Extreme Flood Impact on Estuarine and Coastal Biogeochemistry: the 2013 Elbe Flood

Yoana G. Voynova[1], Holger Brix[1], Wilhelm Petersen[1], Sieglinde Weigelt-Krenz[2], Mirco Scharfe[3]

[1]Institute of Coastal Research, Helmholz-Zentrum Geesthacht (HZG), 21502 Geesthacht, Germany
[2]Federal Maritime and Hydrographic Agency, BSH-Laboratory Sülldorf, 22589 Hamburg, Germany

[3]Alfred Wegener Institut Helmholtz-Zentrum für Polar- und Meeresforschung, Biologische Anstalt Helgoland, P.O. Box 180, 27483 Helgoland, Germany

Correspondence to: Yoana G. Voynova (yoana.voynova@hzg.de)

Abstract. Within the context of the predicted and observed increase in droughts and floods with climate change, large summer floods are likely to become more frequent. These extreme events can alter typical biogeochemical patterns in coastal systems. The extreme Elbe River flood in June, 2013 not only caused major damages in several European countries, but also generated large scale biogeochemical changes in the Elbe Estuary and the adjacent German Bight. The high-frequency monitoring network within the Coastal Observing System for Northern and Arctic Seas (COSYNA) captured the flood influence on the German Bight. Data from a FerryBox station in the Elbe Estuary (Cuxhaven) and from a FerryBox platform aboard the *M/V Funny Girl* ferry (traveling between Büsum and Helgoland) documented the salinity changes in the German Bight, which persisted for about 2 months after the peak discharge. The Elbe flood generated a large influx of nutrients, dissolved and particulate organic carbon on the coast. These conditions subsequently led to the onset of a phytoplankton bloom, observed by dissolved oxygen supersaturation, and higher than usual pH in surface coastal waters. The prolonged stratification also led to widespread bottom water dissolved oxygen depletion, unusual for the south-eastern German Bight in the summer.

1 Introduction

General circulation models have predicted that the frequency of heavy rainfall events will increase over the next centuries with changes in climate (Karl et al., 1995; Meehl et al., 2007; Elsner et al., 2008; Bender et al., 2010), and particularly during summer months (Karl and Knight, 1998; Christensen and Christensen, 2004). Allan and Soden (2008) correlated climate models with satellite observations and concluded that extreme rainfall events and droughts will increase during warm months and these amplifications may be greater than current predictions. Depending on their magnitude, these atypical hydrologic conditions can cause phytoplankton blooms and disruptions in food webs (Paerl et al. 2001; Paerl et al., 2006; Wetz and Paerl 2008; Bauer et al. 2013). It is therefore essential that the impact of extreme rainfall and flood events on the biogeochemistry of estuaries and adjacent coastal regions be better assessed (Scavia et al., 2002; Wetz and Yoskowitz, 2013).

More frequent occurrences of intense flood events and tropical cyclones are likely to generate large infrastructural damages as a result of flooding, high winds and higher storm surges (Wetz and Yoskowitz, 2013). For example, over recent decades, heavy floods in Europe (particularly in August, 2002 and June, 2013) have generated billions of euros in damage (Ionita et al., 2014; Merz et al., 2014). These hydrologic events can also lead to large-scale, prolonged stratification in estuaries and coastal regions as a result of large freshwater influxes (Hickel et al., 1993; Voynova and Sharp, 2012). The stronger stratification and elevated nutrient and organic matter loading to estuarine and coastal systems, associated with these extreme climatic events, along with the increase in temperature already observed in some coastal ecosystems (Wiltshire and Manly, 2004; Luterbacher et al., 2016) could lead to the development of bottom water hypoxia (Statham, 2012; Voynova and Sharp, 2012; Wetz and Yoskowitz, 2013).

One of the most significant discharge events in Central and Western Europe took place in the summer of 2013 (Merz et al., 2014), and caused extensive flood damages on land due to large scale flooding in the southern and eastern parts of Germany, and the western regions of the Czech Republic (Ionita et al., 2014). The meteorological conditions preceding the flood have been extensively documented. During May 2013, weather in and around central Europe was unusually cool and wet (Ionita et al., 2014), due to repeated upper-tropospheric Rossby wave-breaking, and the subsequent occurrence of a quasi-stationary upper-level cutoff low pressure system over Europe (Grams et al., 2014). Heavy precipitation (Global Precipitation Climatology Centre estimates) in Germany during the last two weeks of May amounted to 100-200% of the expected climatological precipitation for the entire month. As a consequence, soils in most of the Elbe River catchment reached record levels of moisture by the beginning of June (Ionita et al., 2014; Grams et al., 2014). Additional heavy precipitation (75-100 mm) between 30 May and 3 June, caused by the passage of three cyclones, Dominik, Frederik, and Günther (Grams et al., 2014), fell over a number of countries including Germany, Austria, Switzerland, Czech Republic, and Poland (Merz et al., 2014). The inability of the already saturated soils to absorb the additional heavy precipitation generated heavy flooding in the Elbe and Danube river basins (Grams et al., 2014; Ionita et al., 2014). A similar progression of events and increased soil moisture have been associated with two other major summer storms, in August, 1954 and August, 2002 (Merz et al., 2014).

This study focuses on the influence of the June 2013 flood on the biogeochemistry of the Elbe Estuary and the German Bight, as an example of the impact of extreme discharge events on the biogeochemistry of estuaries and adjacent coastal regions. The flood event is compared to average conditions, by using a combination of existing historical datasets and high-frequency continuous measurements available from the Coastal Observing System for Northern and Arctic Seas (COSYNA, Baschek et al., 2016). Whereas in 1954 and 2002, autonomous monitoring of the German Bight was scarce or unavailable, recent high-frequency monitoring platforms within COSYNA, along with other available historical datasets (from discrete sampling) have made it possible to capture the impact of a rare summer extreme flood event. A discharge analysis of the 140 year long Elbe River record shows that such rare events have become more prevalent in the last 15 years, and that in the near future they could alter the average coastal and estuarine biogeochemistry.

2 Methods

2.1 Study site

The relatively shallow (10-43 m) German Bight is situated in the south-eastern part of the North Sea, and its topography is dominated by the ancient Elbe River Valley (van Beusekom et al., 1999; Becker et al., 1999). The Wadden Sea is a shallow coastal sea (<10 m), which borders the German Bight along the Dutch, German and Danish coasts (van Beusekom et al., 1999; Fig. 1). The distribution of temperature and salinity in the bottom layers of the German Bight is strongly related to the topography, and follows the ancient Elbe River Valley (Becker et al., 1999). The German Bight is dominated by a counterclockwise residual circulation pattern, which carries a mixture of Atlantic water and continental runoff from the Rhine and several other rivers into the German Bight from the west (Hickel et al., 1993; van Beusekom et al., 1999). The inflow of nutrients and contaminants from the Weser and the Elbe estuaries (van Beusekom et al., 1999), and the residual circulation favor the accumulation of contaminants in the German Bight (Hickel et al., 1993). While the central part of the North Sea is seasonally stratified, the southeast German Bight and the Wadden Sea regions are generally well mixed due to strong tidal currents (Becker et al., 1999).

One of the largest rivers in Northern Europe, the approximately 1100 km long Elbe (Ionita et al. 2014), is the main source of freshwater to the inner German Bight (Hickel et al., 1993). The Elbe stretches from Schmilka, Czech Republic to the Wadden Sea (Fig. 1). The riverine portion extends up to Geesthacht, Germany (Elbe km 580), where a weir marks the head of the tide, and separates the riverine from the estuarine region (Petersen et al., 1999). The estuarine part, characterized by a salinity gradient, extends for about 125 km from Zollenspieker, Germany (599 km) to Cuxhaven, Germany (725 km) (Fig. 1; Petersen et al., 1999; Petersen et al., 2000).

Much of the biogeochemical variability within the salinity gradient of the Elbe River is related to the production and processing of labile organic matter (Amann et al., 2012). High nutrient loads, and damming of the river near Geesthacht, allow for nutrient assimilation by primary production in the nontidal riverine portion, generating high chlorophyll concentrations (> 60 µg L-1), dissolved oxygen supersaturation, and pH levels up to 9.5 in surface waters upstream of the dam weir (Petersen et al., 1999; Scharfe et al., 2009). Within the tidal river and salinity gradient of the Elbe Estuary, nutrients are regenerated from the large amounts of decomposing labile particulate carbon, and oxygen levels can become severely undersaturated; this defines the oxygen minimum zone (OMZ), particularly near Hamburg (Petersen et al., 1999; Amann et al., 2012). Further downstream along the salinity gradient, oxygen levels increase, but typically remain undersaturated.

2.2 Data Sources

A number of stations, and moving or fixed monitoring platforms, shown in Fig. 1, and listed in Table 1, were used to understand the changes that occurred within the Elbe Estuary and the adjacent coastal regions in the southern part of the German Bight. Monthly maps of biogeochemical parameters of interest were generated using a combination of available measurements. For 2013, we focused on the months before (March), and after (July, August and September) the June flood event, when the most complete maps were generated. The datasets used in the maps are listed in Table 1. The FerryBox and MARNET data were downloaded from the COSYNA data portal CODM (Breitbach et al., 2016).

2.2.1 River Discharge

A more than a century long Elbe River daily discharge record (1.11.1874 – 31.08.2015) was available from the Neu Darchau gauging station (Elbe km 536), located in the lower Elbe River catchment area, about 50 km upstream of the weir at Geesthacht (Fig. 1). The data were provided by the German Federal Waterways and Shipping Administration (WSV), and communicated by the German Federal Institute of Hydrology (BfG), and have been analyzed in terms of their daily, monthly and decadal distributions. In addition, a recurrence analysis (von Storch and Zwiers, 2003) on the 5-, 10-, 25-, and 50-year discharges was done to compare the number of occurrences within the last 15 years to the rest of the 140 year record.

2.2.2 Tidal Height at Cuxhaven, Germany

Sea level data (tidal height) were extracted from the GLOSS/CLIVAR database (http://www.gloss-sealevel.org/data/#.VxeHnUaFEak), from a station located near Cuxhaven, Germany (53.87º N, 8.72º W), which has been sampling between 1917 and 2015. In this study we used hourly observations for 2012-2013.

2.2.3 Cuxhaven FerryBox Station

A stationary FerryBox system has been operating at Cuxhaven (53.877º N, 8.705º W) since 2010, measuring temperature, salinity, dissolved oxygen (DO; Aanderaa optode), chlorophyll fluorescence (Chl; Turner Designs, Sunnyvale, CA), pH (Clark electrode) and turbidity (Turner Designs, Sunnyvale, CA) approximately every 10 minutes (Petersen, 2014).

All data from the Cuxhaven FerryBox station were resampled at an hourly interval. The 2012-2013 records had the most complete coverage of all parameters, and were therefore used for analysis in this study. Continuous dissolved oxygen optode data were corrected using six discrete samples taken between 2012 and 2014, and analyzed by Winkler titration. The Winkler titration data were on average 40.72 +/- 2.63 µM higher than the Aanderaa optodes, and thus the Cuxhaven DO optode 2012-2013 data were corrected by adding the average difference to the optode measurements.

Frequency analysis (Voynova et al., 2015) helped to identify a number of modes associated with tidal, daily and lower-frequency harmonics at this station. The frequency spectra for the FerryBox data were compared to sea level frequency spectra from the GLOSS/CLIVAR database, so that biological signals could be identified. In addition to the frequency analysis, isolating the signals associated only with high tide or low tide according to method described in Voynova et al. (2015) allowed to better understand the biogeochemical changes at different locations in the Elbe Estuary and to better visualize the changes in DO related to each water mass end member.

2.2.4 Hamburg Port Authority (HPA) Elbe River Pile

The Cuxhaven FerryBox data were compared to data gathered at a pile operated by the HPA and Helmholtz-Zentrum Geesthacht (HZG), and deployed in the Elbe River (53.859º N, 8.944º W), about 15 km upstream of the Cuxhaven FerryBox, during 2012 and 2013 (March - November). Every 10 minutes a variety of biogeochemical parameters, including temperature, salinity, DO, chlorophyll fluorescence, and turbidity, were measured at the pile, and thus provided another reference station within the Elbe estuary. All HPA Elbe River data were resampled to an hourly interval.

2.2.5 Funny Girl FerryBox

Throughout the summer months, from about May to September, the *M/V Funny Girl* ferry crossed the distance between Büsum and Helgoland in the German Bight two times a day (Fig. 1). A FerryBox installed aboard the ferry in 2008 measured a number of parameters including temperature, salinity, pH, chlorophyll fluorescence, dissolved oxygen, colored dissolved organic matter (Turner Designs, Sunnyvale, CA), and turbidity.

Not all parameters were available every year between 2008 and 2015. The longest available records (2008-2015) were for temperature, salinity and pH; the most complete summer records for every parameter were available during 2012, 2013 and 2014. These data were used to compare the German Bight biogeochemical conditions in 2013, to non-flood years (2012 and 2014), and to quantify the influence of an extreme summer flood event on the German Bight.

Routine service was done on the ferry every 2-3 weeks, and consisted of replacing or calibrating the pH probes, replacing DO optode, cleaning the CDOM and chlorophyll fluorometers, or any additional maintenance of the other instruments and the FerryBox flow-through system. pH was calibrated at every visit using standards with pH range of 4-10; 6 discrete samples (in duplicates) for Winkler titration were collected when the ferry was in Büsum between 2012 and 2015, and only 2 were collected during the summer. The optode measurements were 14-24 µM DO lower than the Winkler titrations, but because of the few samples and the small difference (< 1 % DO saturation), the summer optode measurements from *M/V Funny Girl* were not corrected.

2.2.6 Deutsche Bucht (German Bight) Monitoring Station

The Deutsche Bucht station is located east of Helgoland (53.167º N, 7.45º W). At this station salinity, water temperature, and dissolved oxygen concentrations were measured at depths of 6 and 30 m, every hour. The station has been operated by the Federal Maritime and Hydrographic Agency of Germany (Bundesamt für Seeschiffahrt und Hydrographie (BSH)) since 1989, as part of the Marine Environmental Monitoring Network in the North and Baltic Seas (MARNET), and the data are also available at the COSYNA website (https://www.hzg.de/institutes_platforms/cosyna/index.php). Salinity, temperature and dissolved oxygen data for 2013 were used to understand the water column dynamics in the southern part of the German Bight. This station will be referred to as Deutsche Bucht station further on.

2.2.7 Discrete Samples

BSH and the Biological Station Helgoland of the Alfred Wegener Institute (BAH, AWI) have collected discrete biogeochemical samples (surface and bottom) during routine monthly ship cruises throughout the German Bight over a number of years. Typical sampling station positions are shown in Fig. 1 (Table 1); however, not all stations were sampled every month. In 2013, the data between March and September were used to generate surface maps of salinity, temperature, phosphate, nitrate and nitrite, silicate, and ammonium. The maps were generated using a Gaussian interpolation of all available data for each month (Table 1), including FerryBox and Deutsche Bucht data. In addition, surface and bottom dissolved oxygen samples collected in August and September were compared to data from the Deutsche Bucht station (Fig. 1).

Finally, BAH AWI data, from the Elbe and Eider stations (Fig. 1, Table 1) for the period between 2008 and 2015 (except 2013) were used to compile average monthly maps of nutrient and hydrographic parameters, including salinity, dissolved oxygen, nitrate, nitrite and silicate. Contrasting the average monthly maps to the 2013 monthly maps allowed to visualize how water mass characteristics, nutrient and dissolved oxygen throughout the German Bight were influenced by the flood event.

3 Results

3.1 Discharge Analysis

The average daily discharge for the entire Elbe discharge record (Fig. 2) was 708 ± 446 $m^3 s^{-1}$. However there were distinct seasonal differences, and summer is typically the driest season (Fig. S1). The daily discharge during the June 2013 flood was the highest among all summer daily discharges during the last 140 years, and overall the second highest daily discharge on record, with two daily flows of the same magnitude (4060 $m^3 s^{-1}$) on June 11 and 12, 2013. The highest overall daily discharge (4400

$m^3 s^{-1}$) was recorded on March 25, 1888. The June 2013 flood was so large, that the average discharge for the entire month of June, 2013 was also significantly elevated (Fig. S1a), compared to the June discharge over the rest of the 140-year old record (monthly means).

In recent decades (1966 – 2015, Fig. S1b), most of the elevated discharges in the spring period were distributed over January, February, March and April, instead of concentrated during March and April. Also, the magnitude of the average monthly spring discharge during the last 4 decades was smaller than the March-April decadal averages prior to 1945 (Fig. S1b). This suggests that there is a redistribution of average monthly discharge patterns within the last 4 decades.

The recurrence period of the highest June daily discharge is every 70 years, when considering the entire 140-year discharge record. However, between 1915 and 2015, the June 2013 event (in terms of daily discharge) was the largest flood; therefore it could also be considered as a 100-year storm. Depending on the return period (5, 10, 25, or 50 years, Table 2), 20 to 60% of the large to extreme daily discharges occurred in the last 15 years (2001-2015), resulting in a significant increase in the frequency of these floods since the turn of the century.

3.2 Flood Influence on the Elbe Estuary

In order to understand the influence of the June 2013 flood on the Elbe Estuary, hourly Cuxhaven FerryBox station data were plotted alongside HPA Elbe Pile data for 2012-2013. Although spring discharge during both years was about the same, the 2012 summer discharge was considerably lower (< 1000 $m^3 s^{-1}$, Fig. 3), which is reflected in the higher average salinities observed at both stations in 2012. The 2012 data could be used as a reference for the biogeochemical patterns during a normal season, while 2013 represents an extreme discharge summer.

Despite the stations' relative proximity (~ 15 km distance), the Cuxhaven FerryBox and the HPA Pile were located in two distinct regions in the estuary. In addition, the biogeochemical parameters shown in Fig. 3 also varied considerably over a tidal cycle, over the summer season, and between 2012 and 2013. A frequency analysis of all available data at Cuxhaven (Fig. 4) allowed us to identify the main frequencies associated with each variable in Fig. 3. As a reference, the sea level power spectral density at the FDH station near Cuxhaven is shown next to each parameter (Fig. 4). All parameters (temperature, salinity, DO, Chl, turbidity, pH, sea level) have a pronounced peak associated with the 12.5 hour tidal period (most likely M_2 and S_2 lunar and solar semi-diurnal constituents), as well as with the residual shallow tidal 8, 6 and 4 hour periods (Voynova et al., 2015). In addition, a lower frequency peak is resolved at the 24-25 hour period, most likely associated with the day-night cycles and the O_1 and K_1 lunar diurnal tidal constituents. The 24-hour peak is slightly more pronounced in the DO and temperature plots (Fig. 4), which suggests that these parameters are affected by the day-night cycles in temperature and primary production. Finally, the 60-hour window size did not allow for resolving lower frequencies like spring-neap variability or storms. However, these low-frequency modes, including the seasonal changes in water temperature, likely influenced the biogeochemistry in the Elbe Estuary (Fig. 3).

In order to better visualize the flood influence, and considering the large tidal ranges in the Elbe Estuary (~ 3 m at Cuxhaven), the positions of salinity minima and maxima over a tidal cycle at each station were identified, based on methods described in Voynova et al. (2015). The values of several parameters (salinity, temperature, dissolved oxygen, pH, and chlorophyll fluorescence) at the identified positions were extracted to represent the flood and ebb water mass end members at Cuxhaven and the HPA Pile (Fig. 5). About 4 to 5 days after the peak discharge (June 12-13, 2013), there was a pronounced salinity decrease at Cuxhaven, and the ebb tide salinity dropped below 3 for about 8 days, while the flood tide salinity dropped to about 10 on June 18. The elevated discharge shifted the entire salinity gradient seaward, so that around HPA Pile (Elbe km 710), salinity dropped to below 2 for at least 9 days (Fig. 5). The shortened residence time of 4-5 days is substantially smaller than the residence time at a lower discharge of 250 $m^3\ s^{-1}$ (84 days), or 1200 $m^3\ s^{-1}$ (18 days; Bergemann et al., 1996).

BSH estimated that between 12 June and 8 July, 2013, nutrient loading near Hamburg was significantly elevated (Table 3). Nutrient loads varied with time (Weigelt-Krenz et al., 2014): while the peak nitrate and silicate loading coincided with the peak discharge (12-16 June), the peak ammonium and phosphate loading occurred between June 24 and 28, about 12 days later, reflecting a delayed influx of these nutrients onto the German Bight.

The flood influence on the Elbe Estuary was prolonged, as suggested by the gently sloping falling limb of the flood hydrograph, and the depressed salinity at both stations between the beginning of June and the end of July, 2013 (Fig. 5). Between June and July, 2013, the tidal salinity range at Cuxhaven increased and was close to double the typical range in 2012, while the salinity range at the HPA Pile decreased to about half the typical range. The ebb salinity at Cuxhaven was very similar to the flood salinity at the HPA Pile, which suggests that water was usually transported between the two monitoring stations over a tidal cycle.

Several biogeochemical parameters were also influenced by the flood. Dissolved oxygen decreased when salinity dropped (down to 65% saturation at HPA Pile), suggesting the delivery of oxygen-depleted low salinity water from riverine tidal regions (Amann et al., 2012). Dissolved oxygen bounced back to pre-flood levels, and then increased to close to saturation, likely associated with an increase in local production after the storm. During the flood, oxygen fluctuations were diminished. Before the flood, changes in pH tracked dissolved oxygen, but as salinity started to decrease, pH at Cuxhaven decreased to 7.5 (ebb tide). This suggests that the change in water mass affected both DO and pH. After the storm, pH was still depressed (< 8, Fig. 5), but also tracked DO.

In both 2012 and 2013, DO was typically highest during flood tide at Cuxhaven, and it sometimes supersaturated in surface waters. This indicates that while upstream estuarine regions are generally DO-depleted (Amann et al., 2012), in the coastal regions adjacent to the Elbe Estuary, primary production rates are high. While in 2012 DO was supersaturated in spring/early summer, coincident with elevated pH (> 8), in 2013 the highest DO was measured in July and August. This suggests an increase in primary production after the flood event.

In 2013, high chlorophyll concentrations (Fig. 5) during the flood tide at Cuxhaven coincided with the highest pH values, which suggests that there was a large bloom in the coastal waters near Cuxhaven at the end of May, beginning of June, perhaps stimulated by the elevated precipitation and discharge during May (Merz et al., 2014). The bloom was also observed by the discrete chlorophyll measurements collected just before the flood on June 5-6, 2013 (not shown) along the BAH AWI stations (Fig. 1). The highest chlorophyll concentrations ranging between 6 and16 µg L^{-1} (Weigelt-Krenz et al., 2014) were measured at Elbe stations 4-8 and Eider stations 4-6 (Table 1), which suggests that prior to the flood the coastal bloom was confined to the south-west Wadden Sea (Fig. 1). After the onset of the June flood (June 12-13), chlorophyll fluorescence measurements at Cuxhaven abruptly decreased (Fig. 5) and were lowest around the time of lowest salinity (5 days after the peak discharge at Neu Darchau), DO and pH, indicating that the bloom was flushed out with the surge of freshwater and a large amount of potentially labile organic matter was transported to the German Bight.

To summarize, the extreme discharge event caused a shift in the entire salinity gradient of the Elbe Estuary, and salinity was overall depressed for more than a month compared to typical levels. Prior to the flood, the heavy May rains (Ionita et al., 2014), and the subsequent elevated discharge, had generated a nutrient influx, and a large bloom in the Wadden Sea near Cuxhaven. When this bloom was flushed out during the extreme June discharge, it was a large source of labile organic material, and additional nutrient loading onto the German Bight.

3.4 2013 Flood Influence on the German Bight

To examine the influence of the 2013 June flood on the German Bight, we used several data sources listed in Table 4. The most extensive records of the changes on the coast were available from the *M/V Funny Girl* FerryBox (Fig. 6), which measures temperature, salinity, chlorophyll fluorescence, DO, colored dissolved organic matter (CDOM) fluorescence, and pH (2 Clark electrodes). We were able to contrast an anomalous year (2013) to drier summer conditions (2012 and 2014). The region between Büsum and Helgoland was very dynamic in the summer, with a salinity range of about 5-6 salinity units, and a temperature range of up to 5 degrees between the two ports. In addition, although DO varied seasonally, it was often supersaturated along the ferry transect, suggesting that the region between Büsum and Helgoland is typically productive between April and October.

The highest pH values along the ferry transect typically occurred in the beginning of the summer, or the end of the spring (May-June). In 2012, and 2014, this indicated the end of the spring bloom. In 2012 and 2014, pH had a pronounced seasonal drift reflected in the records of both pH electrodes, so that the lowest pH typically occurred in the fall (Fig. 6). Even though CDOM fluorescence was not calibrated against discrete dissolved organic carbon (DOC) samples, the CDOM range was similar in 2012 and 2014 (Fig. 6). CDOM varied linearly with salinity along the ferry transect (Fig. 7), indicating dilution of continental allochtonous sources of dissolved organic carbon, without a significant source or sink. The similarity of the slopes for 2012, 2013 and 2014 also indicated that the interannual variation of dissolved organic matter was a function of dilution of freshwater sources of organic carbon.

The June 2013 flood caused significant changes in all parameters in Fig. 6. While temperature increased slightly, salinity in the middle of June, 2013 decreased dramatically to below 15 near the Wadden Sea and remained depressed through July and August; at the same time, salinity range increased to about twice the range observed during 2012 and before and after the flood. At first the lower salinity water mass that reached the German Bight was characterized by high chlorophyll concentrations, associated with seaward flushing of the coastal bloom observed near Cuxhaven, and the Wadden Sea. Then, decreasing salinity in the German Bight, tracked a water plume from the Elbe Estuary, characterized by low DO (<100% saturation) and high CDOM (up to double the levels observed in 2012 and 2014, Figs. 6 and 7). This indicates that a large pulse of dissolved organic carbon was quickly delivered to the coast. The slopes of the linear regressions after the flood, in 2013 (Fig. 7c) and in 2014 (Fig. 7d) are slightly more negative, compared to the time before (Fig. 7a-b), indicating that there may have been a switch to higher content of dissolved organic matter in the German Bight as a result of the flood.

The storm discharge also caused the lowest salinity on record (Fig. 8) in all available *M/V Funny Girl* data (2007-2014) particularly near the eastern Wadden Sea. At the end of June and beginning of July, about two weeks after the flood onset and salinity changes at Cuxhaven, the entire ferry transect was fresher than usual. The eastern part of the ferry transect was less saline (salinity < 25) throughout the whole 2013 season compared to non-flood years, and surface water temperatures during May and into June were unusually cold (5-15º C), compared to the rest of the summer records, especially near Helgoland.

During the 7-year record from *M/V Funny Girl* (Fig. 9), pH was typically high in the beginning of summer, due to high biological production during the spring bloom (Blackford and Gilbert, 2007). Later in the year, pH usually decreased, and the lowest pH values occurred at the end of the summer, beginning of fall. During 2013 however, high pH (> 8) persisted throughout spring and into early June.

Then, after a brief period of low pH, which coincided with the lowest salinity water (Fig. 8), the pH values increased to about spring bloom levels. Compared to the typical pattern observed during all other years, the unusually high pH late in the summer (July-August) was most likely associated with a coastal bloom which formed after the flood, in response to the nutrient influx and potential stratification of the water column. Even though the seasonal patterns of the two parameters differed in this region, DO supersaturation in July also supported this suggestion. All of these factors suggest that the June 2013 flood had a substantial effect on the German Bight between Helgoland and Büsum, which had not been observed during any other year on record.

In combination with discrete and autonomous sampling from BSH and BAH AWI (Table 4), the *M/V Funny Girl* and Cuxhaven FerryBox data were used to create maps for March, July, and August for surface salinity, nitrate, nitrite, and silicate (Figs. 10, 11, 12). These months had the most complete records between all data sources, allowing for more detailed surface maps to be generated. The 2013 maps were compared to average distributions of all parameters. The March 2013 parameter distributions were similar to average conditions in patterns and magnitude, especially for salinity and nitrate and nitrite ($NO_3 + NO_2$). In July, following the June 2013 flood, there was a large plume of low salinity (< 28), high nitrate ($NO_3 + NO_2$, 3-43 µM) water along the coastal regions near the western Wadden Sea. It extended north along the coast, and west and slightly south of Helgoland. The plume spread well over the south-east German Bight in July, about a month after the large discharge event. The plume also carried higher concentrations of ammonium (not shown) and silicate onto the coastal shelf regions, although their patterns differed slightly from the salinity distributions. The July 2013 maps were quite different from average high salinity (> 25) and low nitrate (0.01-1 µM) patterns typically found in July (Fig. 11). Also, before the flood (June 4-6), west of 8.5 °E, BAH AWI measurements (Fig. S2) of nitrate and nitrate (0.14-5.85 µM), silicate (2.16-13.99 µM) and phosphate (0.06-0.75 µM) were low and similar to the average June distributions (maps not shown).

To analyze the influence of the freshwater plume on water column stratification and dissolved oxygen distribution, we used temperature, salinity and DO data from the Deutsche Bucht MARNET station, located east of Helgoland (Fig. 13). This station was affected by the low salinity and high nitrogen loading (Fig. 11). Surface water temperature and salinity at the end of July and during August differed from bottom distributions, suggesting the establishment of persistent water column stratification. Even though the vertical temperature gradient decreased after the middle of August, the presence of low salinity surface water probably helped to maintain stratification up to September. Surface dissolved oxygen supersaturation (at 6 m) indicates enhanced production within the surface mixed layer in July and August, while DO undersaturation at 30 m indicates respiration of organic matter in the isolated bottom waters (Fig. 13). Even though supersaturation also occurred in the spring (April-May), bottom water DO was only undersaturated during the summer, after the water column had remained stratified for about two months. At the end of September, and beginning of October, after stratification broke (there was no vertical gradient in temperature and salinity), DO in surface and bottom waters equilibrated to about saturation levels.

In 2013, the most complete DO records within the German Bight were available in August and September from surface and bottom samples, measured by BSH and BAH AWI cruises (Fig. 14). Most of the surface samples in August (93 %) were supersaturated, indicating high primary production in surface waters throughout the southeast German Bight; in September, only 6% of the surface samples were supersaturated. Bottom water DO undersaturation suggests that prolonged water column stratification established within the German Bight. In August, 2013, 71% of the bottom oxygen measurements were undersaturated, and 42% of the stations measured DO < 85% saturation. In September, 91% of the bottom samples were undersaturated and 40% experienced DO of 85% saturation or less. The maps in Fig. 14 suggest that in the German Bight, especially within the Elbe River valley, and east of Helgoland near the Deutsche Bucht station, bottom dissolved oxygen was undersaturated in both August and September. The discrete sample data combined with continuous observations made by the fixed Deutsche Bucht MARNET station suggest that the observed stratification and dissolved oxygen depletion in bottom waters was widespread within the southeast German Bight, and persisted at least 2-3 months after the extreme June discharge.

To summarize, the June 2013 flood generated a large plume of low salinity waters from the Elbe Estuary and over most of the southeast German Bight, and carried large amounts of nutrients and dissolved organic carbon onto the coastal regions. The storm outflow affected the eastern Wadden Sea, and spread north of Büsum along the coast, but also west and south of Helgoland. The flood plume was present in July and August, and caused persistent stratification on the coast. The influx of nutrients and the establishment of atypical prolonged water column stratification increased primary production and oxygen supersaturation (> 110%) in the surface mixed layer, and also contributed to widespread oxygen depletion in the isolated bottom waters.

4 Discussion

The June 2013 flood event was the second largest in the 140 year discharge record of the Elbe River at Neu Darchau, and had a significant influence on the biogeochemistry of the Elbe Estuary. The residence time in the estuary decreased to 4-5 days, and even though salinity changes at the mouth of the Elbe Estuary were small compared to upstream regions, there was a notable constriction of the salinity gradient, and larger salinity fluctuations over a tidal cycle at Cuxhaven station during and after the storm. Based on available observations it can be deduced that a large bloom in the coastal waters near Cuxhaven was flushed out by the storm outflow onto the shelf near the eastern Wadden Sea.

The doubling of CDOM fluorescence detected by the ferry *M/V Funny Girl*, suggests that the low salinity water plume carried a large load of continental-based colored dissolved organic matter which doubled the typical levels observed on the coast. Similarly, extreme floods have been shown to significantly increase and even double the dissolved organic carbon in estuaries and coastal regions (Paerl et al. 2001; Bauer et al. 2013). The average DOC concentrations in the freshwater tidal river of the Elbe Estuary are relatively high, 500-600 µmol L^{-1} (Amann et al., 2012), and due to the reduced residence time, a large portion of that DOC pool was transported on the coast during the flood. Typically, about one third of the organic matter loads into the Ems Estuary and the western Dutch Wadden Sea is derived from freshwater sources (van Buesekom and de Jonge, 1998), and 25-33% of the dissolved and particulate continental-based organic carbon sources are labile (Smith and Hollibaugh, 1993). Therefore, river discharge has a large influence on the carbon cycle in the German Bight and can contribute to high rates of remineralization. Extreme discharges like the June 2013 flood are responsible for most of the particulate organic carbon transport from watersheds to coastal regions (Bauer et al. 2013). From the large fluctuations in chlorophyll fluorescence (Fig. 6), it can be deduced that POC loading on the coast was high after the flood, despite the lack of particulate organic carbon measurements. With increased discharge from the Elbe River in summer 2013, sources of labile organic carbon from freshwater and coastal phytoplankton blooms increased significantly, and probably altered the carbon cycle in the east Wadden Sea and adjacent coastal regions.

In addition, the more negative slope in the post–flood salinity vs. CDOM regressions suggests that there may have been a change in the amount and type of dissolved organic carbon on the coast after the flood, which persisted in 2014. This could be due to remineralization of the increased allochtonous particulate organic carbon load after the flood. In the last 25 years, with decreasing pollution, the amount of particulate organic carbon in the Elbe Estuary has increased from 10 to 30 % of the total organic carbon pool. Half of this pool is efficiently remineralized in the oxygen minimum zone of the Elbe Estuary before reaching the turbidity maximum, and the rest is remineralized in the turbidity maximum (Amann et al., 2012), located upstream of the HPA Pile in Fig. 1. A large flood event, like the June 2013 extreme discharge substantially decreases the residence time of the estuary, and shortens the time for remineralization of POC, thus increasing loading of continental-based organic carbon to the shelf where it can contribute to respiration (Cai et al., 2011). The observed oxygen depletion after the flood (Fig. 8) for example may have resulted from increased respiration of both allochtonous and autochtonous labile organic carbon. Extreme floods like the 2013 June event can therefore substantially alter the carbon sinks and sources in coastal areas, and more measurements of dissolved and particulate organic carbon (unavailable for this study) would be useful to quantify their influence on carbon budgets in coastal and shelf seas.

In addition, the June flood delivered large amounts of nitrogen from the Elbe estuary to the southeast German Bight. Despite the significant decrease of ammonium loads since 1989 (Petersen et al., 1999), nitrogen loading in the Elbe in the form of nitrate is still high (> 150 µM about 15 km from the mouth of the estuary), and represents a significant nutrient source to the German Bight (Hickel et al., 1993). The June 2013 discharge generated nutrient loads in the estuary that were 2-50 times higher than average nutrient loads, measured for the month of June between 1996 and 2005 (Table 3; Weigelt-Krenz et al., 2014). The nutrient loading spread onto a large portion of the German Bight, extending north along most of the eastern Wadden Sea, as well as south and west of Helgoland, in regions that are typically nitrogen depleted during the summer (Fig. 11-12). The plume was observed up to 1-2 months after the flood, in both surface salinity and nutrient distributions. The sudden nitrogen influx stimulated growth of primary producers in the surface waters, which was supported by the dissolved oxygen supersaturation measured by *M/V Funny Girl* after the flood event. By August, nitrate and nitrite concentrations were much lower, suggesting efficient uptake of nitrogen in the German Bight.

Typically, in summer, when nutrient influx from rivers is reduced, remineralization of organic matter plays an important role in sustaining high primary production in the German Bight. The annual turnover rate in the North Sea and the Wadden Sea is high (van Beusekom et al., 1999; Brockmann et al., 1999; Reimer et al., 1999). Therefore, a sudden influx of nitrogen-rich water on the coast is likely to stimulate the already efficient high rates of primary production and remineralization (van Beusekom et al., 1999). The faster rates of phosphate remineralization (Hickel et al., 1993) probably helped to sustain increased primary production, despite the low phosphate influx after the flood event (Fig. 12). This was observed in 2013, as more than 90% of the surface dissolved oxygen measurements in August were supersaturated, even 2 months after the extreme discharge.

The June 2013 flood had two important effects on the coastal carbon cycle. On one hand the freshwater plume delivered allochtonous organic carbon to the coast that is otherwise typically processed within or near the Elbe estuary. On the other hand, the nutrient influx in the German Bight stimulated phytoplankton growth, and the increased production of autochtonous organic carbon. Both of these processes probably affected the coastal carbon cycle up to 2-3 months after the flood event. A further implication may be a longer term effect from the flood event on the carbon and nutrient budgets and eutrophication state of the German Bight. This may be substantiated by the change in the salinity to CDOM regression slope after the flood in 2013 and 2014 (Fig 7c-d). Hickel et al. (1993) suggested that eutrophication (and changes in nutrient loads) in the inner regions of the German Bight may have a delayed effect of up to several years on the outer German Bight through the transport and subsequent recycling of plankton and detritus. Similarly, after 3 consequential hurricanes in 1999, Paerl et al. (2001) observed multiannual ecosystem changes in Pamlico Sound, NC, USA, which included an increase in organic carbon content in sediments from autochtonous and allochtonous sources, enhanced primary production, and bottom water hypoxia, as well as changes in phytoplankton communities. Even though the changes in this lagoonal estuary were facilitated by the large residence time characteristic of this system (Paerl et al. 2001), similar cascading and multiannual biogeochemical and ecological changes can be expected in other coastal systems affected by large hydrologic events. Therefore the June 2013 discharge may have had an even more prolonged and widespread effect on the ecosystem of the German Bight than has been emphasized in this study. To further investigate this in the future, it is necessary to do a long term study on the carbon dynamics at existing stations, and include a more detailed analysis of the carbon sinks and sources in the southeast German Bight and adjacent regions.

Near the Deutsche Bucht station, the water column stratified, and stratification and the presence of a bloom in the surface waters resulted in the undersaturation of dissolved oxygen in bottom waters up to 2 months after the discharge. From a number of additional discrete samples (Fig. 14), stratification and dissolved oxygen depletion seemed to have been widespread throughout the regions affected by the plume. As a reference, Topcu and Brockmann (2015) found that the mean bottom water dissolved oxygen in the German Bight has a saturation rate between 83.9 and 99.6%. Most of the bottom water dissolved oxygen (% saturation) was much lower in August and September, 2013. This suggests that bottom water oxygen depletion and hypoxia in the southeast German Bight may be another detrimental effect from an extreme discharge event. One of the reasons for the persistence of water column stratification was probably due to the overall stable conditions on the coast. Callies et al. (2016) used the results from a principal component analysis of the daily model output of the residual circulation in the German Bight and determined that during most of summer 2013 conditions were stable, with overall low wind conditions. Hickel et al. (1993) similarly observed that calm wind conditions after a flood event (summer 1981) allow the development of stratification and favorable light conditions for phytoplankton growth in the stratified surface layer, whereas strong winds lead to vertical mixing, poor light conditions and no bloom after a flood event (winter-spring 1987-88).

The large scale influence and potential long-term effects from extreme discharges on estuarine and coastal systems may become more frequent with changes in climate (Statham, 2012; Voynova and Sharp, 2012), and the June 2013 discharge and its influence on the German Bight serves as an excellent example. Although average summer precipitation is predicted to decrease within the next 100 years, extreme precipitation events are expected to increase (Christensen and Christensen, 2004), and this is what has been observed in the discharge patterns of major rivers like the Elbe. Up to 20-60 % of the very large and extreme discharge events have taken place in the last 15 years, and two of the largest discharges took place during summer, in August, 2002 and June, 2013. Water temperature increases in two of the major northern European river basins, the Elbe and the Danube Rivers have already been observed as a response to air temperature increase driven by climate change (Markovic et al., 2013), and summer air temperatures in recent years have been the highest on record over the past 2000 years (Luterbacher et al., 2016). Therefore, as we are already seeing the changes that have been predicted with climate change models (Karl et al., 1995; Allen and Soden, 2008; Bender et al., 2010), it is important to better prepare for how to study and manage coastal systems affected by these extreme events. Whereas large spring flood events may be predicted based on snowpack and snowmelt characteristics months before the discharge, summer discharges generated by large precipitation events are more difficult to predict in advance (Ionita et al., 2014). It is useful to have monitoring networks like COSYNA in place, which can be further expanded with biogeochemical parameters, like bottom dissolved oxygen sensors to help track the state of the ecosystem before and after an extreme event. In addition, further studies of dissolved and particulate carbon and nitrogen species could help determine the immediate and more long-term effect of these extreme events on the carbon and nitrogen cycles in coastal ecosystems.

5 Conclusions

The influence of the June 2013 Elbe River flood on the Elbe Estuary and the adjacent German Bight was captured using discrete samples and COSYNA continuous monitoring platforms. This flood event serves as a well-documented example of how extreme discharges can alter the biogeochemistry of estuarine and coastal regions. The flood delivered large loads of particulate and dissolved organic carbon, and nutrients on the coast. The increased loading of labile organic carbon most likely altered the coastal carbon cycle, as observed by the doubling of CDOM after the flood and the initial decrease in dissolved oxygen and pH shortly after the flood event in July, suggesting increased respiration of organic matter. Up to 2 months after the flood, water column stratification and enhanced primary production, as evidenced by high pH and prolonged dissolved oxygen supersaturation in surface waters throughout the southeast German Bight, caused a more long-term and widespread effect on the coast.

The atypical depletion of dissolved oxygen in the stratified bottom waters could be another potentially detrimental effect on coastal ecosystems, particularly in the summer, when temperature is high and reaction rates are fast. Finally, it is possible that the increased loading could have an even more prolonged influence on the coastal ecosystem, due to recycling of the increased loads of organic carbon and nutrients on the coast. This remains to be tested in the future, although the slight shift in slope of salinity vs CDOM regressions after the flood suggests an increase in the carbon content of surface waters which persisted in 2014. Since large and extreme floods have increased in frequency in recent decades, and 20-60 % of them (depending on discharge magnitude) have occurred in the last 15 years, the biogeochemical changes described in this study may become more prevalent in the future, particularly during summer months. This effect of climate change has already been observed in a number of watersheds, and establishing continuous monitoring platforms becomes essential for quantifying the influence of these events on coastal and estuarine biogeochemistry.

6 Author Contribution

Y.G. Voynova, H. Brix and W. Petersen contributed to the study design and conception and drafting of the initial manuscript, and all authors listed contributed to analysis and interpretation of the data, editing and critical revision of the final draft of the manuscript. W. Petersen, H. Brix, S. Weigelt-Krenz, and M. Scharfe contributed to data collection for COSYNA, and for the discrete sample datasets. Y.G. Voynova performed the calculations, created the graphic material, managed the drafting of the manuscript and coordinated author contributions.

7 Acknowledgements

We would like to thank the FerryBox team at HZG for data collection and maintenance of the FerryBox systems, as well as all people responsible for the COSYNA data collection. Also, we would like to thank the Nutrients team at BSH, who collected and analysed the discrete samples for nutrients, dissolved oxygen, salinity and temperature, as well as the Biosciences and Shelf Sea System Ecology teams at AWI in Helgoland for collecting and analysing the discrete samples along the Helgoland cruises. We would like to acknowledge the German Federal Waterways and Shipping Administration (WSV), and the German Federal Institute of Hydrology (BfG) for providing the discharge data from the Elbe River, and the GLOSS/CLIVAR database (http://www.gloss-sealevel.org/data/#.VxeHnUaFEak), from which we obtained the sea level height for Cuxhaven tidal station. Finally, we would like to thank two anonymous reviewers, whose thoughtful and beneficial comments helped to considerably strengthen the manuscript. This work has been supported through the Coastal Observing System for Northern and Arctic Seas (COSYNA).

References

Allan, R.P., and B.J. Soden. 2008. Atmospheric warming and the amplification of precipitation extremes. Science 321: 1481-1484.

Amann, T., A. Weiss, and J. Hartmann. 2012. Carbon dynamics in the freshwater part of the Elbe estuary, Germany: Implications of improving water quality. Estuarine, Coastal and Shelf Science 107: 112-121.

Bauer, J.E., W.-J. Cai, P.A. Raymond, T.S. Bianchi, C.S. Hopkinson, and P.A.G. Regnier. 2013. The changing carbon cycle of the coastal ocean. Nature 504: 61-70, doi:10.1038/nature12857

Baschek, B., F. Schroeder, H. Brix, R. Riethmüller, T. Badewien, G. Breitbach, B. Brügge, F. Colijn, R. Doerffer, C. Eschenbach, J. Friedrich, P. Fischer, S. Garthe, J. Horstmann, H. Krasemann, K. Metfies, N. Ohle, W. Petersen, R. Röttgers, M. Schlüter, J. Schulz, J. Schulz-Stellenfleth, E. Stanev, H.v. Storch, C. Winter, K. Wirtz, O. Zielinski, and F. Ziemer. 2016. The Coastal Observing System for Northern and Arctic Seas (COSYNA). Ocean Science, submitted.

Becker, G.A., H. Giese, K. Isert, P. König, H. Langenberg, T. Pohlmann, and C. Schrum. 1999. Mesoscale structures, fluxes and water mass variability in the German Bight as exemplified in the KUSTOS-experiments and numerical models. German Journal of Hydrography Volume 51.

Bender, M.A., T.R. Knutson, R.E. Tuleya, J.J. Sirutis, G.A. Vecchi, S.T. Garner, and I.M. Held. 2010. Modeled Impact of Anthropogenic Warming on the Frequency of Intense Atlantic Hurricanes. Science 327: 454-458.

Bergemann, v.M., G. Blöcker, H. Harms, M. Kerner, R. Meyer-Nehls, W. Petersen, and F. Schroeder. 1996. Der Sauerstoffhaushalt der Tideelbe. In GKSS Report. Geesthacht, Germany: GKSS.

Blackford, J.C. and F.J. Gilbert. 2007. pH variability and CO2 induced acidification in the North Sea. Journal of Marine Systems 64: 229 – 241.

Breitbach, G., H. Krasemann, D. Behr, S. Beringer, U. Lange, N. Vo, and F. Schroeder. 2016. Accessing Diverse Data Comprehensively - CODM the COSYNA Data Portal. Ocean Science, 12:909-923, http://www.ocean-sci.net/12/909/2016/

Brockmann, U. H., T. Raabe, K. Hesse, K. Viehweger, S. Rick, A. Starke, B. Fabiszisky, D. Topcu, and R. Heller. 1999. Seasonal budgets of the nutrient elements N and P at the surface of the German Bight during winter 1996, spring 1995, and summer 1994. German Journal of Hydrography 51: 267-290.

Cai, W.J. 2011. Estuarine and coastal ocean carbon paradox: CO2 sinks or sites of terrestrial carbon incineration? Ann Rev Mar Sci 3: 123-145.

Callies, U., L. Gaslikova, H. Kapitza, and M. Scharfe. 2016. Residual current variability in the German Bight, North Sea - Reconstruction based on multi-decadal 2D hydrodynamic simulations. Geo-Mar Letters doi:10.1007/s00367-016-0466-2

Christensen, O.B., and J.H. Christensen. 2004. Intensification of extreme European summer precipitation in a warmer climate. Global and Planetary Change 44: 107-117.

Claus S., N. De Hauwere, B. Vanhoorne, F. Souza Dias, P. Oset García, F. Hernandez, and J. Mees. 2016. MarineRegions.org. Flanders Marine Institute. Accessed at http://www.marineregions.org on 2016-09-02.

Elsner, J.B., J.P. Kossin, and T.H. Jagger. 2008. The increasing intensity of the strongest tropical cyclones. Nature 455: 92-95.

Grams, C.M., H. Binder, S. Pfahl, N. Piaget, and H. Wernli. 2014. Atmospheric processes triggering the central European floods in June 2013. Natural Hazards and Earth System Science 14: 1691-1702.

Hickel, W., P. Mangelsdorf, and J. Berg. 1993. The human impact in the German Bight: Eutrophication during three decades (1962-1991). Helgol~inder Meeresunters 47: 243-263.

Ionita, M., M. Dima, G. Lohmann, P. Scholz, and N. Rimbu. 2014. Predicting the June 2013 European Flooding Based on Precipitation, Soil Moisture, and Sea Level Pressure. Journal of Hydrometeorology 16: 598-614.

Karl, T.R., R.W. Knight, and N. Plummer. 1995. Trends in high-frequency climate variabilityin the twentieth century. Nature 377: 217-220.

Knight, R.W., and T.R. Karl. 1998. Secular trends of precipitation amount, frequency, and intensity in the United States. Bulletin of the American Meteorological Society 79: 231-241.

Luterbacher, J., J.P. Werner, J.E. Smerdon, L. Fernández-Donado, F.J. González-Rouco, D. Barriopedro, F.C. Ljungqvist, U. Büntgen, E. Zorita, S. Wagner, J. Esper, D. McCarroll, A. Toreti, D. Frank, J.H. Jungclaus, M. Barriendos, C. Bertolin, O. Bothe, R. Brázdil, D. Camuffo, P. Dobrovolný, M. Gagen, E. García-Bustamante, Q. Ge, J.J. Gómez-Navarro, J. Guiot, Z. Hao, G.C. Hegerl, K. Holmgren, V.V. Klimenko, J. Martín-Chivelet, C. Pfister, N. Roberts, A. Schindler, A. Schurer, O. Solomina, L. von Gunten, E. Wahl, H. Wanner, O. Wetter, E. Xoplaki, N. Yuan, D. Zanchettin, H. Zhang, and C. Zerefos. 2016. European summer temperatures since Roman times. Environmental Research Letters 11: 024001.

Markovic, D., U. Scharfenberger, S. Schmutz, F. Pletterbauer, and C. Wolter. 2013. Variability and alterations of water temperatures across the Elbe and Danube River Basins. Climatic Change 119: 375-389.

Meehl, G.A., C. Tebaldi, H. Teng, and T.C. Peterson. 2007. Current and future U.S. weather extremes and El Niño. Geophysical Research Letters 34.

Merz, B., F. Elmer, M. Kunz, B. Mühr, K. Schröter, and S. Uhlemann-Elmer. 2014. The extreme flood in June 2013 in Germany. La Houille Blanche: 5-10.

Paerl, H.W.,, J.D. Bales, L.W. Ausley, C.P. Buzzelli, L.B. Crowder, Lisa A. Eby, J.M. Fear, M. Go, B.L. Peierls, T.L.Richardson, and J.S. Ramus. 2001. Ecosystem impacts of three sequential hurricanes (Dennis, Floyd, and Irene) on the United States' largest lagoonal estuary, Pamlico Sound, NC. PNAS, 98(10): 5655-5660.

Paerl, H.W. 2006. Assessing and managing nutrient-enhanced eutrophication in estuarine and coastal waters: Interactive effects of human and climatic perturbations. Ecological Engineering 26: 40-54.

Petersen, W., L. Bertino, U. Callies, and E. Zorita. 2000. Process identification by statistical analysis of water-quality data. In GKSS report. Geesthacht, Germany: GKSS.

Petersen, W., G. Blöcker, N. Mehlhorn, and F. Schroeder. 1999. Consequences of Altered Load of Pollutants on the Oxygen Budget of the Elbe River Vom Wasser 92: 37-50.

Petersen, W., H. Wehde, H. Krasemann, F. Colijn, and F. Schroeder. 2008. FerryBox and MERIS – Assessment of coastal and shelf sea ecosystems by combining in situ and remotely sensed data. Estuarine, Coastal and Shelf Science 77: 296-307.

Petersen, W. 2014. FerryBox systems: State-of-the-art in Europe and future development. Journal of Marine Systems 140: 4 –12

Reimer, A., S. Brasse, R. Doerffer, C.-D. Durselen, S. Kempe, W. Michaelis, H.-J. Rick, and R. Siefert. 1999. Carbon cycling in the German Bight: An estimate of transformation processes and transport. German Journal of Hydrography 51: 313-329.

Scavia, D., J.C. Field, D.F. Boesch, R.W. Buddemeier, V. Burkett, D.R. Cayan, M. Fogarty, M.A. Harwell, R.W. Howarth, C. Mason, D.J. Reed, T.C. Royer, A.H. Sallenger, and J. Titus. 2002. Climate Change Impacts on U.S. Coastal and Marine Ecosystems. Estuaries 25: 149-164.

Scharfe, M., U. Callies, G. Blöcker, W. Petersen, and F. Schroeder. 2009. A simple Lagrangian model to simulate temporal variability of algae in the Elbe River. Ecological Modelling, 220 (18): 2173-2186.

Statham, P.J. 2012. Nutrients in estuaries-an overview and the potential impacts of climate change. Sci Total Environ 434: 213-227.

Topcu, H.D., and U.H. Brockmann. 2015. Seasonal oxygen depletion in the North Sea, a review. Mar Pollut Bull 99: 5-27.

van Beuesekom, J.E.E., U.H. Brockmann, K.-J. Hesse, W. Hickel, K. Poremba, and U. Tillmann. 1999. The importance of sediments in the transformation and turnover of nutrients and organic matter in the Wadden Sea and German Bight. German Journal of Hydrography 51:245-266.

van Beuesekom, J.E.E., and V.N. de Jonge. 1998. Retention of Phosphorus and Nitrogen in the Ems Estuary. Estuaries 21: 527-539.

von Storch, H. and F.W. Zwiers. 2003. Statistical analysis in climate research. Cambridge University Press, Cambridge, pp 45-50, ISBN 0 511 01018 4 virtual.

Voynova, Y.G., K.C. Lebaron, R.T. Barnes, and W.J. Ullman. 2015. In situ response of bay productivity to nutrient loading from a small tributary: The Delaware Bay-Murderkill Estuary tidally-coupled biogeochemical reactor. Estuarine, Coastal and Shelf Science 160: 33-48.

Voynova, Y.G., and J.H. Sharp. 2012. Anomalous Biogeochemical Response to a Flooding Event in the Delaware Estuary: A Possible Typology Shift Due to Climate Change. Estuaries and Coasts 35: 943-958.

Weigelt-Krenz, S., N. Theobald, S. Schmolke, H. Klein, A. Schulz, F. Janssen, M. Scharfe, and N. Michel. 2014. Auswirkungen des Elbehochwassers vom Juni 2013 auf die Deutsche Bucht. Hamburg and Rostock, Germany: Bundesamt für Seeschifffahrt und Hydrographie (BSH).

Wetz, M.S., and H.W. Paerl. 2008. Estuarine Phytoplankton Responses to Hurricanes and Tropical Storms with Different Characteristics (Trajectory, Rainfall, Winds). Estuaries and Coasts 31: 419-429.

Wetz, M.S., and D.W. Yoskowitz. 2013. An 'extreme' future for estuaries? Effects of extreme climatic events on estuarine water quality and ecology. Mar Pollut Bull 69: 7-18.

Wiltshire, K.H., and B.F.J. Manly. 2004. The warming trend at Helgoland Roads, North Sea: phytoplankton response. Helgoland Marine Research 58: 269-273.

Table 1. Data sources: sampling dates, position, depth and parameters measured at different stations or moving platforms in the Elbe Estuary and the German Bight. BAH AWI stands for the Biological Station Helgoland, at the Alfred Wegener Institute (AWI); BSH stands for Federal Maritime and Hydrographic Agency of Germany (Bundesamt für Seeschifffahrt und Hydrographie); HPA stands for Hamburg Port Authority; HZG stands for Helmholz-Zentrum Geesthacht.* Station Elbe 9 is located at about the same position as Elbe 3.

Station Platform	**Organization**	**Latitude**	**Longitude**	**Station Depth**	**Measurement Depth**	**Time Frame**	**Frequency**	**Salinity Temp**	**Nutrients**	**DO**	**Chl**	**Bottom data**
Elbe 1	**BAH AWI**	54.15	7.89	51	1	2008-2015	monthly	yes	yes	no	no	yes
Elbe 2	**BAH AWI**	54.10	7.99	28	1	2008-2015	monthly	yes	yes	no	no	yes
Elbe 9*	**BAH AWI**	54.05	7.99	28	1	2008-2015	monthly	yes	yes	no	no	yes
Elbe 3	**BAH AWI**	54.05	8.08	20	1	2008-2015	monthly	yes	yes	no	no	yes
Elbe 4	**BAH AWI**	54.01	8.24	20	1	2008-2015	monthly	yes	yes	no	no	yes
Elbe 5	**BAH AWI**	53.99	8.31	18	1	2008-2015	monthly	yes	yes	no	no	yes
Elbe 6	**BAH AWI**	53.98	8.41	18	1	2008-2015	monthly	yes	yes	no	no	yes
Elbe 7	**BAH AWI**	53.95	8.50	15	1	2008-2015	monthly	yes	yes	no	no	yes
Elbe 8	**BAH AWI**	53.90	8.67	18	1	2008-2015	monthly	yes	yes	no	no	yes
Eider 1	**BAH AWI**	54.18	7.95	10	1	2008-2015	monthly	yes	yes	no	no	yes
Eider 2	**BAH AWI**	54.18	8.04	29	1	2008-2015	monthly	yes	yes	no	no	yes
Eider 3	**BAH AWI**	54.21	8.15	20	1	2008-2015	monthly	yes	yes	no	no	yes
Eider 4	**BAH AWI**	54.23	8.31	12	1	2008-2015	monthly	yes	yes	no	no	yes
Eider 5	**BAH AWI**	54.23	8.40	10	1	2008-2015	monthly	yes	yes	no	no	yes
Eider 6	**BAH AWI**	54.22	8.48	7	1	2008-2015	monthly	yes	yes	no	no	yes
Eider 7	**BAH AWI**	54.16	8.37	11	1	2013-2015	monthly	yes	yes	no	no	yes
Eider 8	**BAH AWI**	54.05	8.43	11	1	2013-2015	monthly	yes	yes	no	no	yes
P8 1	**BAH AWI**	54.15	7.89	53	1	2008-2015	monthly	yes	yes	yes	no	yes
P8 2	**BAH AWI**	54.18	7.79	41	1	2008-2015	monthly	yes	yes	yes	no	yes
P8 3	**BAH AWI**	54.16	7.67	34	1	2008-2015	monthly	yes	yes	yes	no	yes
P8 4	**BAH AWI**	54.15	7.57	35	1	2008-2015	monthly	yes	yes	yes	no	yes
P8 5	**BAH AWI**	54.25	7.38	37	1	2008-2015	monthly	yes	yes	yes	no	yes
P8 6	**BAH AWI**	54.27	7.19	36	1	2008-2015	monthly	yes	yes	yes	no	yes
FerryBox Funny Girl	**HZG COSYNA**	54.17-54.13	7.91-8.82	varied	1	2008-2015	May-Sept (moving)	yes	no	yes	yes	no
FerryBox Cuxhaven	**HZG COSYNA**	53.88	8.71		1	2010-2015	10 minutes	yes	yes	yes	yes	no
HPA Pile	**HPA, HZG**	53.86	8.94		1	2012-2013	10 minutes	yes	no	yes	yes	yes
Deutsche Bucht	**BSH**	54.17	7.45	30	6	2013	hourly	yes	no	yes	no	yes
MEDEM	**BSH**	53.88	8.72	16	1	2013	4 times/yr	yes	yes	no	no	yes
ELBE1	**BSH**	54.00	8.11	24	6	2013	4 times/yr	yes	yes	no	no	yes
WESER	**BSH**	53.85	8.00	17	5	2013	4 times/yr	yes	yes	no	no	yes
STG 16	**BSH**	53.94	7.40	25	5	2013	4 times/yr	yes	yes	no	no	yes
HLOCH	**BSH**	54.08	7.83	43	5	2013	4 times/yr	yes	yes	no	no	yes
HELGO	**BSH**	54.25	8.10	18	5	2013	4 times/yr	yes	yes	no	no	yes
EIDER	**BSH**	54.23	8.38	14	5	2013	4 times/yr	yes	yes	no	no	yes
KS11	**BSH**	54.07	8.13	20	5	2013	4 times/yr	yes	yes	no	no	yes
UE28	**BSH**	54.50	8.20	13	5	2013	4 times/yr	yes	yes	no	no	yes
AMRU2	**BSH**	54.67	7.83	14	5	2013	4 times/yr	yes	yes	no	no	yes
URST2	**BSH**	54.67	7.50	23	6	2013	4 times/yr	yes	yes	no	no	yes
URST1	**BSH**	54.42	7.58	28	6	2013	4 times/yr	yes	yes	no	no	yes
UFSDB	**BSH**	54.18	7.43	39	5	2013	4 times/yr	yes	yes	no	no	yes
HPAE3	**BSH**	54.05	7.97	31	5	2013	4 times/yr	yes	yes	no	no	yes

Table 2. Number of daily discharges ($m^3 s^{-1}$) above a threshold, for 2 time periods: discharges within the last 15 years (since 2001) vs. discharges during the entire period (1874-2015). The highest threshold is 50 years, and the lowest is 5 years. The discharge thresholds are based on return periods for 5, 10, 25 and 50 year-storms. For example, any storm with discharge higher than 3901 $m^3 s^{-1}$ is a 50-year storm.

Threshold Discharge	**Return Period (years)**	**Number of Discharges (2001-2015)**	**Number of Discharges (1874-2015)**	**% Discharges during the last 15 years**
3901	50	3	5	60
3566	25	7	20	35
3076	10	27	121	22
2653	5	49	249	20

Table 3. Minimum and maximum nutrient loads measured during the elevated storm discharge in June-July 2013 near Hamburg, Germany. The loads were reproduced with permission from the BSH report (Weigelt-Krenz et al. 2014).

12.06. - 8.07. 2013	**NO_3 (tons/day)**	**NH_4 (tons/day)**	**PO_4 (tons/day)**	**Si (tons/day)**
Min	200	5	3	400
Max	1100	28	15	1300
June average (1996-2005)	105	na	2.3	24

Table 4. Sampling dates of the different stations and platforms during different months in 2013.

Source	March	July	August	September
BSH	15-16	9-11	10-12	11-13
Helgoland Transects	25-27	2-4	6-8	4-5
FerryBox *M/V Funny Girl*	none	9-11	10-12	11-13
Deutsche Bucht (MARNET)	15-16	none	10-12	11-13

[redacted]

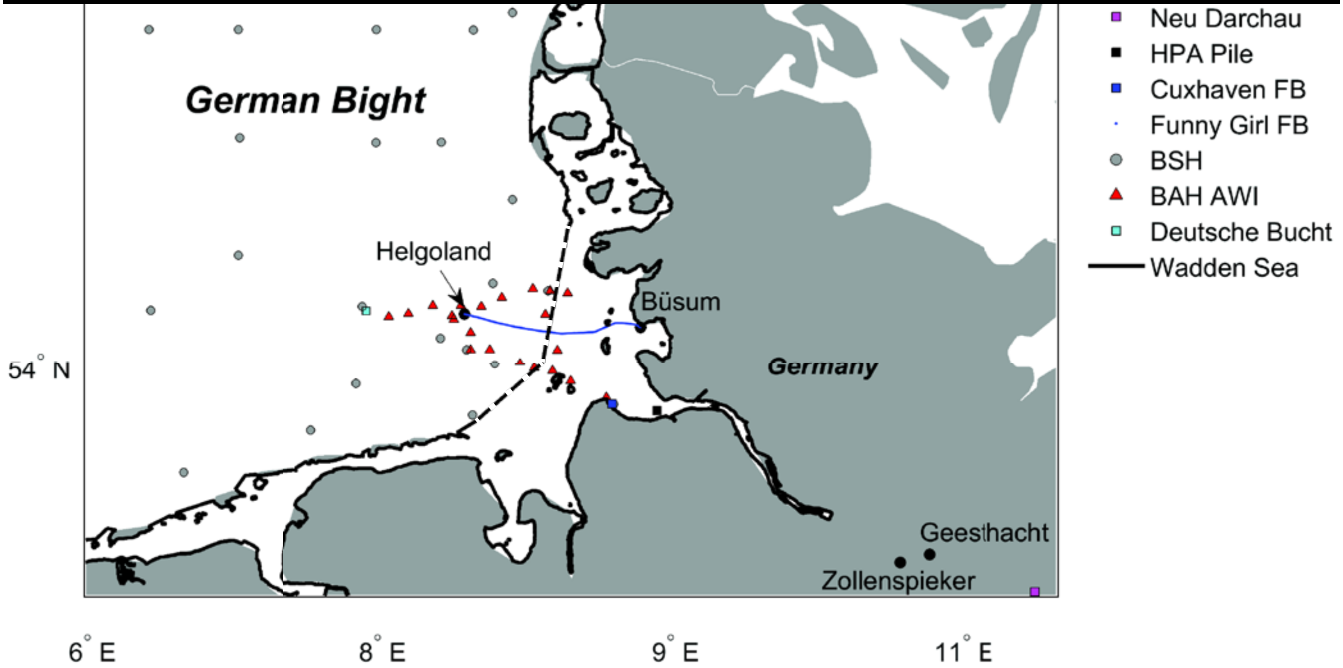

Fig. 1: Map of German Bight, Elbe Estuary, Wadden Sea and the continental regions around them. Stations are indicated with different symbols. Neu Darchau discharge gauging station (magenta square), operated by the German Federal Waterways and Shipping Administration (WSV); HPA Pile (black square), operated by Bundesamt für Seeschifffahrt und Hydrographie (BSH) and Helmholz-Zentrum Geesthacht (HZG); Cuxhaven FerryBox (FB, blue square), operated by HZG, *M/V Funny Girl* FB transect (blue line) between Büsum and Helgoland, operated by HZG; BSH discrete sampling stations (grey circles); Biological Station Helgoland at the Alfred Wegener Institute (BAH AWI) discrete sampling stations (red triangles); Deutsche Bucht MARNET monitoring station, operated by BSH (cyan square). The Wadden Sea outline was obtained as a shape file from Claus et al. (2016), and the dashed line represents the imaginary boundary of the shapefile, rather than the Wadden Sea.

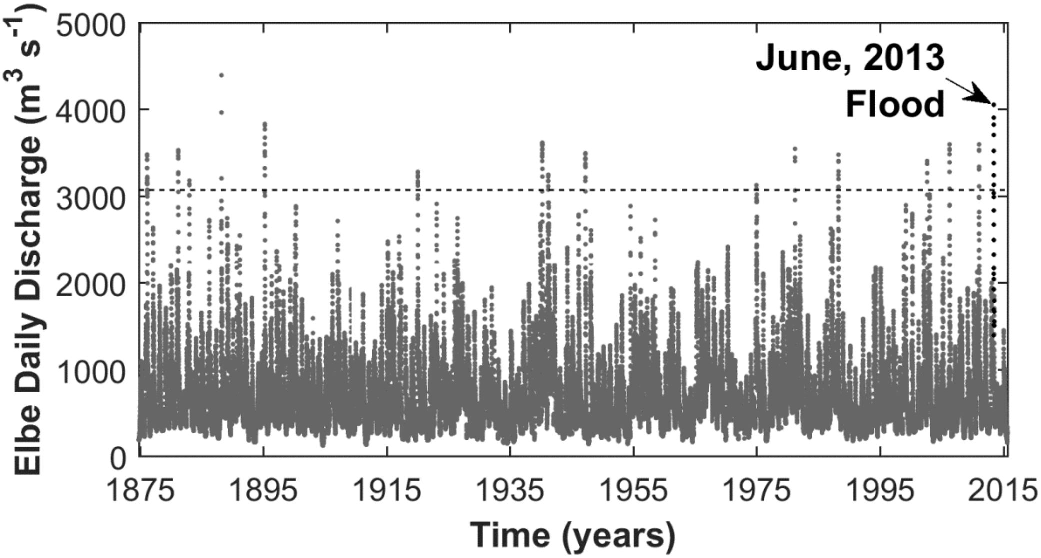

Fig. 2: Daily discharge from the Elbe River between 1874 and 2015. The dashed black line indicates the level of 10-year storm, as listed in Table 2. The June, 2013 flood discharge is highlighted in black and indicated with an arrow.

5

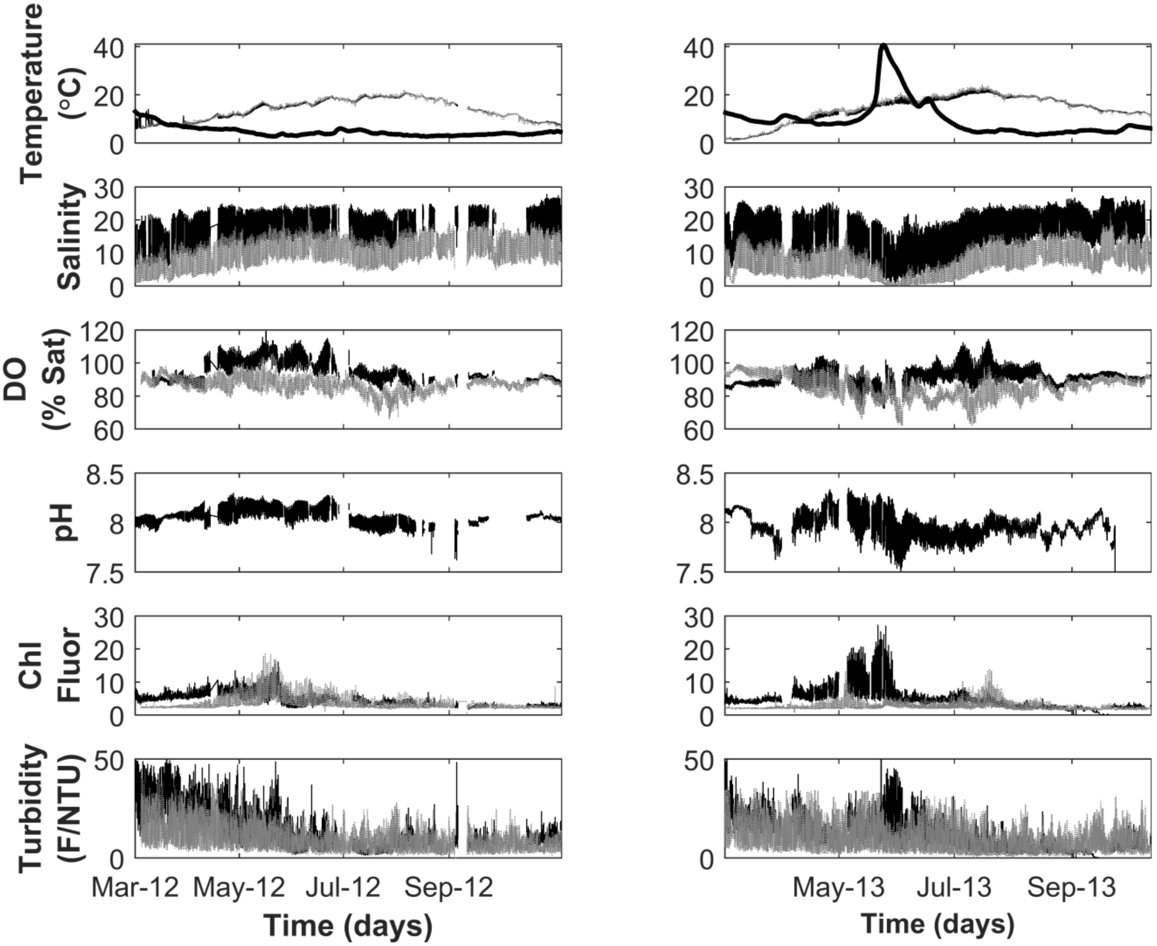

Fig. 3: Hourly measurements of temperature, salinity, DO (% saturation), pH, chlorophyll (µg L^{-1}), and turbidity (F/NTU), measured at Cuxhaven (725 river km, black line) and HPA Pile (710 river km, gray line) in the Elbe Estuary, for 2012 (left panels) and 2013 (right panels). As a reference, the Elbe discharge (m^3 s^{-1}) at Neu Darchau station (thick black line) scaled by dividing it by 100, was also included in the temperature plots.

`

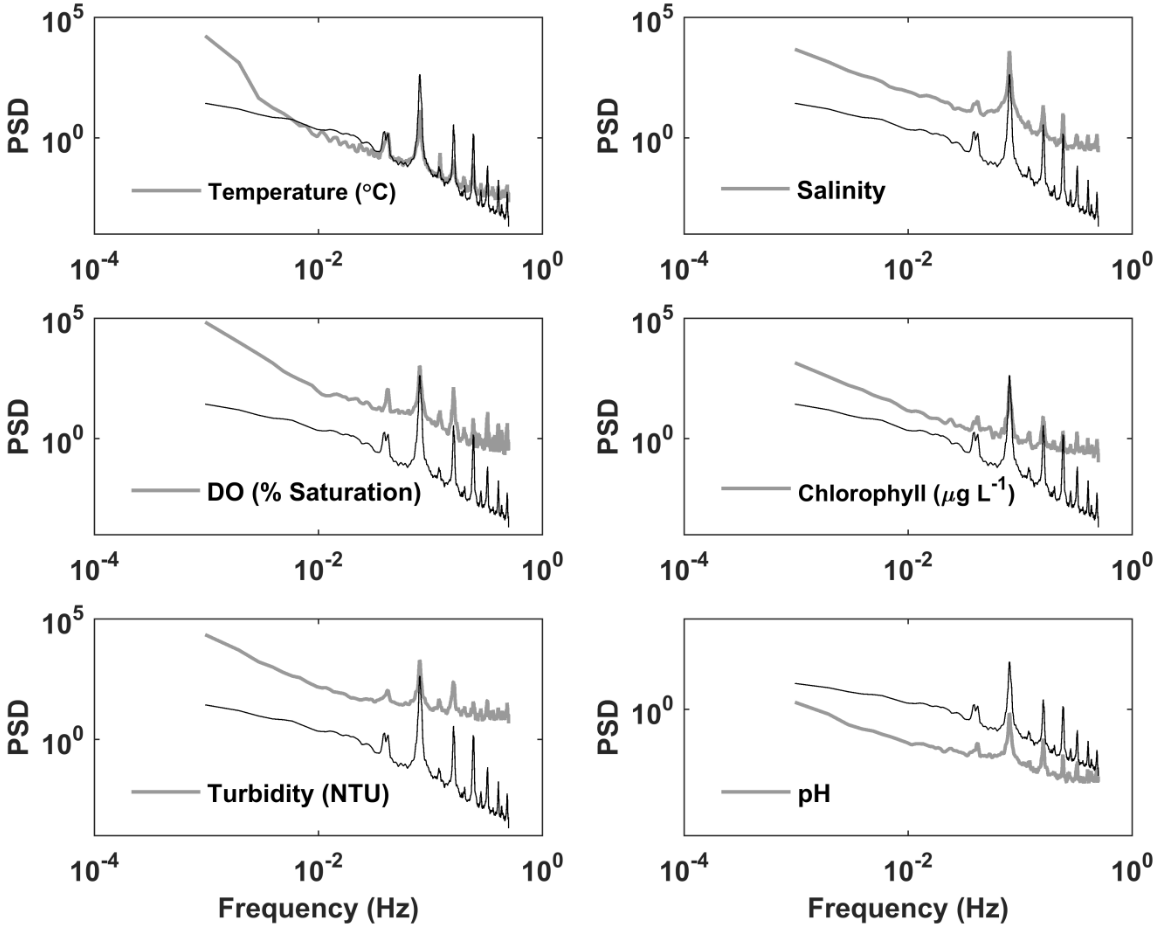

Fig. 4: Power spectral density (PSD) plots (gray) of 6 parameters measured at the Cuxhaven FerryBox station (temperature, salinity, DO, chlorophyll, turbidity and pH). Also shown on each panel in black is the PSD for sea level measured at a station near Cuxhaven.

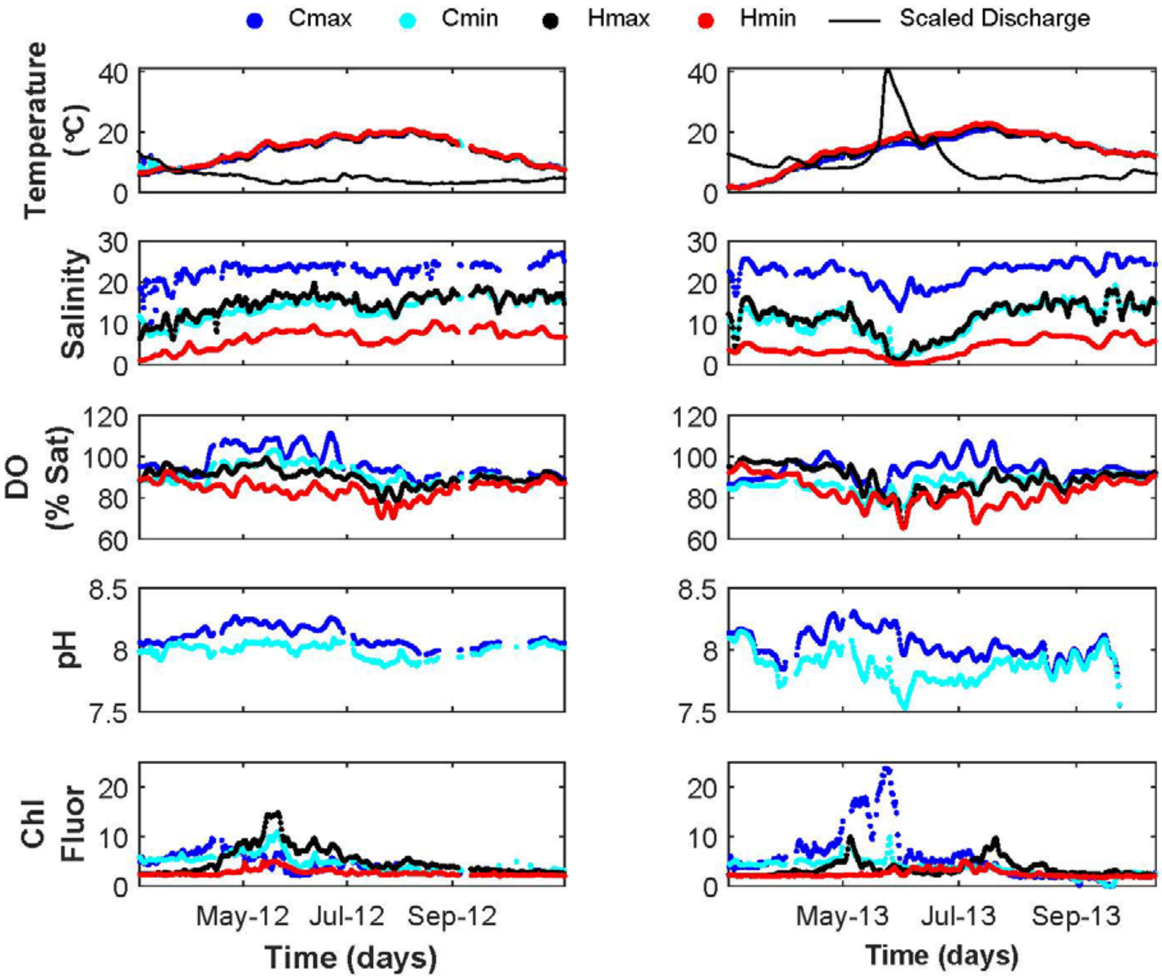

Fig. 5: Temperature, salinity, DO (% saturation), pH and chlorophyll (µg L^{-1}) measured at Cuxhaven and HPA Pile in the Elbe Estuary, for 2012 (left panels) and 2013 (right panels). The colors represent the data identified for each parameter, and at each station, at the times of salinity maxima (Cmax at Cuxhaven, blue; Hmax at HPA Pile, black), and salinity minima (Cmin at Cuxhaven, cyan; Hmin at HPA Pile, red). As a reference, the Elbe River discharge (originally measured in $m^3 s^{-1}$) at Neu Darchau station (Fig. 1), was scaled by dividing it by 100 and was included in the temperature plots.

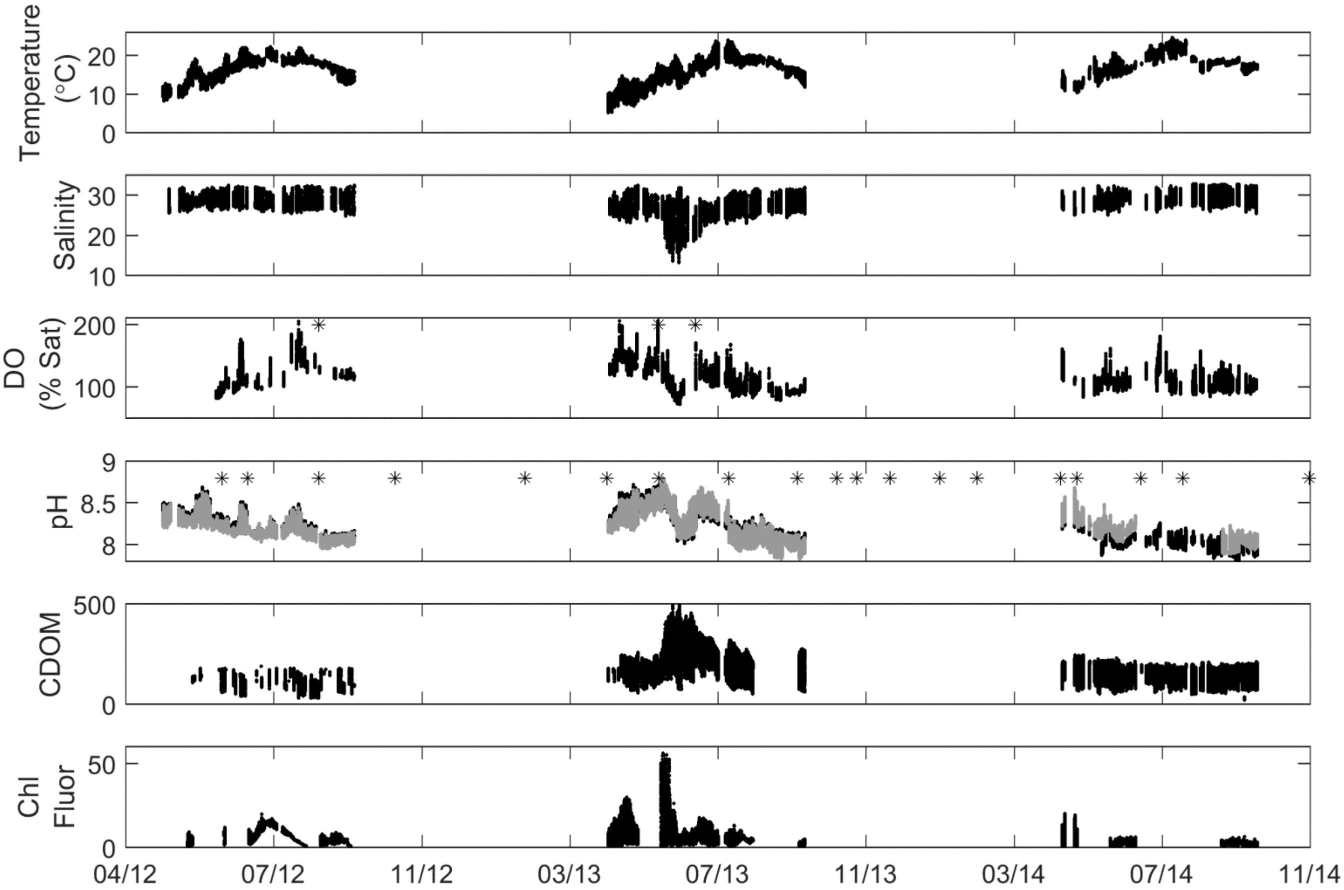

Fig. 6: FerryBox data from *M/V Funny Girl* for temperature, salinity, dissolved oxygen (DO, % saturation), pH, CDOM, and chlorophyll fluorescence between May 2012, and October, 2015. For pH, there were 2 electrodes, one in black and the other in gray. The ferry data is a compilation of all transects between Büsum and Helgoland. Data along the entire ferry transect are used, therefore the figure captures the change along the ferry transect (vertical data range) with time. The stars on the DO and pH panels signify service dates, when the DO optode was changed or when the pH electrodes were calibrated.

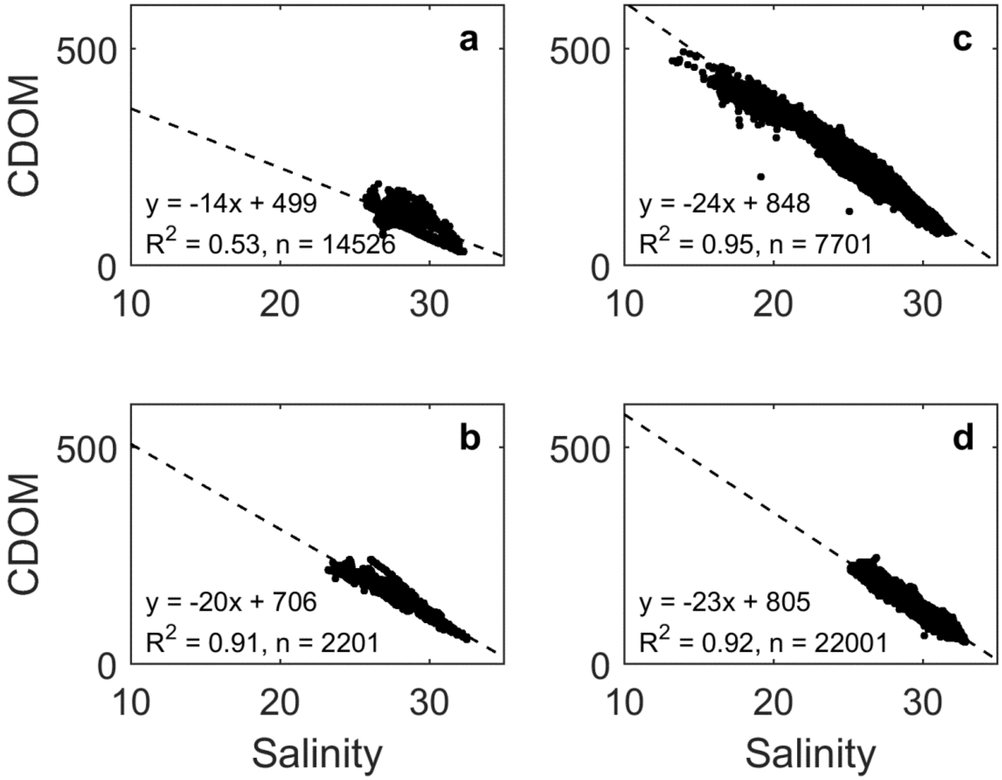

Fig. 7: Salinity vs. CDOM fluorescence from *M/V Funny Girl* for the period between 2012 and 2014 (summer seasons): a. 2012, b. before 2013 flood, c. during and after 2013 flood, d. 2014.

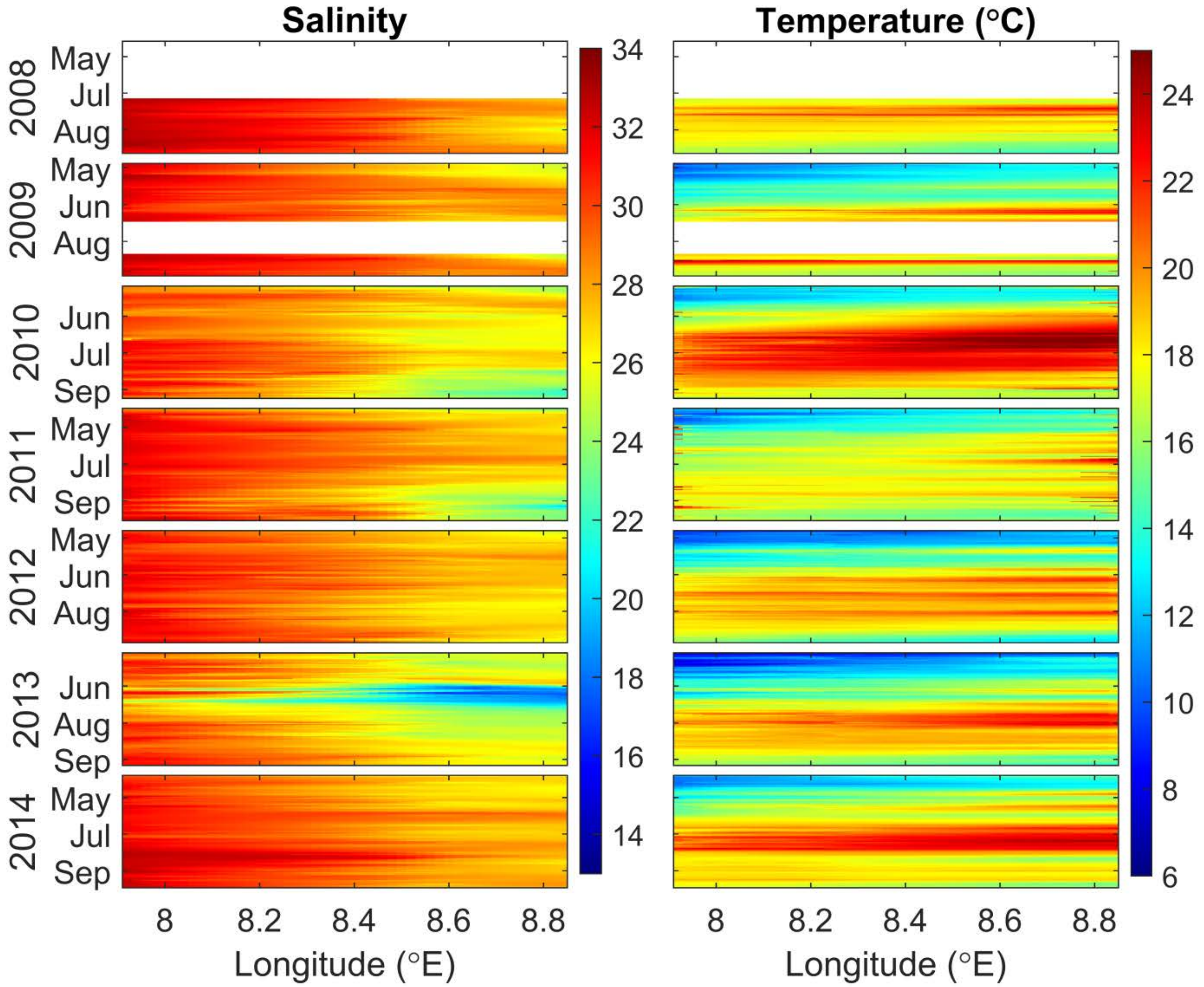

Fig. 8: Salinity (left) and temperature (right) between Büsum and Helgoland for each summer between 2008 and 2014, collected by the M/V Funny Girl FerryBox. The ferry transect is shown in Fig. 1.

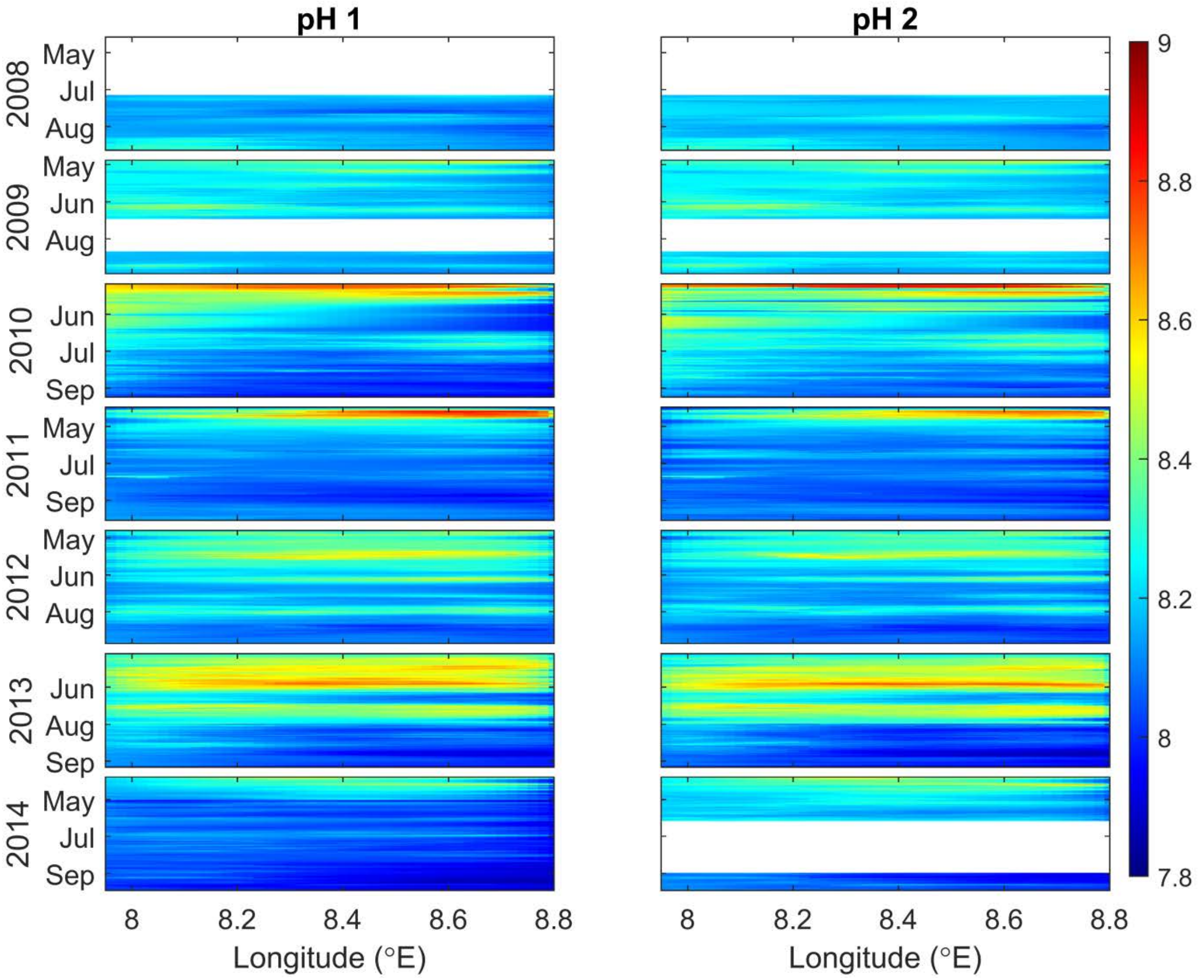

Fig. 9: pH ferry data between Büsum and Helgoland for each summer between 2008 and 2014. There were two pH probes available on the ferry M/V Funny Girl. The white sections represent times when data were not available.

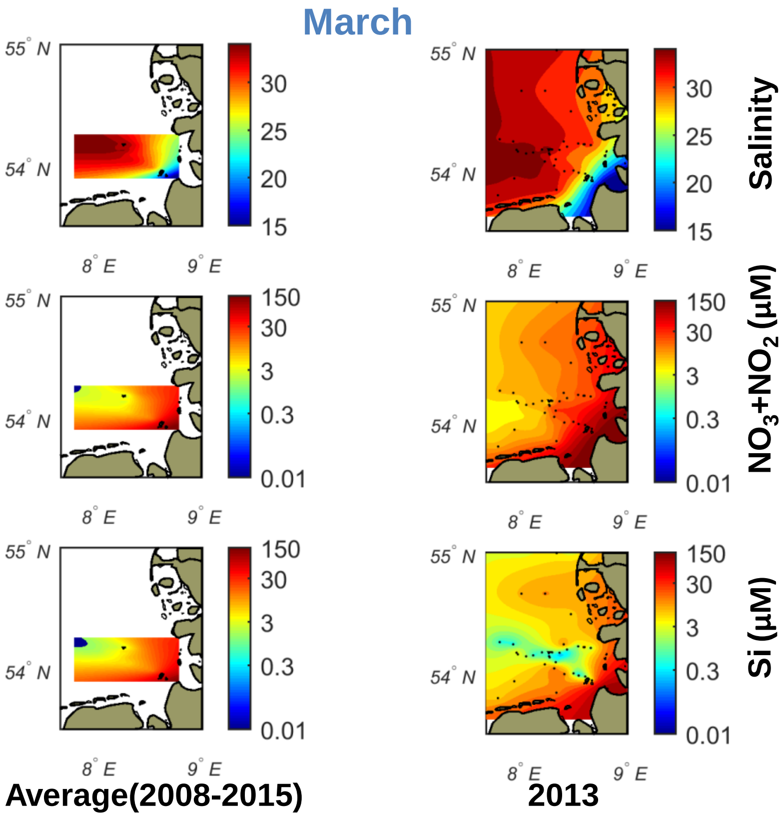

Fig. 10: Maps of interpolated (Kriging method of interpolation) salinity, nitrate + nitrite (NO_3+NO_2 (µM)), and silicate (Si (µM)) for the month of March. The left panels show average parameter distributions in March, based on 7 years of data (2008-2015, excluding 2013) from BAH AWI stations (Table 1); the right panels show interpolated parameters from 15 to 27 March, 2013, measured at BAH AWI, BSH, FerryBox and HPA stations (Table 1 and 4).

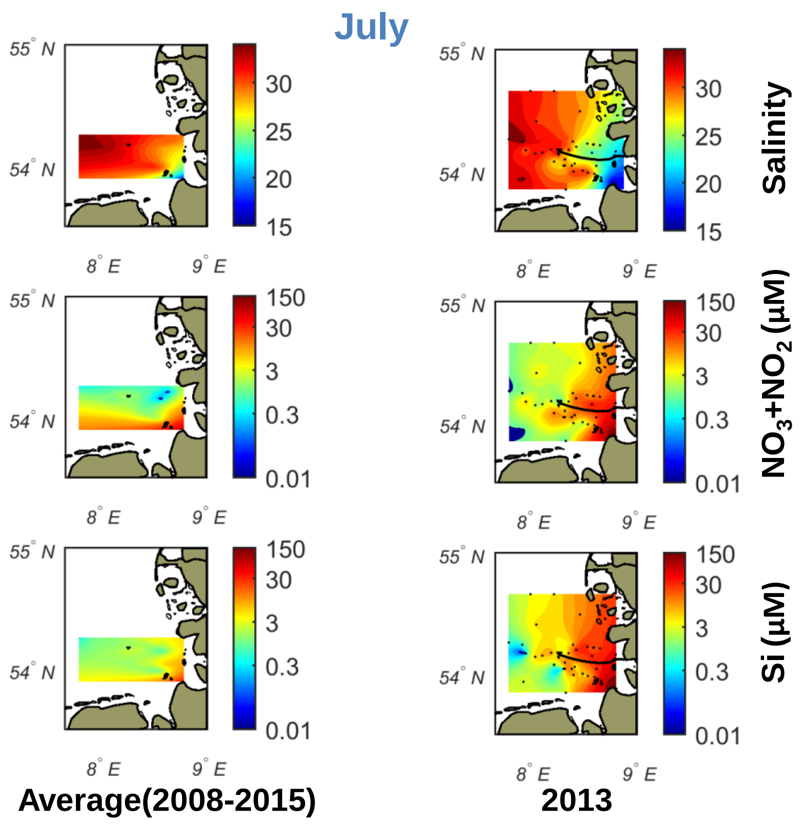

Fig. 11: Same description as in Fig. 10, for the month of July. The left panels show average parameter distributions in July, based on 7 years of data (2008-2015, excluding 2013) from BAH AWI stations (Table 1); the right panels show interpolated parameters from 2 to 11 5 July, 2013, measured at BAH AWI, BSH, FerryBox and HPA stations (Table 1 and 4).

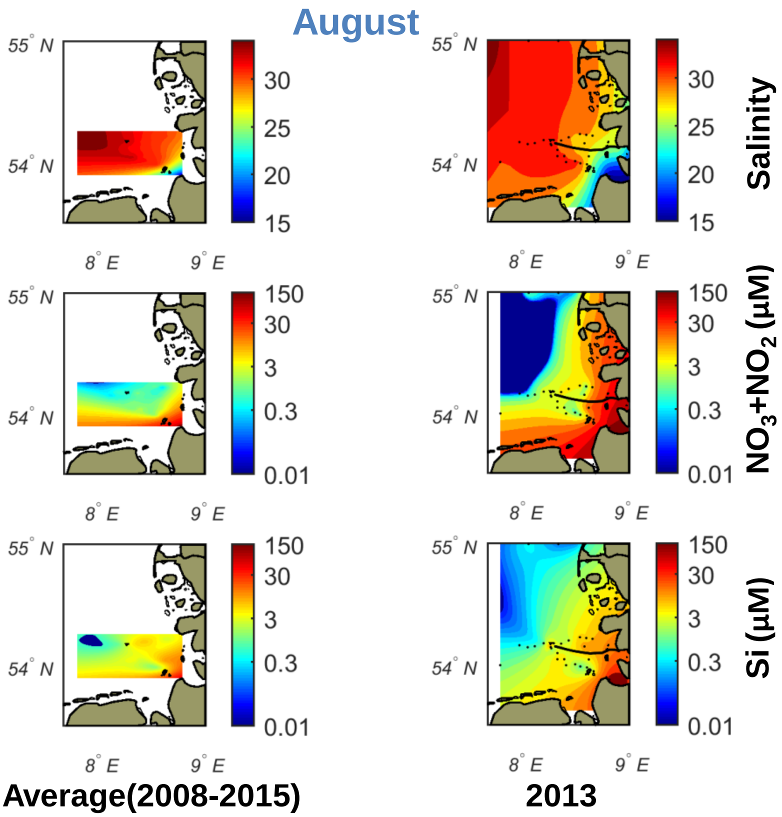

Fig. 12: Same description as in Fig. 10, for the month of August. The left panels show average parameter distributions in August, based on 7 years of data (2008-2015, excluding 2013) from BAH AWI stations (Table 1); the right panels show interpolated parameters from 6 to 5 12 August, 2013, measured at BAH AWI, BSH, FerryBox and HPA stations (Table 1 and 4).

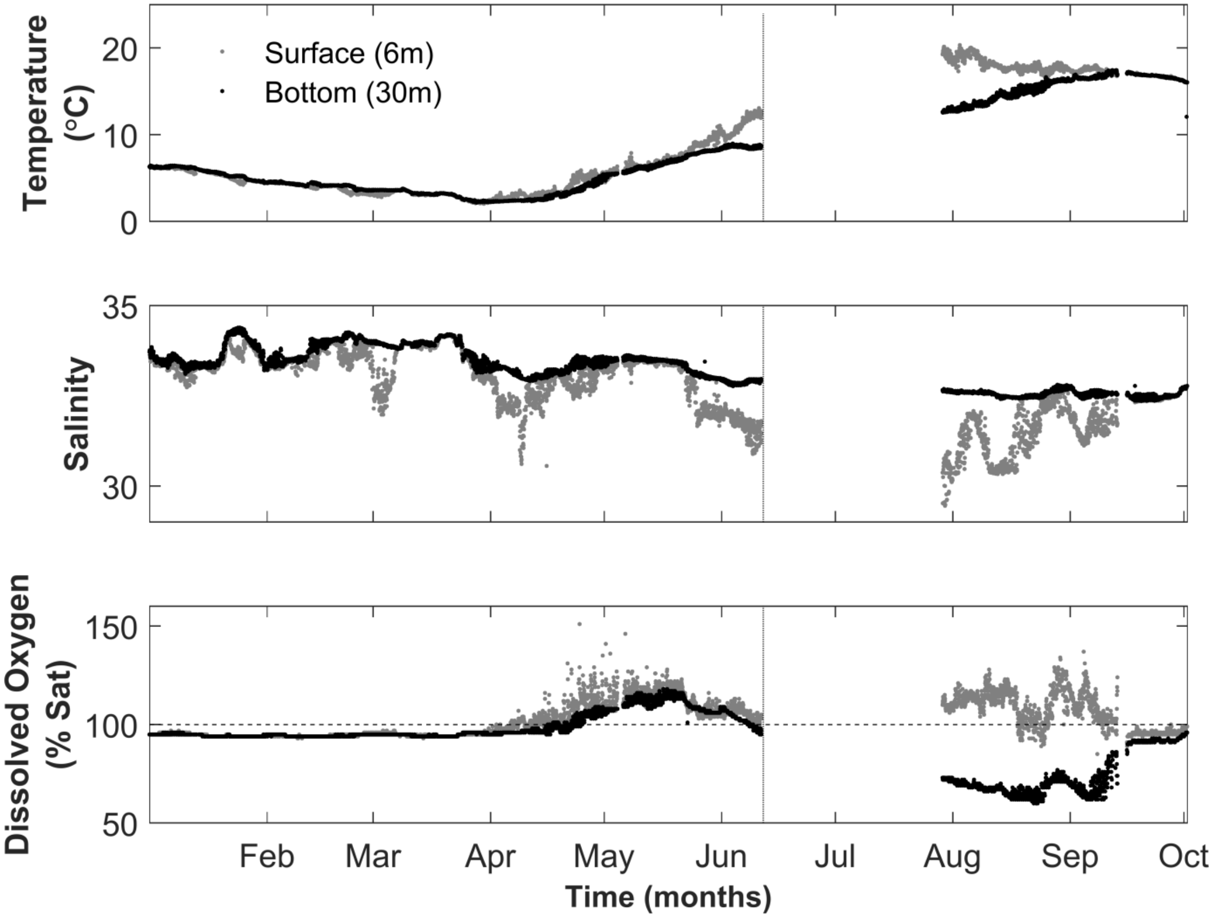

Fig. 13: Surface (6 m, gray) and bottom (30 m, black) temperature, salinity and dissolved oxygen (% saturation) measured at the Deutsche Bucht station (Fig. 1, Table 1), part of the MARNET monitoring network. The data covers a time frame between January and October, 2013. The onset of the June flood is marked by a vertical line.

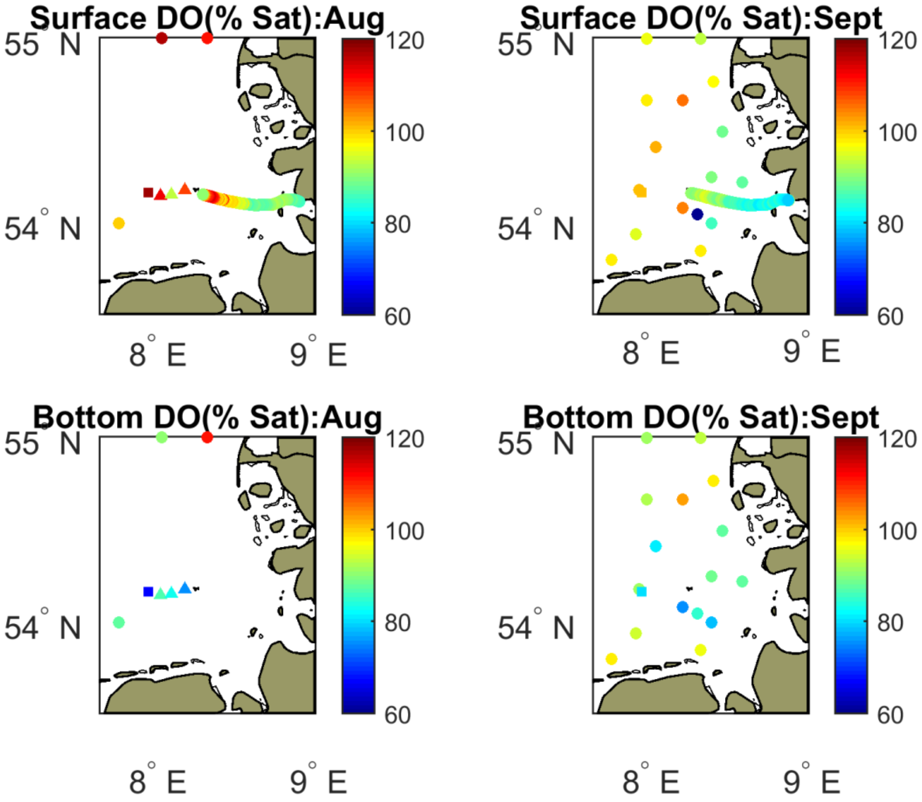

Fig. 14: Dissolved oxygen (% saturation) in surface and bottom waters measured in August and September, 2013. The surface and bottom dissolved oxygen were measured at available discrete stations from AWI and BSH stations, along with FerryBox (*M/V Funny Girl*) and Deutsche Bucht MARNET station. The dates of coverage are listed in Table 4.