

## - a seasonal to decadal spatial analysis

Anoxic/euxinic



Hypoxic conditions



Oxic conditions



Water samples of the central Baltic Sea – stagnation period

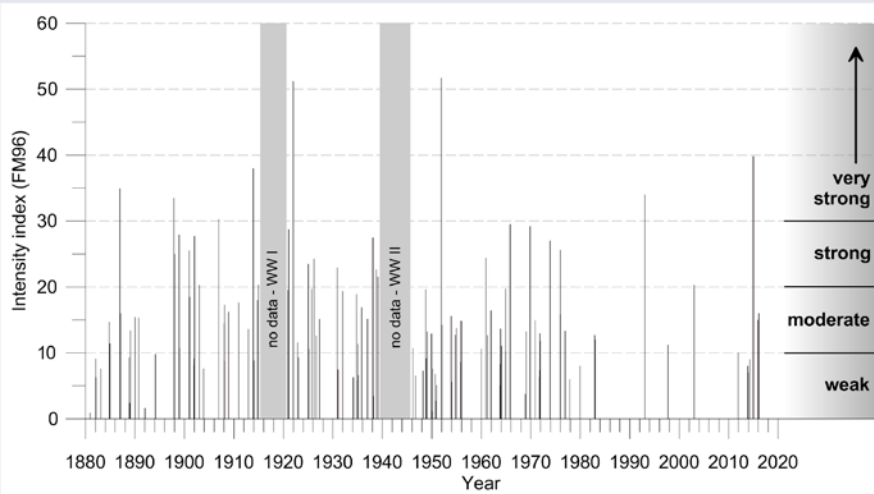
Michael Naumann<sup>1</sup>, Susanne Feistel<sup>1</sup>, Günther Nausch<sup>1</sup>, Thomas Ruth<sup>2</sup>, Jakob Zabel<sup>2</sup>, Markus Plangg<sup>2</sup>,  
Martin Hansson<sup>3</sup>, Lars Andersson<sup>3</sup>, Lena Viktorsson<sup>3</sup>, Elzbieta Lysiak-Pastuszek<sup>4</sup>, Rainer Feistel<sup>1</sup>,  
Dietwart Nehring<sup>1</sup>, Wolfgang Matthäus<sup>1</sup>, H.E. Markus Meier<sup>1,3</sup>

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<sup>2</sup>Fraunhofer Institute for Computer Graphics Research, Maritime Graphics, Rostock, Germany

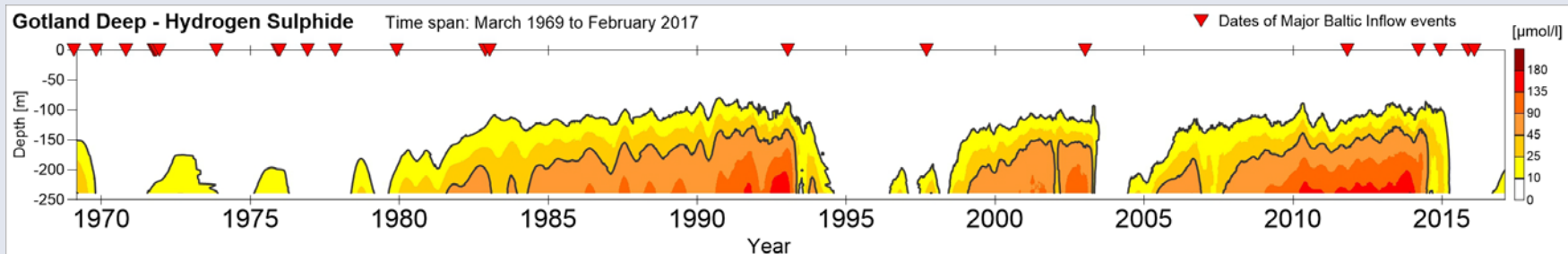
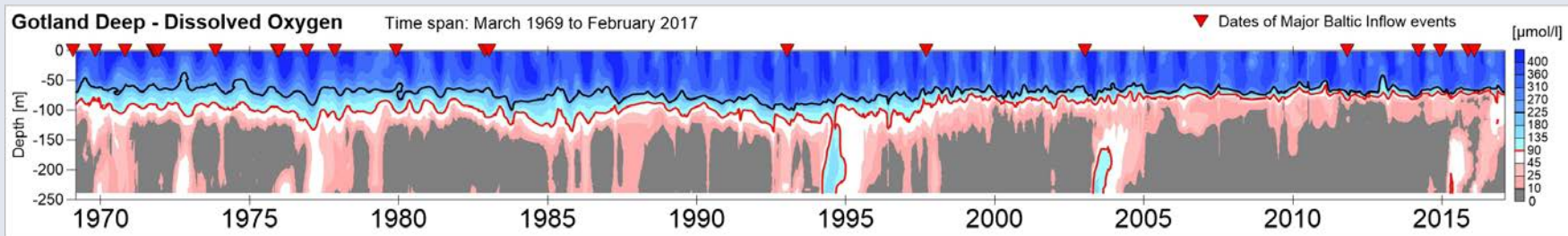
<sup>3</sup>Swedish Meteorological and Hydrological Institute, Norrköping and Västra Frölunda, Sweden

<sup>4</sup>Institute of Meteorology and Water Management, Maritime Branch, Gdynia, Poland

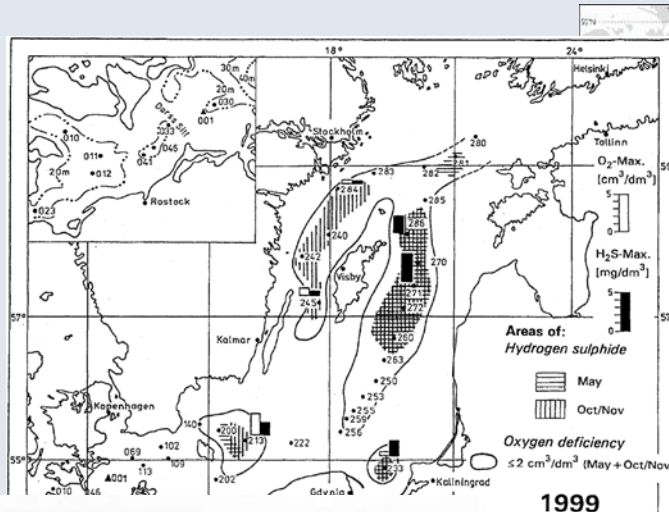


Intensity Index of observed Major Baltic Inflows between 1880-2016 (extended after Matthäus et al. 2008)

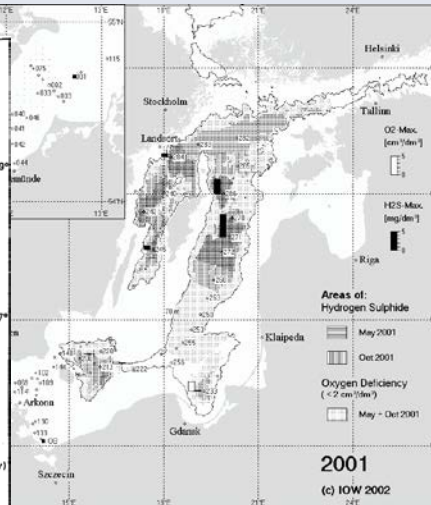
- Hypoxic to anoxic conditions are dominating the deep-water of the central basins
  - Ventilations and renewals of this water layer are controlled by saltwater intrusions from the North Sea
- ... spatial development of these areas are of general interest



Long-term data of dissolved oxygen and hydrogen sulphide at the station Gotland Deep (BY15 / TF271) – central Baltic Sea

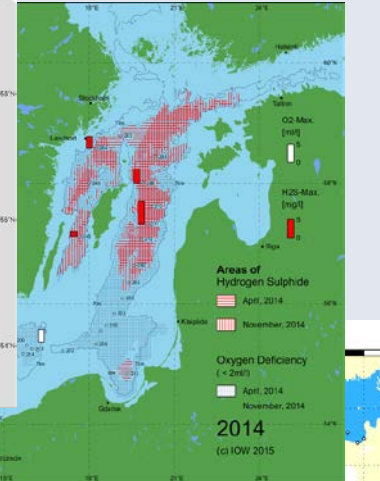


1999



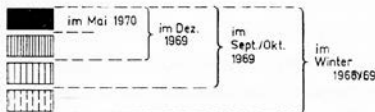
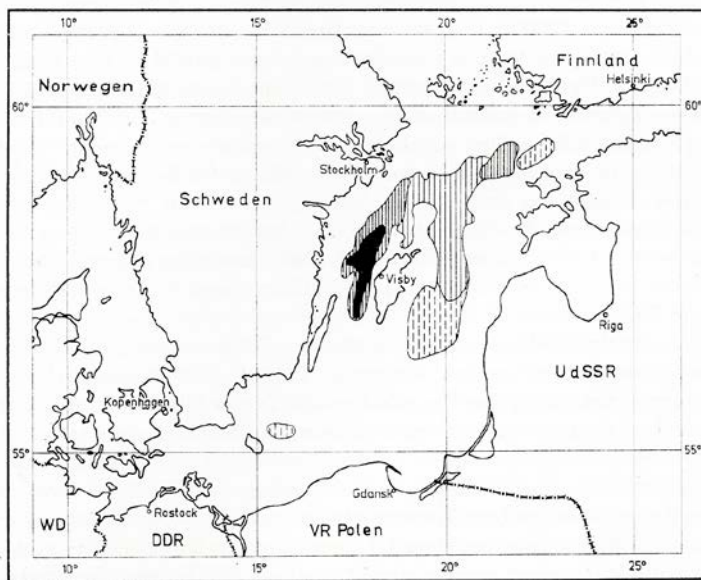
2001

(c) IOW 2002



2014

(c) IOW 2015



- first basin-wide maps drawn manually by FONSELIUS (1969), NEHRING & FRANCKE (1971)
- since 1991 supplemented by histograms at key stations by NEHRING & MATTHÄUS (1992/92)
- development of an automatic software tool by NAUSCH et al. (2002), update in 2015



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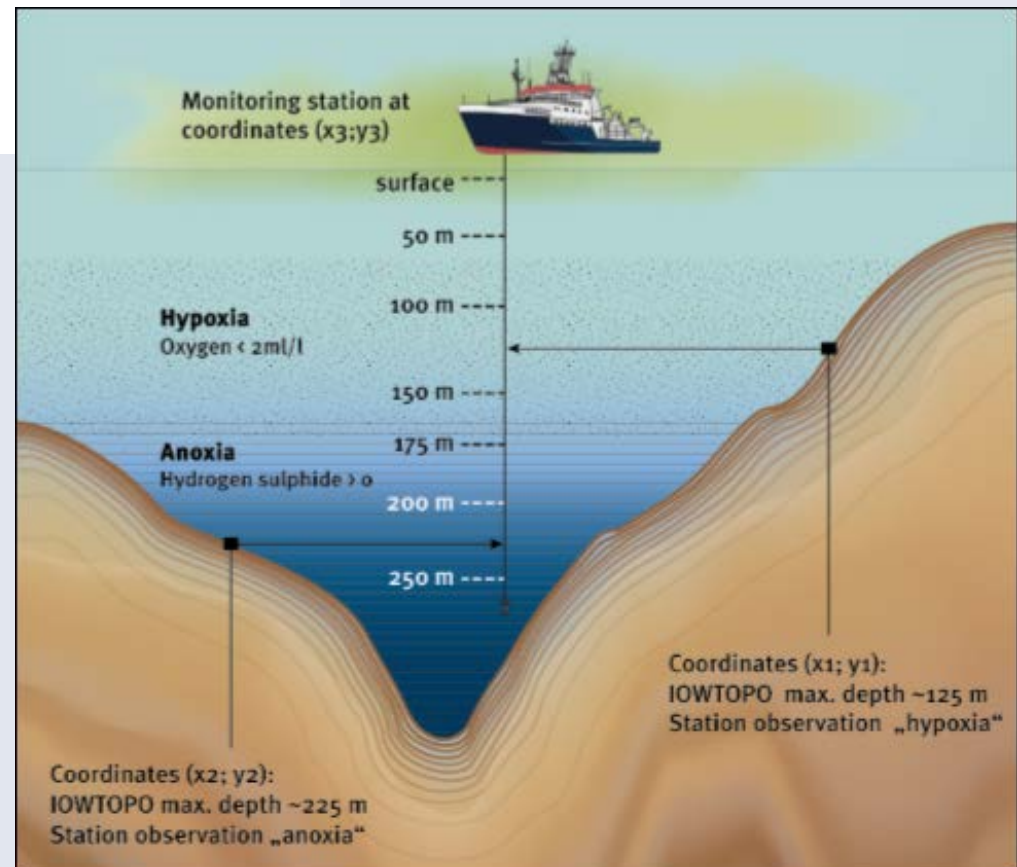
1 H2S&O2, Level File
2 Version , 1.0
3 Cruise 1, 11, 2015
4 Cruise 2,
5 Stn, Lon,      Lat,      z (O2<2), z (H2S 1), z (H2S 2), Btm.O2max, Btm.H2Smax
6 001,12.710628,54.696155,999,999,999,6.49,
7 002,12.450832,54.650433,999,999,999,5.75,
...
46 271,20.050332,57.320015,80.41,999,999,0.1,
47 285,20.333120,58.441352,80.38,100.39,999,0.42,1.07
48 286,19.900188,58.000002,70.38,90.4,999,0.24,1.14
49 360,10.452572,54.600162,999,999,999,3.37,
50 361,10.769240,54.658305,999,999,999,5.21,

```

Section from a level file compiled from the data base

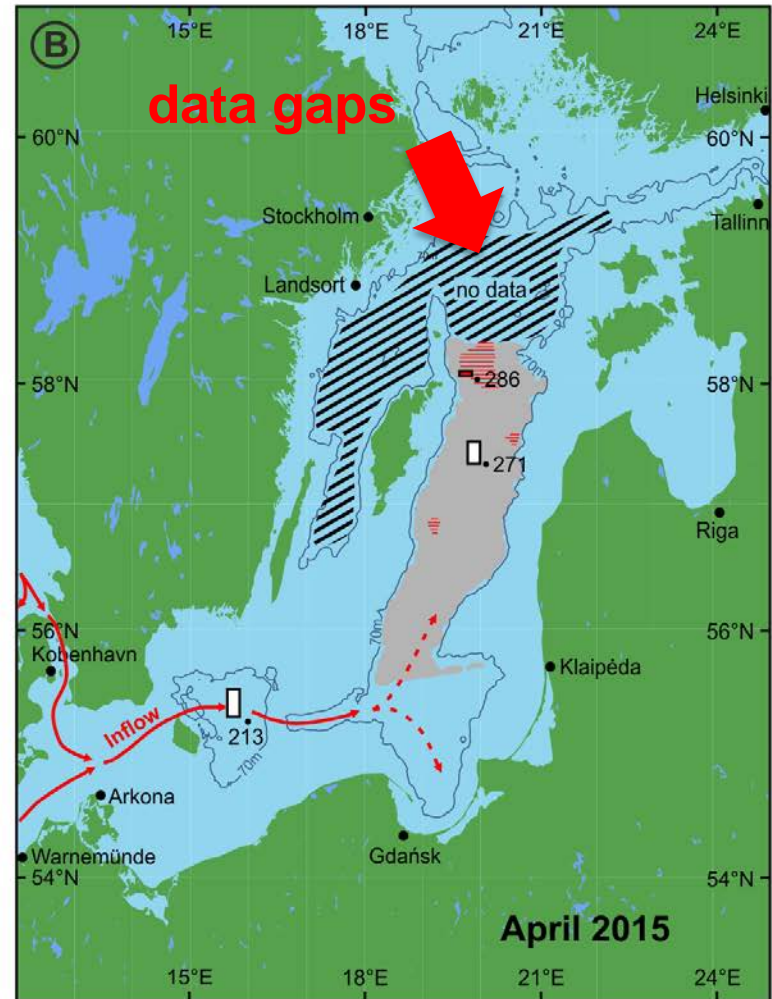
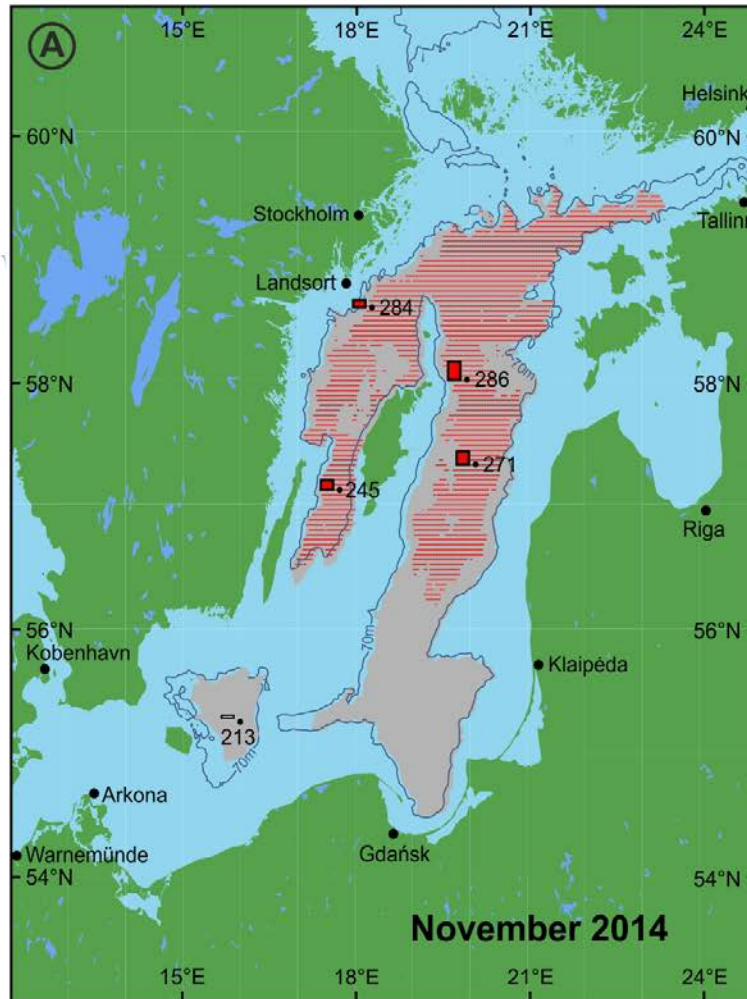
## Map production:

- database request in a defined time span:
  - > depth levels for dissolved oxygen starting to fall below 2 ml/l (90  $\mu\text{mol/l}$ )
  - > occurrence of hydrogen sulphide
  - > near bottom values
- spreading of this depth values to the margins of the basins, constructing areas
- Map export as „classic“ figure
- GIS shape production as polygons and interpolated grids (1 NM)
- GIS analysis: slicing into subareas, calculation of areas



Production of maps using level files and bathymetry (SEIFERT et al. 2001)

# Motivation for the next steps



Measurements (selection)

□ 5 O<sub>2</sub>-Max. [ml/l]    ■ 5 H<sub>2</sub>S-Max. [mg/l]

Stations:

213 - Bornholm Deep    284 - Landsort Deep  
245 - Karlsö Deep    286 - Farö Deep  
271 - Gotland Deep

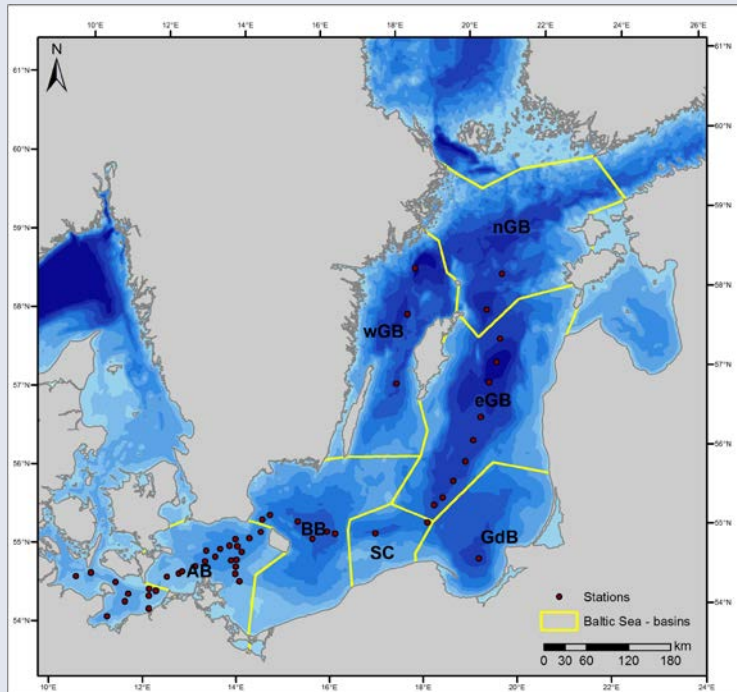
Areas of

■ Oxygen Deficiency (suboxic; <2ml/l)

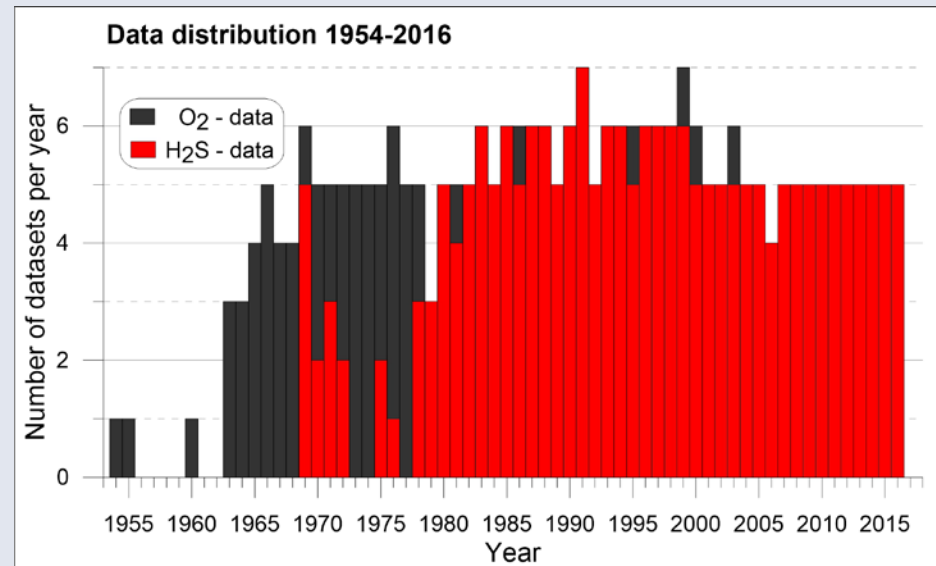
■ Hydrogen Sulphide

A: November 2014 - stagnation prior the MBI of December 2014

B: April 2015 - arrival of the MBI December 2014



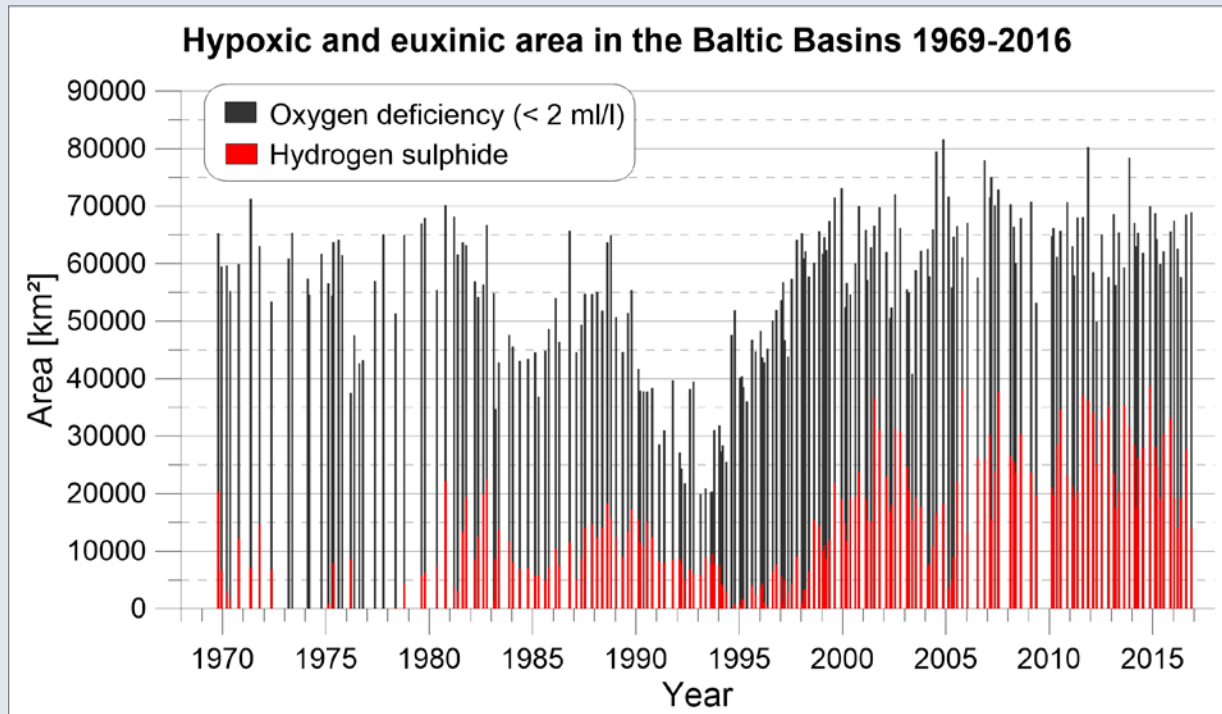
Map of stations and analysed subareas



Distribution of long-term data since 1954



- **compilation of german, swedish and polish monitoring data to a consistent dataset in space and time (data distribution in all subareas per analysed time step)**
- **division in 7 subareas from the western to the central Baltic Sea: Arkona Basin (AB), Bornholm Basin (BB), Slupsk Channel (SC), Gdansk Basin (GdB), eastern Gotland Basin (eGB), northern Gotland Basin (nGB), western Gotland Basin (wGB)**
- **284 time steps since 1954**
  - > since 1969 five datasets per year in mean of dissolved oxygen
  - > since 1978 continuous hydrogen sulphide measurements



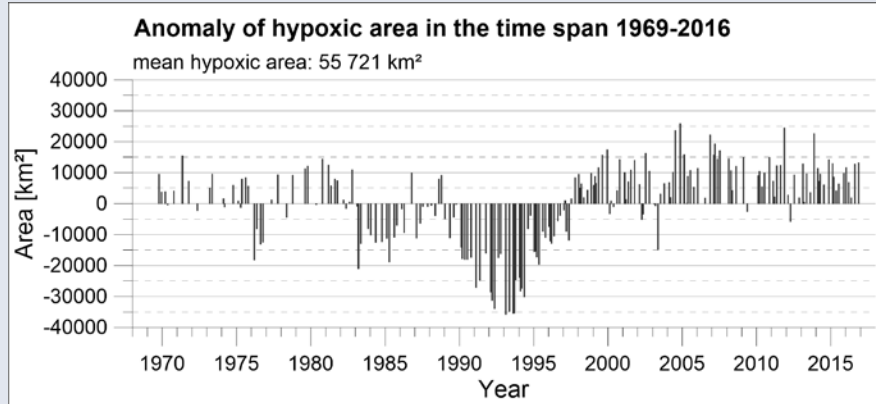
Spatial analysis of hypoxic to euxinic conditions in the Baltic Sea since 1969

| Time                | Mean areal extent [km <sup>2</sup> ] | Standard deviation [km <sup>2</sup> ] | Max [km <sup>2</sup> ] | Min [km <sup>2</sup> ] |
|---------------------|--------------------------------------|---------------------------------------|------------------------|------------------------|
| Hypoxic (1969-2016) | 55721                                | 13074                                 | 81590                  | 19891                  |
| Euxinic (1969-2016) | 14607                                | 9872                                  | 38712                  | 0                      |

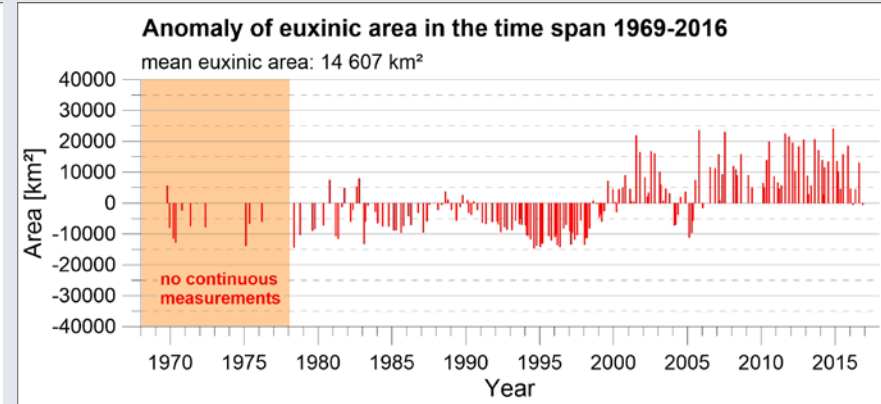
- **Oxygen: 195 datasets out of 284 covering all basins (resolution: ~ 4.1 datasets/year)**
- **Hydrogen sulphide: 181 datasets out of 218 covering all basins (resolution: ~ 3.9 datasets/year)**



## Total area – in more detail



Anomaly of hypoxic area (mean: 55 721 km<sup>2</sup>)



Anomaly of euxinic area (mean: 14 607 km<sup>2</sup>)

| Time                | Mean areal extent [km <sup>2</sup> ] | Max [km <sup>2</sup> ] | Min [km <sup>2</sup> ] |
|---------------------|--------------------------------------|------------------------|------------------------|
| Hypoxic (1970-1979) | 57923                                | 71237                  | 37482                  |
| Euxinic (1970-1979) | 6098                                 | 14557                  | 198                    |
| Hypoxic (1980-1989) | 53033                                | 70179                  | 34651                  |
| Euxinic (1980-1989) | 11066                                | 22572                  | 1308                   |
| Hypoxic (1990-1999) | 44270                                | 73109                  | 19891                  |
| Euxinic (1990-1999) | 7003                                 | 21855                  | 0                      |
| Hypoxic (2000-2009) | 63679                                | 81590                  | 40821                  |
| Euxinic (2000-2009) | 20546                                | 38190                  | 3457                   |
| Hypoxic (2010-2016) | 64617                                | 80219                  | 49894                  |
| Euxinic (2010-2016) | 26023                                | 38712                  | 13976                  |

Decadal analysis

| Season               | Mean areal extent [km <sup>2</sup> ] |
|----------------------|--------------------------------------|
| Hypoxic (Jan.-Feb.)  | 54323                                |
| Euxinic (Jan.-Feb.)  | 12444                                |
| Hypoxic (March))     | 53672                                |
| Euxinic (March)      | 11823                                |
| Hypoxic (April-May)  | 52066                                |
| Euxinic (April-May)  | 11742                                |
| Hypoxic (July-Sept.) | 57427                                |
| Euxinic (July-Sept.) | 19576                                |
| Hypoxic (Oct.-Dez.)  | 60717                                |
| Euxinic (Oct.-Dez.)  | 17467                                |

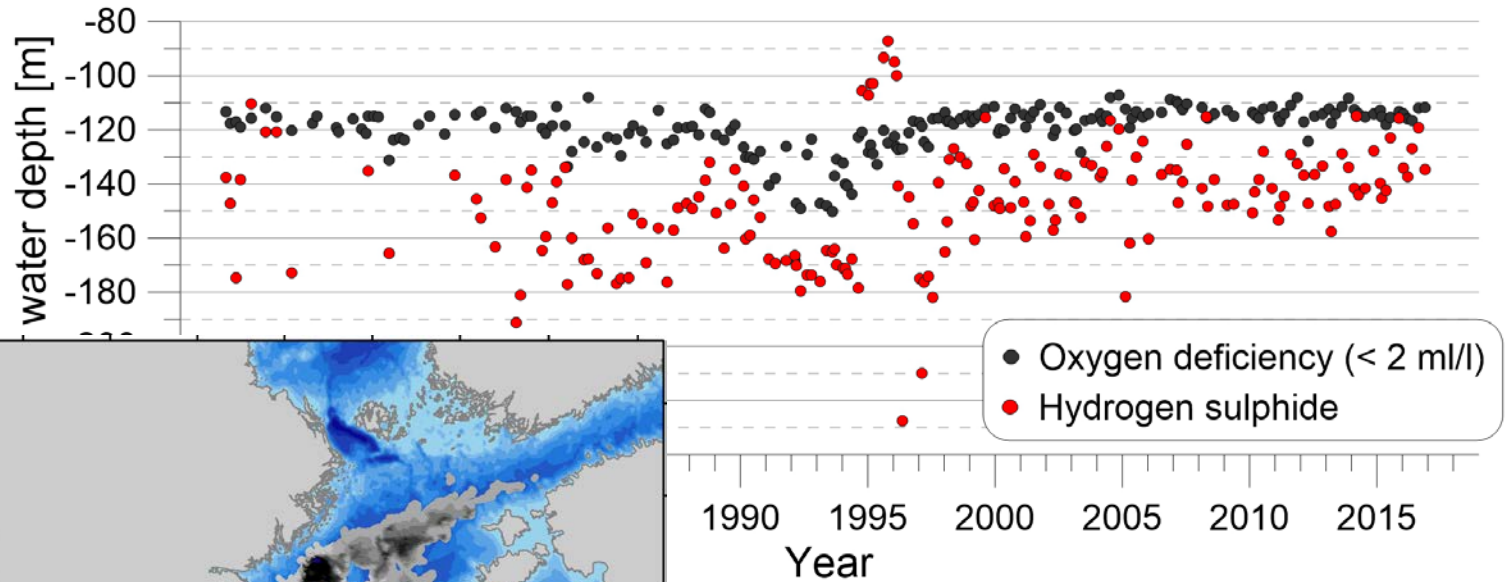
Seasonal analysis

- Hypoxia: only slightly increase since 70's (6000 km<sup>2</sup> / 9 %)
- H<sub>2</sub>S: since 1978 continuous measurements (last 3 stagnation periods), increase in last 2 decades, more persistent
- seasonal: min in spring, max late summer/early winter

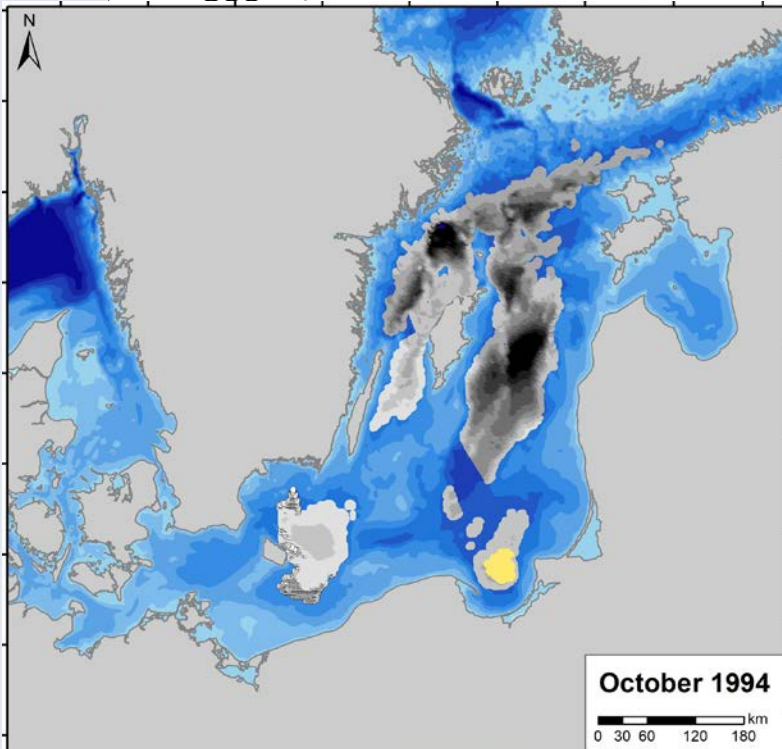


## Total area – water depth

Depth of the hypoxic and euxinic water layer in the Baltic Basins 1969-2016

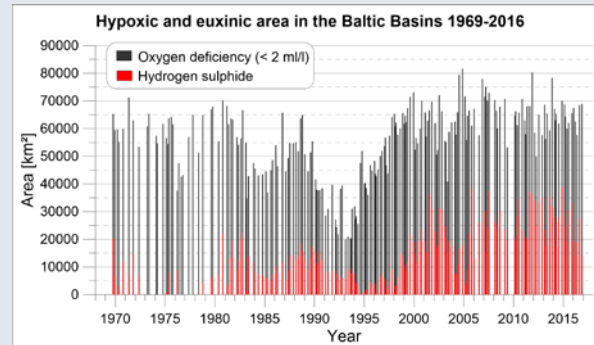


the Baltic Sea since 1969  
– mean value of water depth considering all deep basins

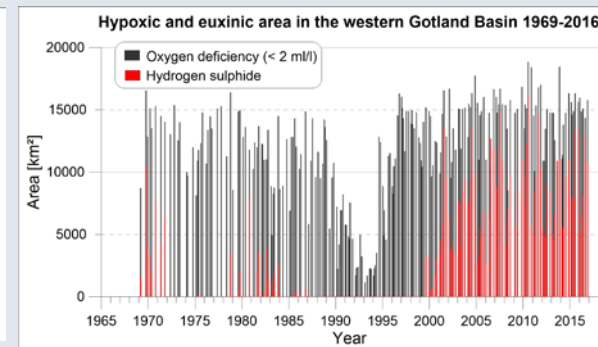
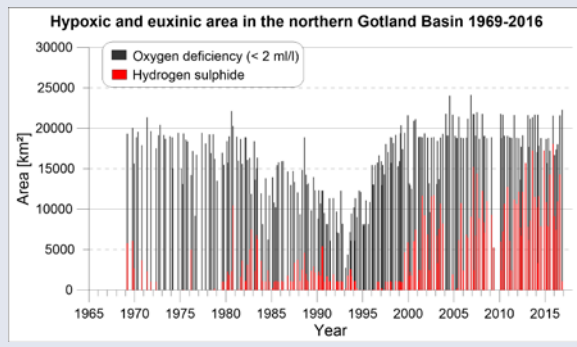
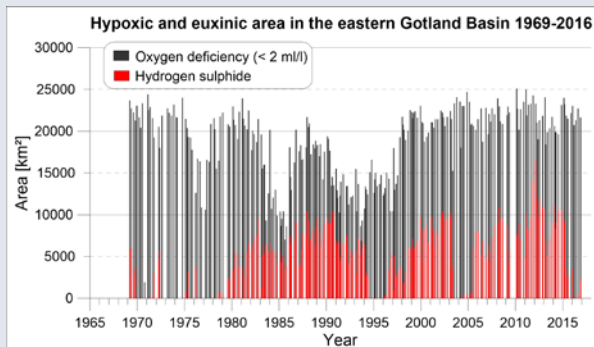
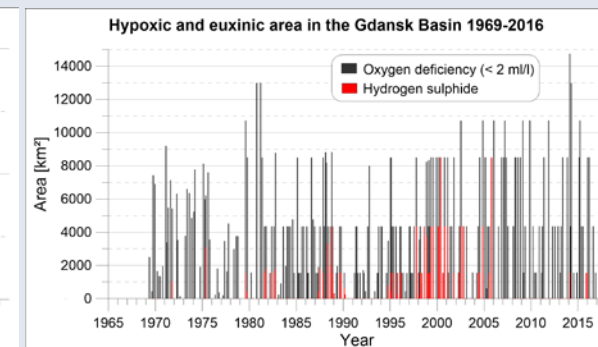
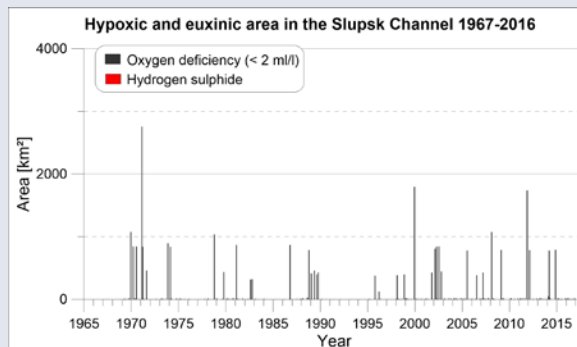
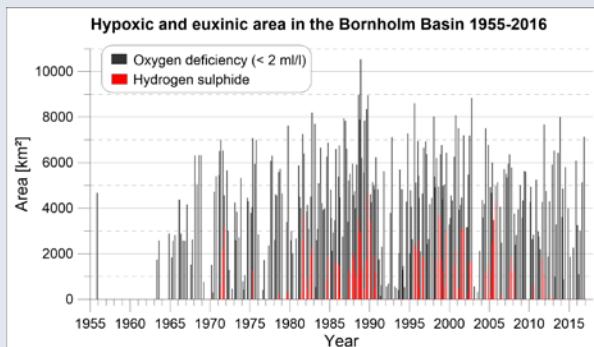
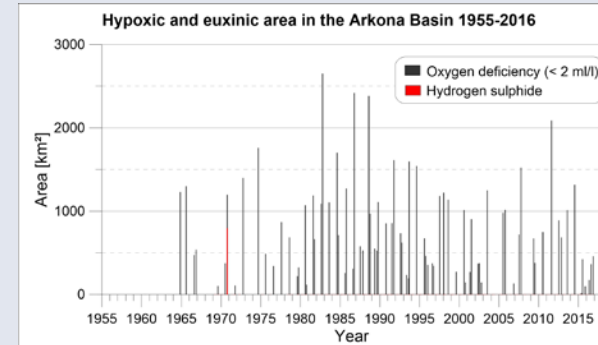


| areal | Standard deviation | Water depth Max [m] | Water depth Min [m] |
|-------|--------------------|---------------------|---------------------|
| 0     | 9                  | 168                 | 107                 |
| 8     | 23                 | 238                 | 87                  |

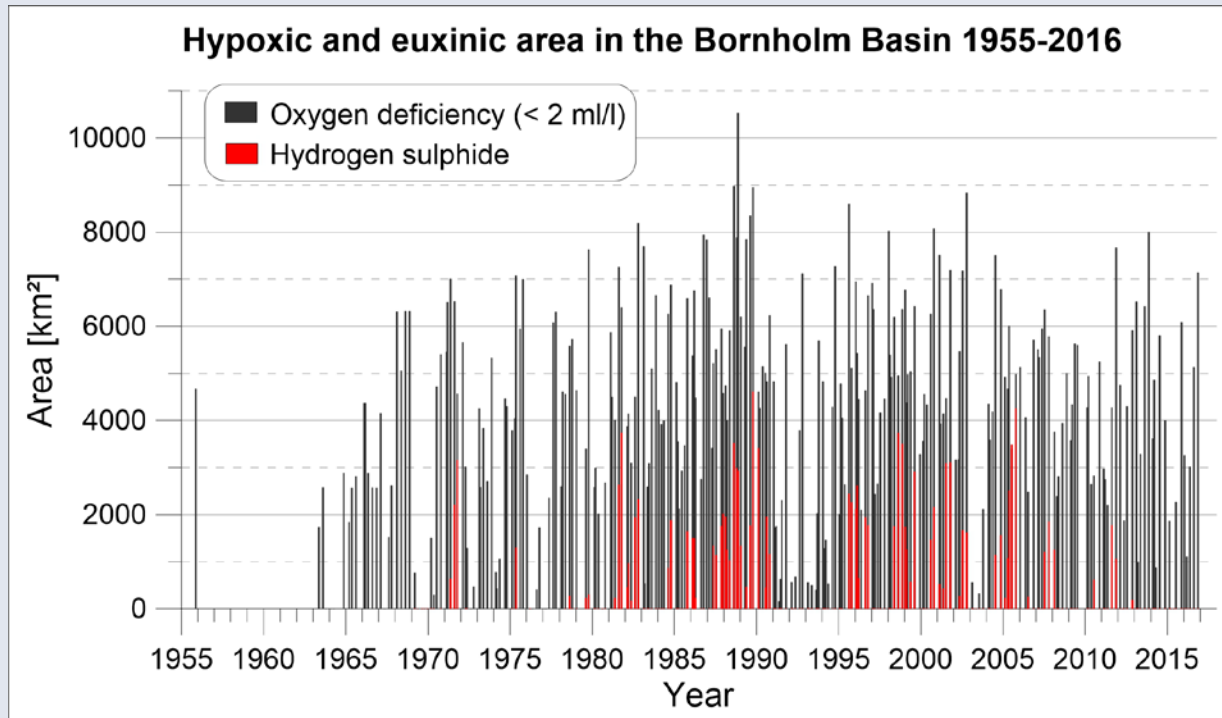
## Overview of all basins



area seperated  
into subbasins



## Bornholm Basin

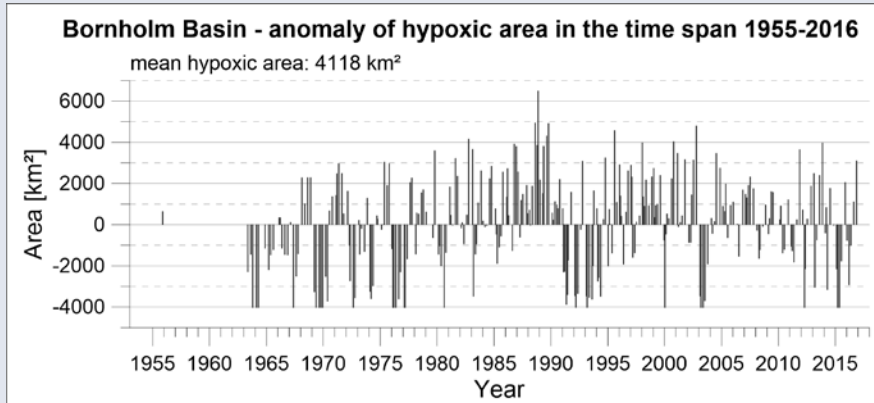


Spatial analysis of hypoxic to euxinic conditions in the Bornholm Basin since 1955

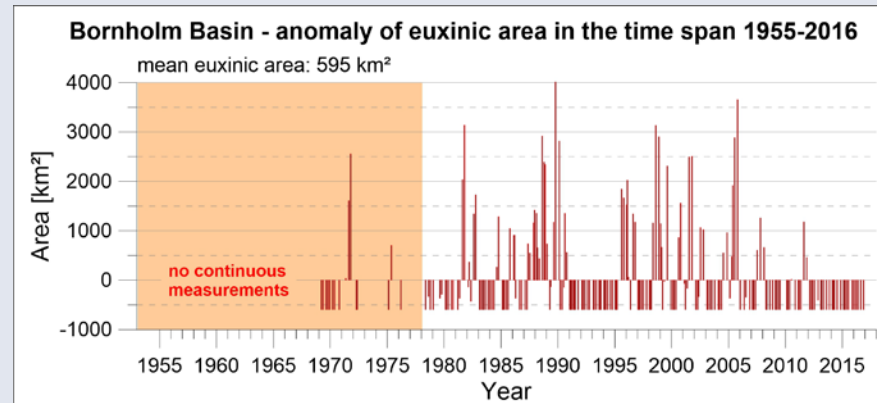
| Time                | Mean areal extent [km <sup>2</sup> ] | Standard deviation [km <sup>2</sup> ] | Max [km <sup>2</sup> ] | Min [km <sup>2</sup> ] |
|---------------------|--------------------------------------|---------------------------------------|------------------------|------------------------|
| Hypoxic (1955-2016) | 4029                                 | 2335                                  | 10534                  | 0                      |
| Euxinic (1955-2016) | 595                                  | 1029                                  | 4608                   | 0                      |

- **Oxygen: 270 datasets out of 284 covering the Bornholm Basin (resolution: ~ 4.4 datasets/year)**
- **Hydrogen sulphide: 217 datasets out of 218 covering the Bornholm Basin (resolution: ~ 3.5 datasets/year)**

## Bornholm Basin – in more detail



Anomaly of hypoxic area (mean: 4118 km<sup>2</sup>)



Anomaly of euxinic area (mean: 595 km<sup>2</sup>)

| Time                | Mean areal extent [km <sup>2</sup> ] | Max [km <sup>2</sup> ] | Min [km <sup>2</sup> ] |
|---------------------|--------------------------------------|------------------------|------------------------|
| Hypoxic (1960-1969) | 2379                                 | 6323                   | 0                      |
| Euxinic (1960-1969) | 0                                    | 0                      | 0                      |
| Hypoxic (1970-1979) | 3509                                 | 7624                   | 0                      |
| Euxinic (1970-1979) | 476                                  | 3152                   | 0                      |
| Hypoxic (1980-1989) | 5125                                 | 10534                  | 0                      |
| Euxinic (1980-1989) | 908                                  | 4608                   | 0                      |
| Hypoxic (1990-1999) | 3986                                 | 8603                   | 0                      |
| Euxinic (1990-1999) | 614                                  | 3729                   | 0                      |
| Hypoxic (2000-2009) | 4461                                 | 8835                   | 0                      |
| Euxinic (2000-2009) | 690                                  | 4252                   | 0                      |
| Hypoxic (2010-2016) | 3739                                 | 8004                   | 0                      |
| Euxinic (2010-2016) | 104                                  | 1774                   | 0                      |

Decadal analysis

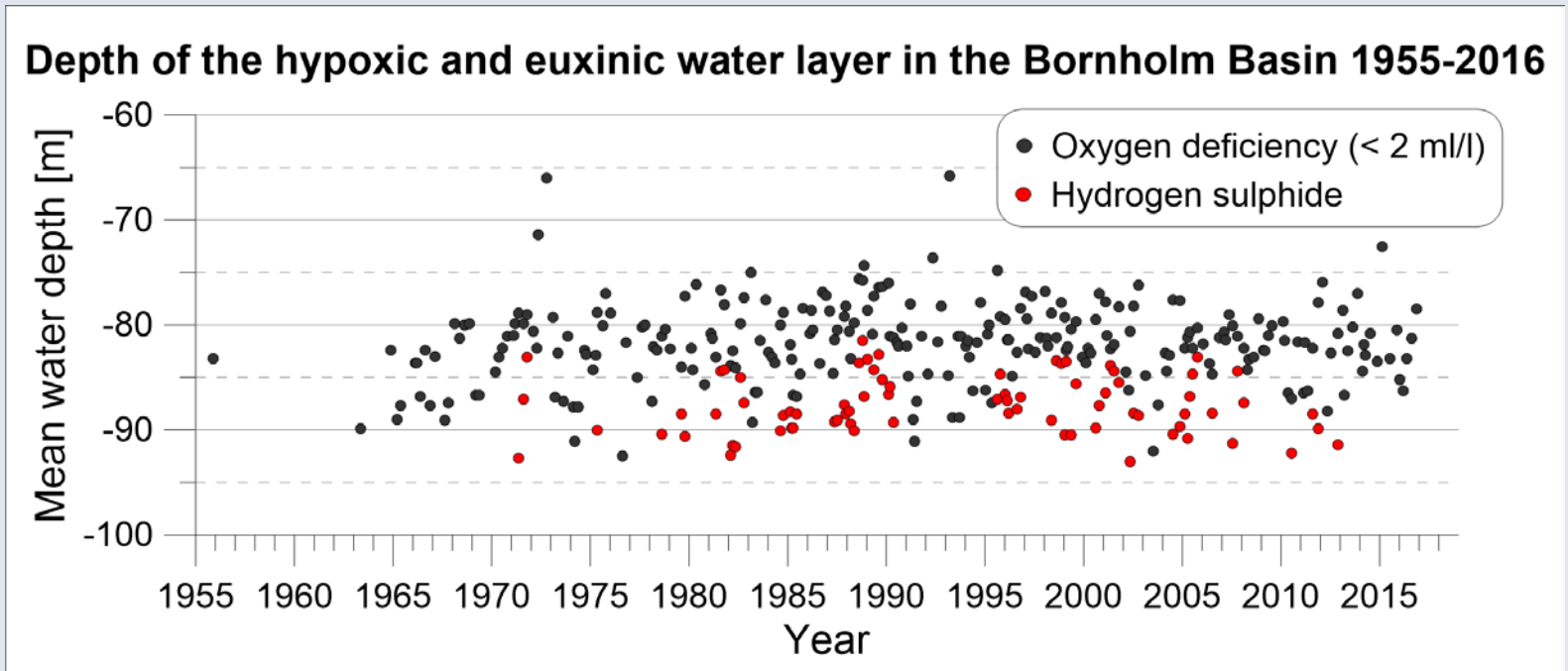
| Season               | Mean areal extent [km <sup>2</sup> ] |
|----------------------|--------------------------------------|
| Hypoxic (Jan.-Feb.)  | 4164                                 |
| Euxinic (Jan.-Feb.)  | 409                                  |
| Hypoxic (March)      | 2999                                 |
| Euxinic (March)      | 136                                  |
| Hypoxic (April-June) | 3066                                 |
| Euxinic (April-June) | 247                                  |
| Hypoxic (July-Sept.) | 4311                                 |
| Euxinic (July-Sept.) | 1004                                 |
| Hypoxic (Oct.-Dez.)  | 5524                                 |
| Euxinic (Oct.-Dez.)  | 1178                                 |

Seasonal analysis

- Hypoxia: highly dynamic, no increase detectable, max at the end of 80's
- H<sub>2</sub>S: sporadic, max in the 80's, since 2005 decreasing, since 2012 not measured
- seasonal: min in March, max early winter



## Bornholm Basin – water depth

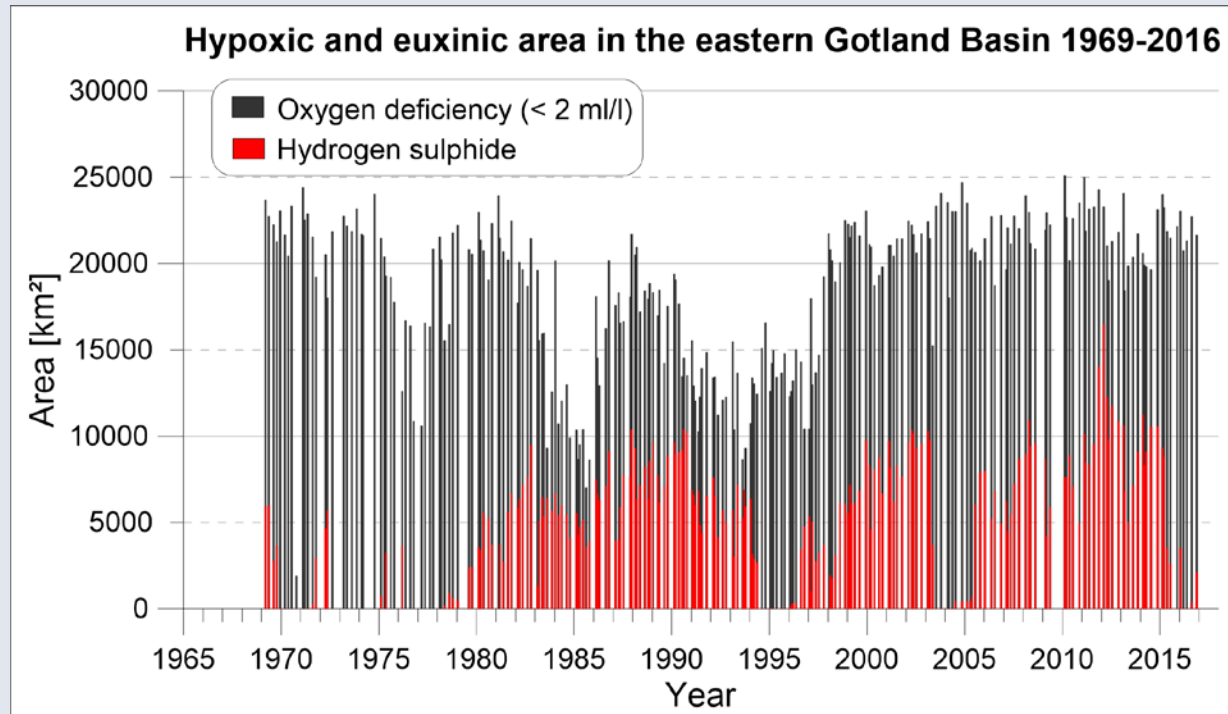


Spatial analysis of hypoxic to euxinic conditions in the Baltic Sea since 1969

– mean value of water depth considering all deep basins

| Time                | Mean water depth [m] | Standard deviation [m] | Water depth Max [m] | Water depth Min [m] |
|---------------------|----------------------|------------------------|---------------------|---------------------|
| Hypoxic (1969-2016) | 82                   | 4                      | 93                  | 66                  |
| Euxinic (1969-2016) | 88                   | 3                      | 93                  | 82                  |

## eastern Gotland Basin



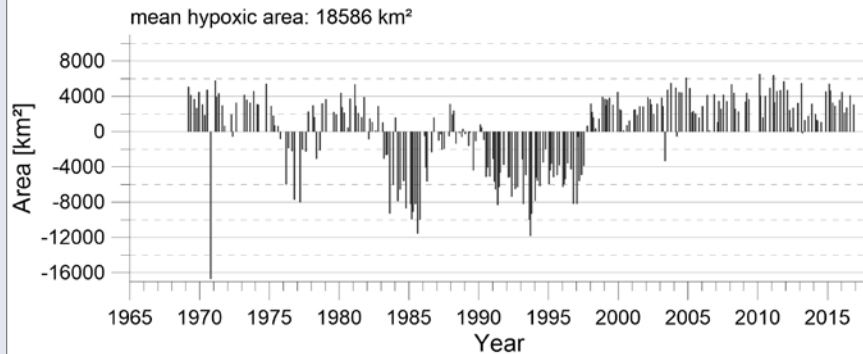
Spatial analysis of hypoxic to euxinic conditions in the eastern Gotland Basin since 1969

| Time                | Mean areal extent [km <sup>2</sup> ] | Standard deviation [km <sup>2</sup> ] | Max [km <sup>2</sup> ] | Min [km <sup>2</sup> ] |
|---------------------|--------------------------------------|---------------------------------------|------------------------|------------------------|
| Hypoxic (1969-2016) | 18586                                | 4415                                  | 25101                  | 1898                   |
| Euxinic (1969-2016) | 5511                                 | 3392                                  | 16493                  | 0                      |

- **Oxygen: 240 datasets out of 284 covering the eastern Gotland Basin (resolution: ~ 5.1 datasets/year)**
- **Hydrogen sulphide: 215 datasets out of 218 covering the east. Gotland Basin (resolution: ~ 4.6 datasets/year)**

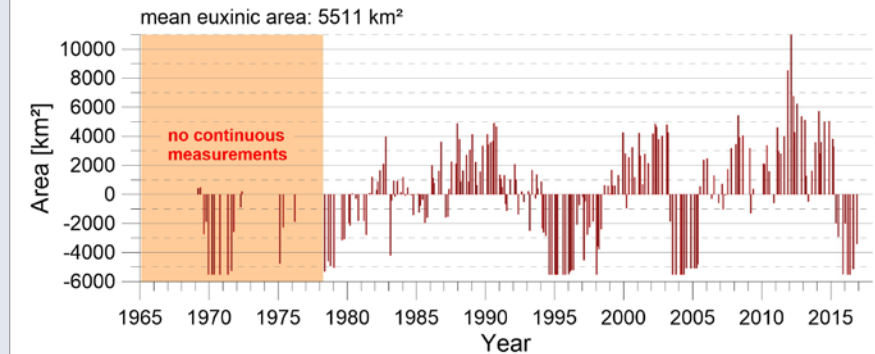
## eastern Gotland Basin – in more detail

Eastern Gotland Basin - anomaly of hypoxic area in the time span 1969-2016



Anomaly of hypoxic area (mean: 18586 km<sup>2</sup>)

Eastern Gotland Basin - anomaly of euxinic area in the time span 19569-2016



Anomaly of euxinic area (mean: 5511 km<sup>2</sup>)

| Time                | Mean areal extent [km <sup>2</sup> ] | Max [km <sup>2</sup> ] | Min [km <sup>2</sup> ] |
|---------------------|--------------------------------------|------------------------|------------------------|
| Hypoxic (1970-1979) | 19345                                | 24396                  | 1898                   |
| Euxinic (1970-1979) | 1654                                 | 5712                   | 0                      |
| Hypoxic (1980-1989) | 16898                                | 23935                  | 7015                   |
| Euxinic (1980-1989) | 6103                                 | 10388                  | 1308                   |
| Hypoxic (1990-1999) | 15086                                | 23041                  | 6760                   |
| Euxinic (1990-1999) | 4546                                 | 10412                  | 0                      |
| Hypoxic (2000-2009) | 21485                                | 24680                  | 15242                  |
| Euxinic (2000-2009) | 6093                                 | 10934                  | 0                      |
| Hypoxic (2010-2016) | 21942                                | 25101                  | 18424                  |
| Euxinic (2010-2016) | 7611                                 | 16493                  | 0                      |

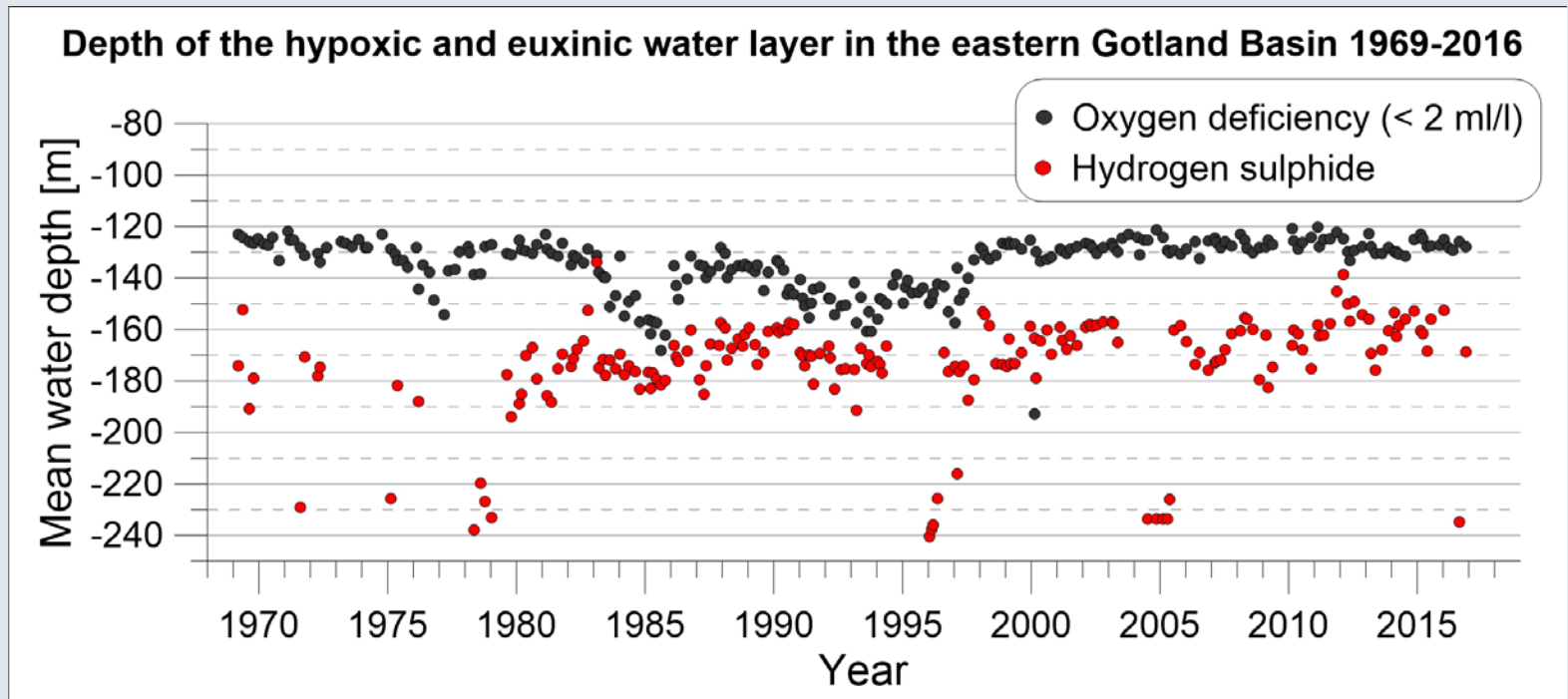
Decadal analysis

| Season               | Mean areal extent [km <sup>2</sup> ] |
|----------------------|--------------------------------------|
| Hypoxic (Jan.-Feb.)  | 19471                                |
| Euxinic (Jan.-Feb.)  | 5799                                 |
| Hypoxic (March)      | 18634                                |
| Euxinic (March)      | 5325                                 |
| Hypoxic (April-June) | 17830                                |
| Euxinic (April-June) | 5203                                 |
| Hypoxic (July-Sept.) | 18093                                |
| Euxinic (July-Sept.) | 5563                                 |
| Hypoxic (Oct.-Dez.)  | 18908                                |
| Euxinic (Oct.-Dez.)  | 5660                                 |

Seasonal analysis

- Hypoxia: only slightly increase since 70's (2000 km<sup>2</sup> /11 %)
- H<sub>2</sub>S: slight increase in the last decade, comparing the stagnation periods, more persistent
- seasonal: only minor changes, min in spring to early summer

## eastern Gotland Basin – water depth

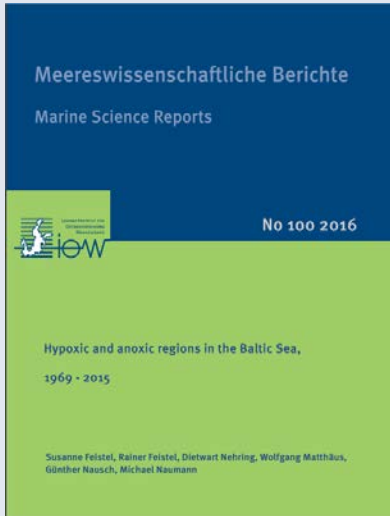


Spatial analysis of hypoxic to euxinic conditions in the eastern Gotland Basin since 1969

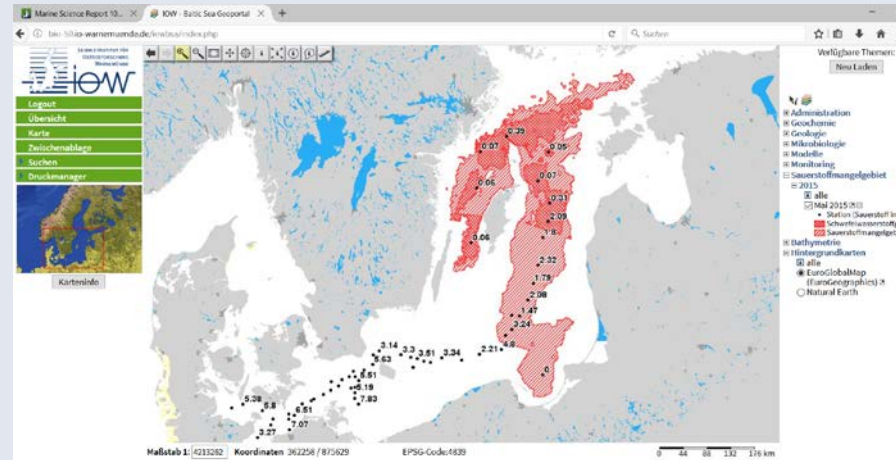
– mean value of water depth considering all deep basins

| Time                | Mean water depth [m] | Standard deviation [m] | Water depth Max [m] | Water depth Min [m] |
|---------------------|----------------------|------------------------|---------------------|---------------------|
| Hypoxic (1969-2016) | 135                  | 11                     | 193                 | 120                 |
| Euxinic (1969-2016) | 174                  | 24                     | 241                 | 134                 |





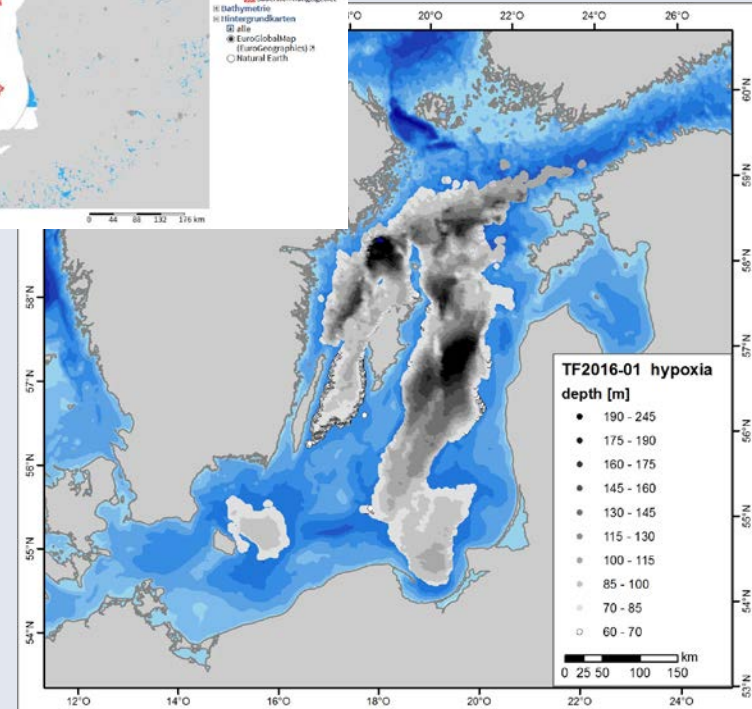
Updates of the report as atlas



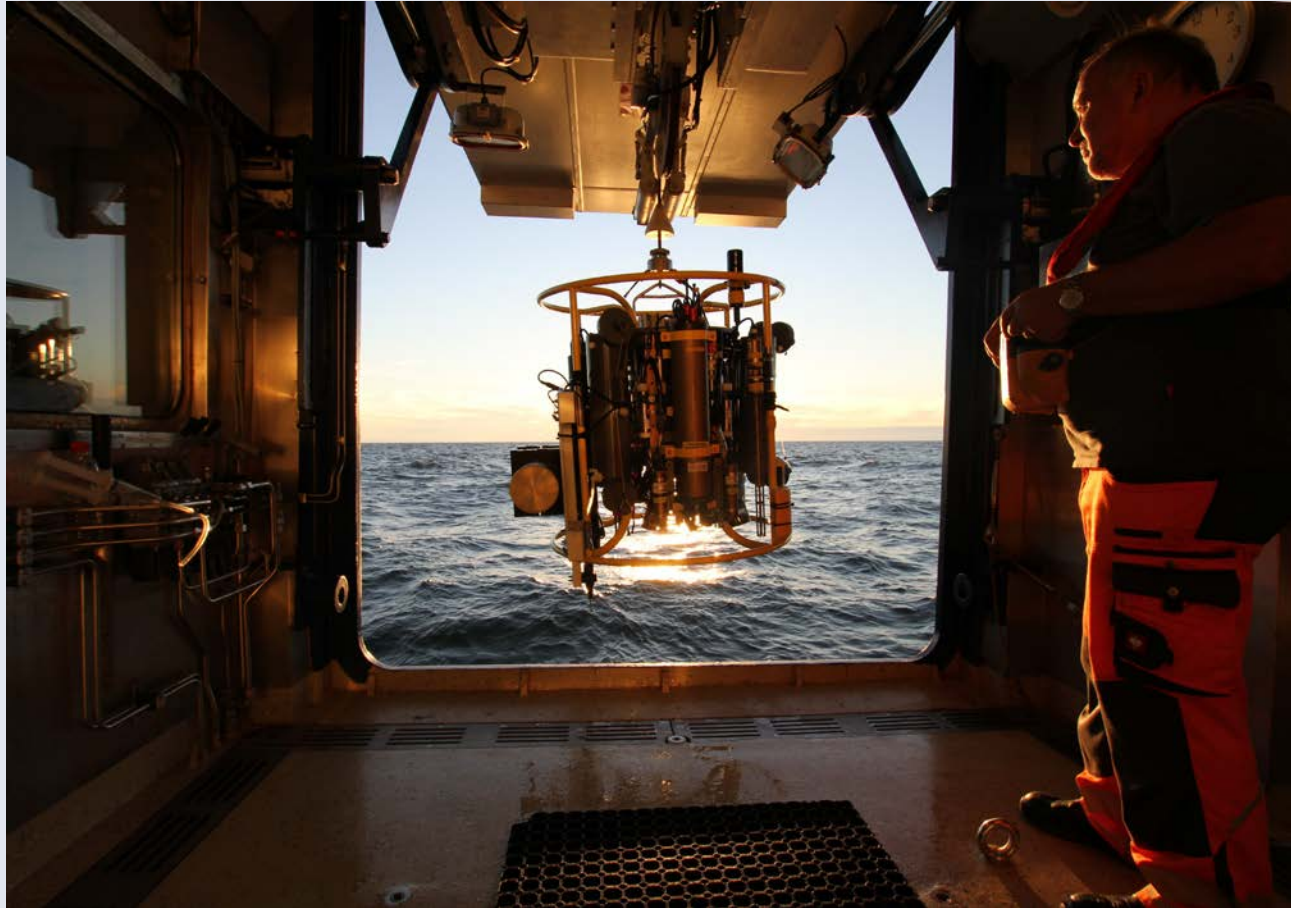
WebGIS – availability

- annual update of the atlas, WebGIS and providing of shapefiles

-> all kinds of users: informative to professional



GIS shapefiles – grid with depth values of the hypoxic and euxinic layer



- all involved crews, technicians and scientists collecting this long-term dataset