygen (0.02-0.04 ml/l) at 225 m in May. Already in autumn, high H_2S concentrations were found again and, at the end of the year, the whole water column below 137 m was anoxic. In the western Gotland Basin the stagnation continued undiminishedly (NAUSCH et al., 2008).

2008

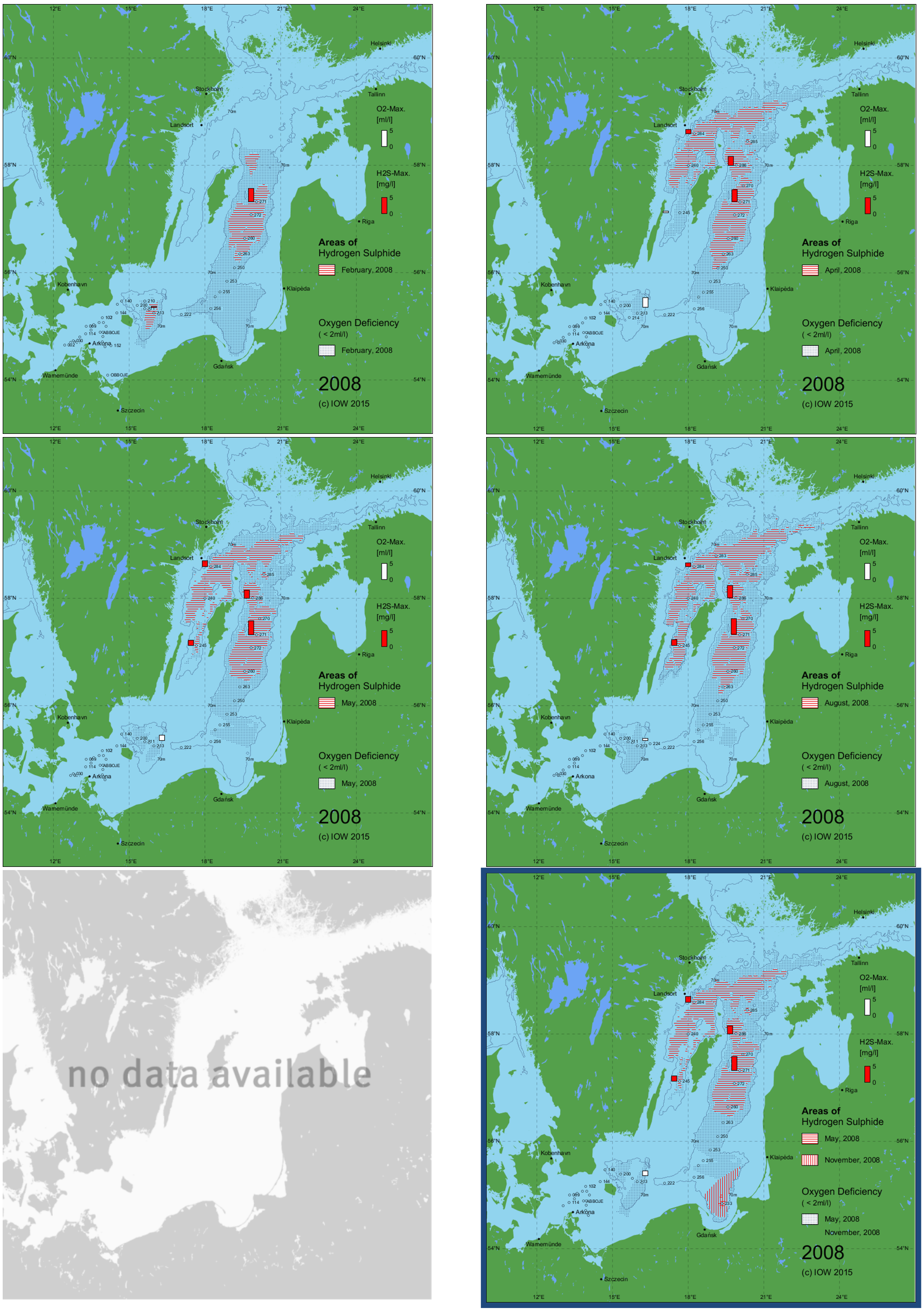

Fig. 54: Distribution maps for 2008. Similar to 2007, several barotropic and baroclinic inflow events were able to ventilate the near-bottom layer from the Bornholm Basin to the Gdańsk Deep several times. In contrast, conditions in the eastern and western Gotland Basin were coined by the lasting stagnation period. Thus, the annual mean of H_2S concentrations in the Gotland Deep decreased continuously from -0.23 ml/l (2005) to -2.22 ml/l (2008). In the Landsort Deep, the hydrogen sulphide concentration increased continuously during the last 5 years (NAUSCH et al., 2009).

2009

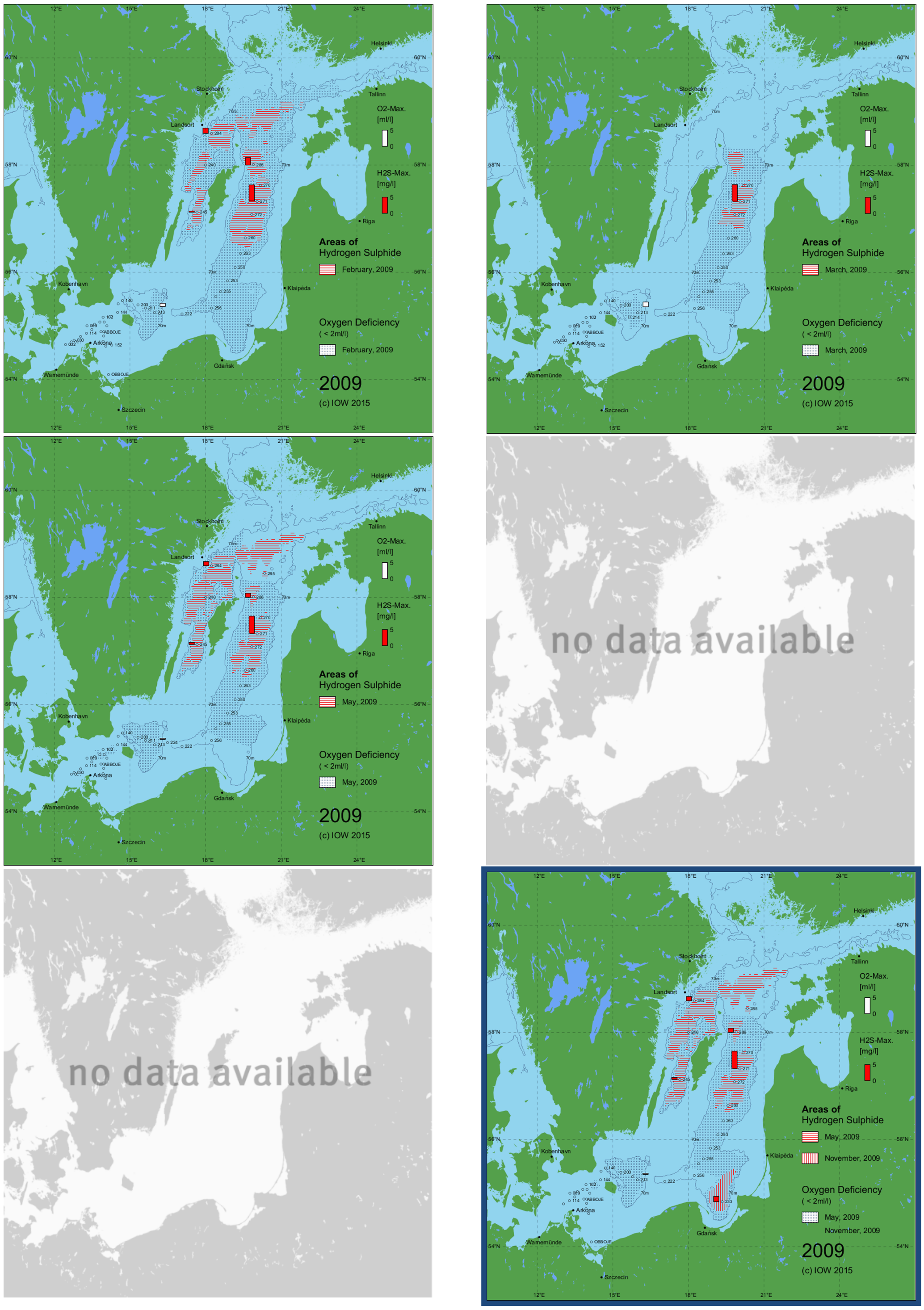

Fig. 55: Distribution maps for 2009. A relatively intensive baroclinic inflow of April/May caused only minor effects in the Bornholm Basin but could maintain oxic conditions in the depth. In the eastern Gotland Basin, H_2S concentrations increased further (-3.09 ml/l) and were in the same range as at the end of the last stagnation period in 2002 (-3.82 ml/l). The same development was observed in the more northerly situated Fårö Deep. The MBI of January 2003 was unable to ventilate effectively the western Gotland Basin and stagnant conditions prevailed (NAUSCH et al., 2010).

2010

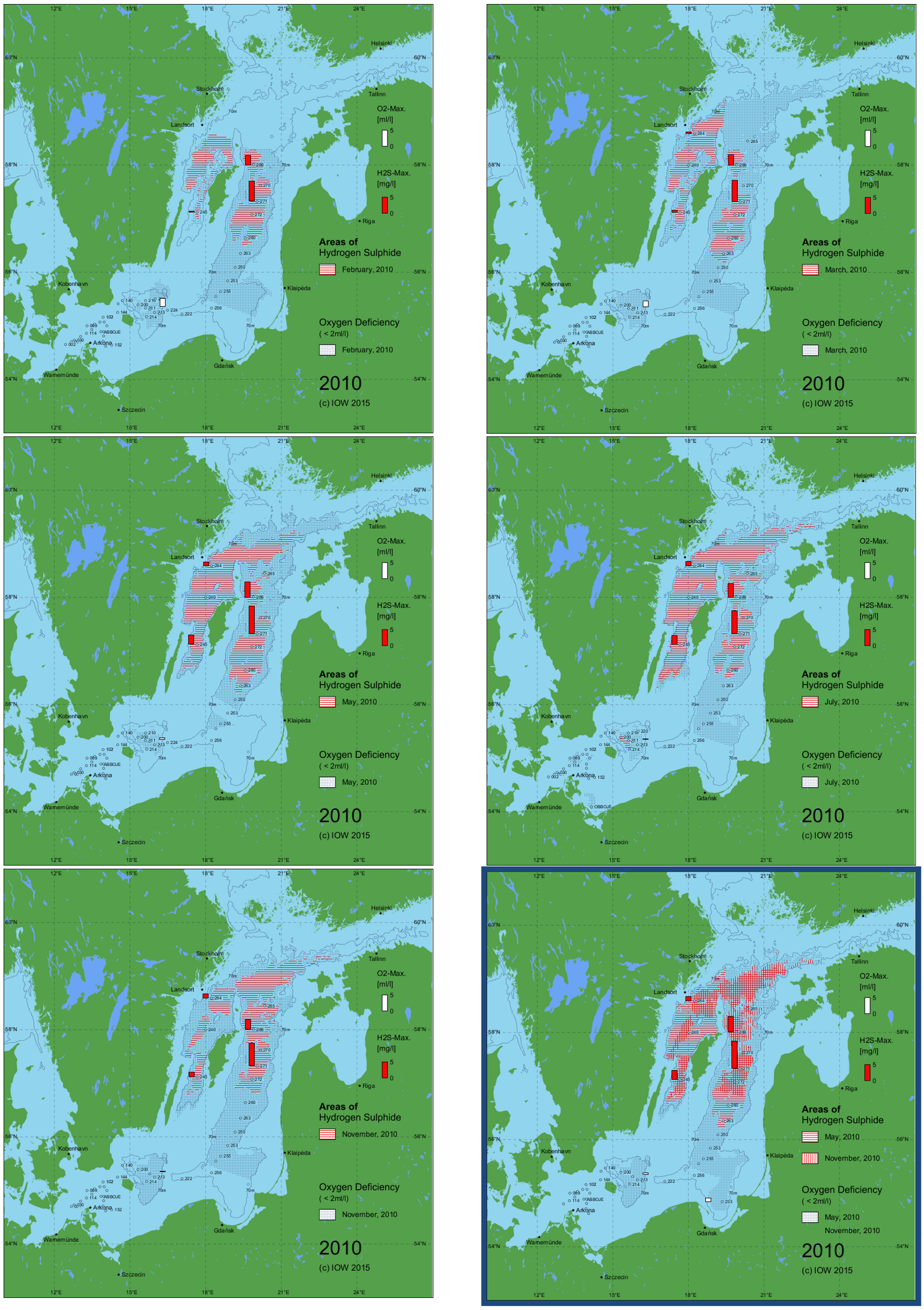

Fig. 56: Distribution maps for 2010. The warm baroclinic inflow of Nov/Dec. 2009 ventilated the Bornholm Basin. From January to March, O_2 concentrations of 2–3 ml/l were measured at 80 m depth. In the eastern Gotland Basin, this warm water mass was detected within the halocline in March, still containing 0.9-1.0 ml/l O_2. The deep water was not oxygenated. The annual mean of H_2S concentrations of -4.29 ml/l at 200 m depth was higher than the year before (-3.09 ml/l) and higher than the one measured at the end of the last stagnation period in 2002 (NAUSCH et al., 2011).

2011

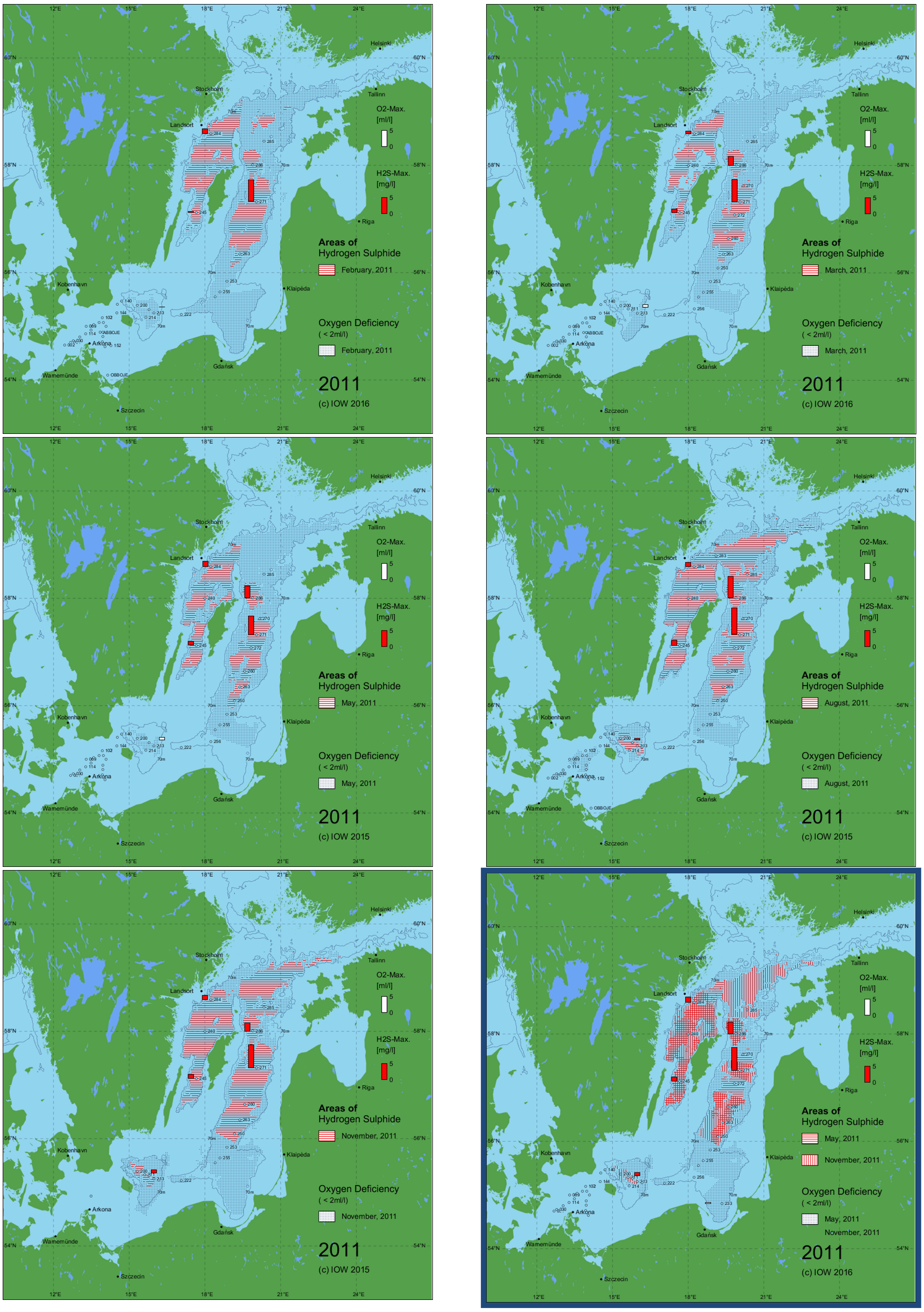

Fig. 57: Distribution maps for 2011. In the deep water of the Bornholm Basin, baroclinic inflows were recorded repeatedly during the last years which influenced the oxygen situation positively with oxic conditions throughout 2011. In the deep water of the eastern Gotland Basin, temperature and salinity decreased further and showed extremely low standard deviations illustrating the exceptional low inflow activity. The H_2S containing layer has a thickness of around 100 m with a mean H_2S content of -3.98 ml/l at 200 m water depth (NAUSCH et al., 2012).

2012

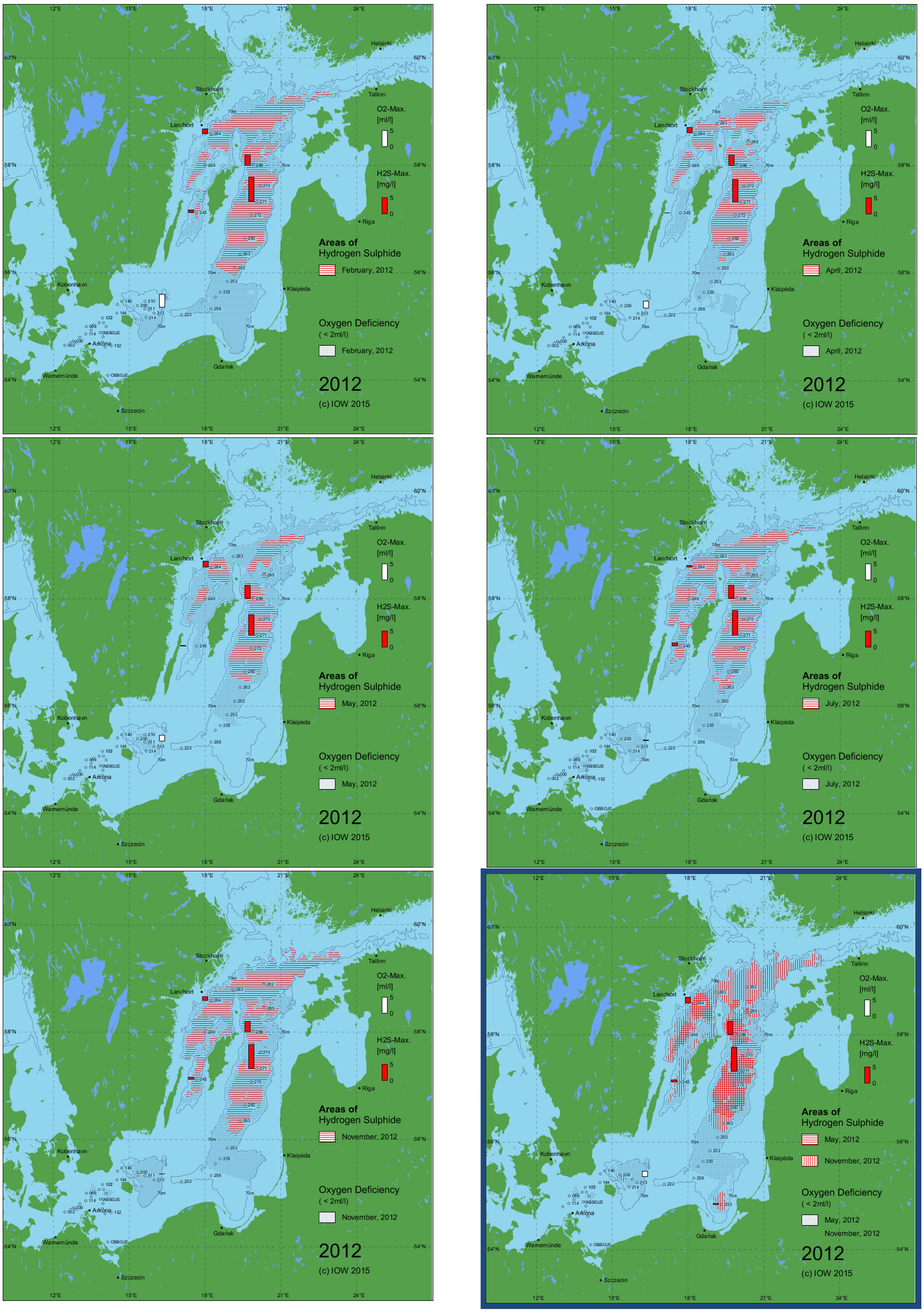

Fig. 58: Distribution maps for 2012. A relatively strong inflow signal of November/December 2011 was registered in the Bornholm Basin only in February 2012. With an estimated input of 1 Gt of salt and a transported amount of oxygen of 450 000 t, the inflow can be characterized as a small MBI. It was the first MBI since 2003. The inflow was strong enough to reach the southern Baltic Sea and the Gdańsk Basin in spring 2012 but did not reach the central Gotland Basin where the stagnation period was continuing undiminishedly with further increasing H_2S concentrations (NAUSCH et al. 2013).

2013

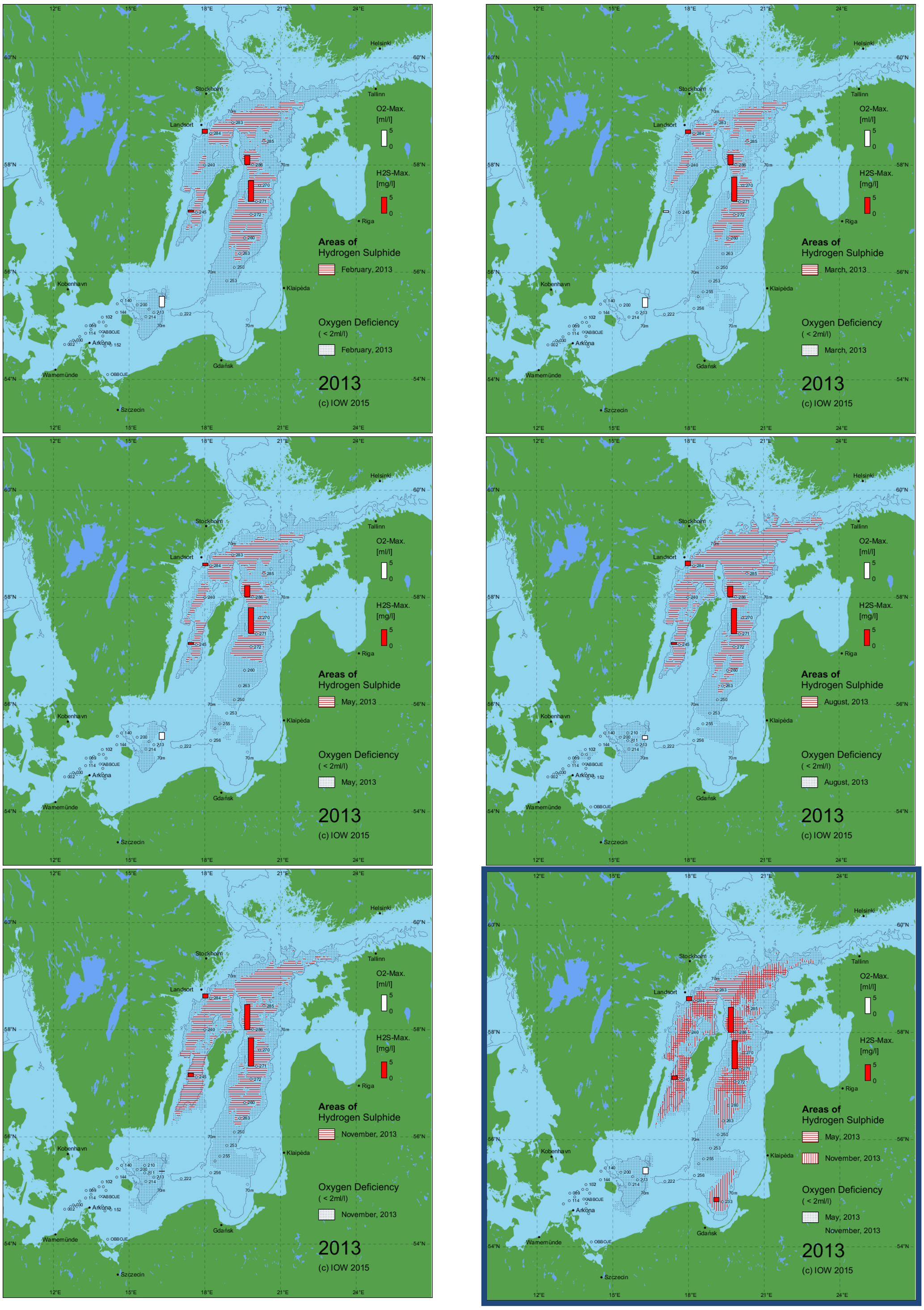

Fig. 59: Distribution maps for 2013. Inflows are frequently able to ventilate the deep water in the Bornholm Basin. Thus, the basin contains oxygen in the depth since 2006. However, the intensity of four observed inflow events was, as in the years before, not strong enough to reach the central Baltic Sea. Salinity and temperature decreased further, with only small variations throughout the year. In the Gotland Deep, highest H_2S concentration (-5.30 ml/l), was measured during the present stagnation period lasting since 2005 (cf. Fig. 3) (NAUSCH et al., 2014).

2014

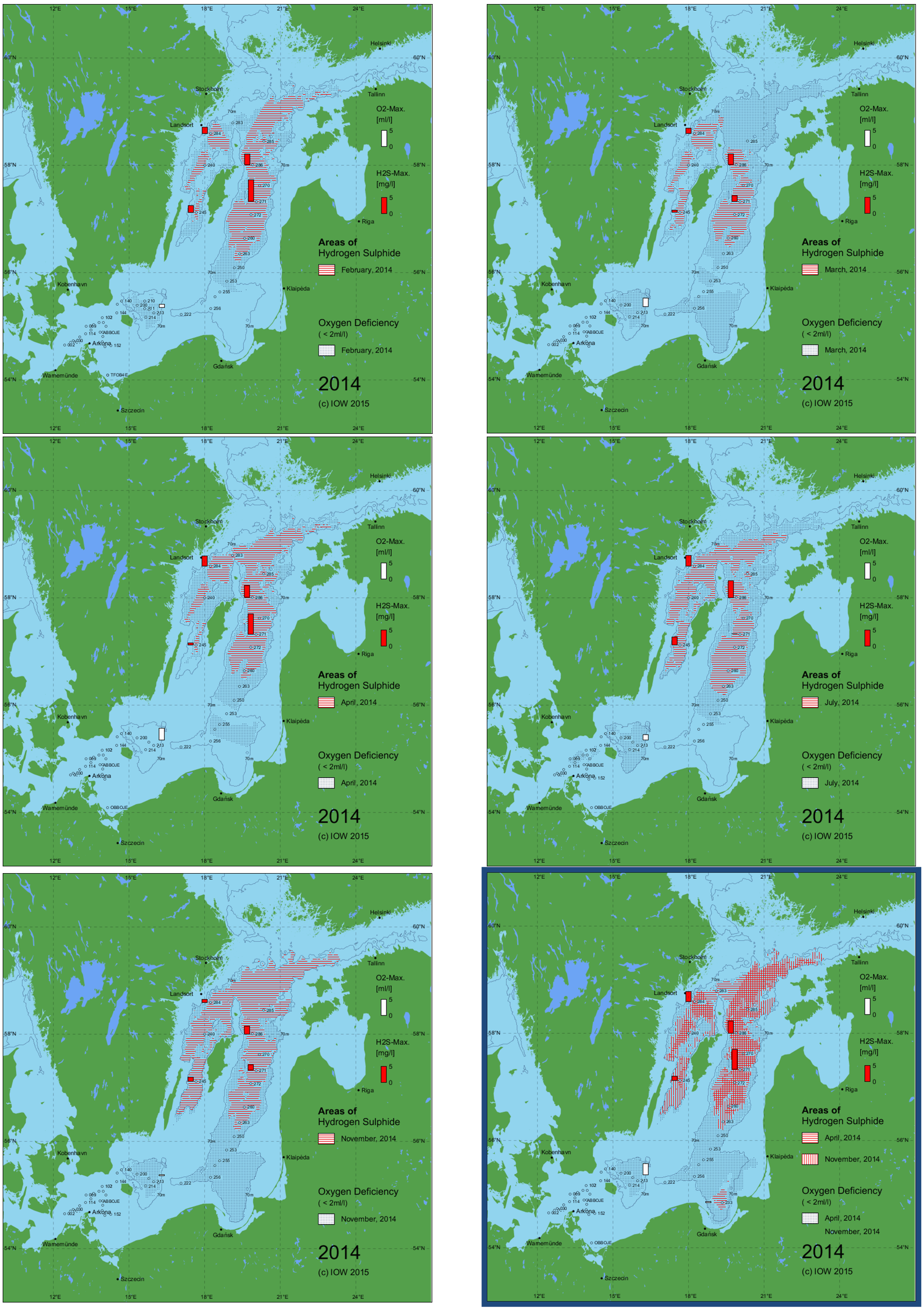

Fig. 60: Distribution maps for 2014. In 2014, the situation in the deep water was changed by the effects of three moderate resp. weak inflows in autumn 2013, February and March 2014 (cf. Table 1). Although none of these three events fulfilled the typical characteristics of a Major Baltic Inflow, they produced a novel complex interaction reaching the Gotland Deep in late May and oxygenated its deep water briefly for the first time since 2003. In December, the third largest Major Baltic Inflow on record since 1880 occurred (cf. Fig. 2). Effects can be seen mainly in 2015 (NAUMANN & NAUSCH, 2015, NAUSCH et al., 2015).

2015

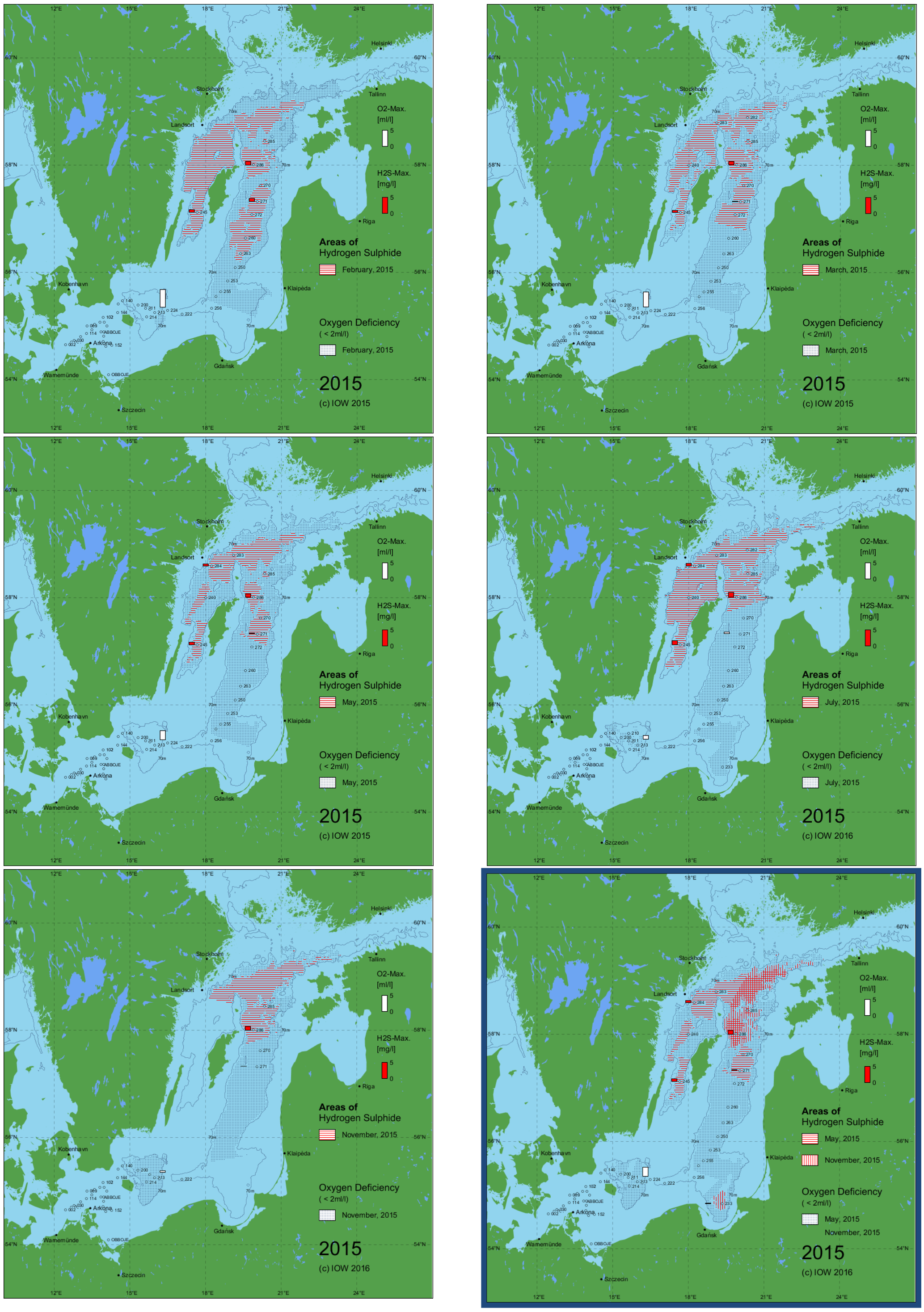

Fig. 61: Distribution maps for 2015. The very strong MBI of December 2014 reached the Bornholm Basin in February (80-90% O_2 saturation in the deep water) and the Gotland Deep in April with nearly 3 ml/l O_2 at the bottom. Astonishingly high O_2 consumption rates were observed since September reducing the O_2 content to < 1 ml/l. Unexpectedly, the oxic period was shorter than during the MBIs in 1993 and 2003 and the northern and western Gotland Basins were not affected. A further MBI in Nov. could improve the situation again (MOHRHOLZ et al., 2015, NAUSCH et al., 2016).

Feistel, S., Feistel, R., Nehring, D., Matthäus, W., Nausch, G., Naumann, M.:

Hypoxic and anoxic regions in the Baltic Sea, 1969-2015

CONTENT

Leibniz-Institut für Ostseeforschung Warnemünde