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Extreme flood impact on estuarine and coastal biogeochemistry: the 2013 Elbe flood

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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 and 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 southeastern 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 (Knight and Karl, 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, 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 prolonged large-scale 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

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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 quasistationary upper-level cutoff low pressure system over Europe (Grams et al., 2014). Heavy precipitation (Global Precipitation Climatology Centre estimates) in Germany during the last 2 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 southeastern 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 southeastern 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, Germany, to the Wadden Sea (Fig. 1). The riverine portion extends up to Geesthacht, Germany (Elbe, 580 river km), 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 river km), to Cuxhaven, Germany (725 river km) (Fig. 1; Petersen et al., 1999, 2001).

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 non-tidal riverine portion, generating high chlorophyll concentrations ($> 60\,\mu g\,L^{-1}$), dissolved oxygen (DO) 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, particularly near Hamburg (Petersen et al., 1999; Amann et al., 2012). Further downstream along the salinity gradient, oxygen levels increase, but typically remain undersaturated.

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; BSH stands for Federal Maritime and Hydrographic Agency of Germany (Bundesamt für Seeschifffahrt und Hydrographie); HPA stands for Hamburg Port Authority; HZG stands for Helmholtz-Zentrum Geesthacht.

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–Sep (moving)	yes	no	yes	yes	no
FerryBox Cuxhaven	HZG COSYNA	53.88	8.71		1	2010–2015	10 min	yes	yes	yes	yes	no
HPA pile	HPA, HZG	53.86	8.94		1	2012–2013	10 min	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^{-1}	yes	yes	no	no	yes
ELBE1	BSH	54.00	8.11	24	6	2013	4 times yr^{-1}	yes	yes	no	no	yes
WESER	BSH	53.85	8.00	17	5	2013	4 times yr^{-1}	yes	yes	no	no	yes
STG 16	BSH	53.94	7.40	25	5	2013	4 times yr^{-1}	yes	yes	no	no	yes
HLOCH	BSH	54.08	7.83	43	5	2013	4 times yr^{-1}	yes	yes	no	no	yes
HELGO	BSH	54.25	8.10	18	5	2013	4 times yr^{-1}	yes	yes	no	no	yes
EIDER	BSH	54.23	8.38	14	5	2013	4 times yr^{-1}	yes	yes	no	no	yes
KS11	BSH	54.07	8.13	20	5	2013	4 times yr^{-1}	yes	yes	no	no	yes
UE28	BSH	54.50	8.20	13	5	2013	4 times yr^{-1}	yes	yes	no	no	yes
AMRU2	BSH	54.67	7.83	14	5	2013	4 times yr^{-1}	yes	yes	no	no	yes
URST2	BSH	54.67	7.50	23	6	2013	4 times yr^{-1}	yes	yes	no	no	yes
URST1	BSH	54.42	7.58	28	6	2013	4 times yr^{-1}	yes	yes	no	no	yes
UFSDB	BSH	54.18	7.43	39	5	2013	4 times yr^{-1}	yes	yes	no	no	yes
HPAE3	BSH	54.05	7.97	31	5	2013	4 times yr^{-1}	yes	yes	no	no	yes

* Station Elbe 9 is located at about the same position as Elbe 3.

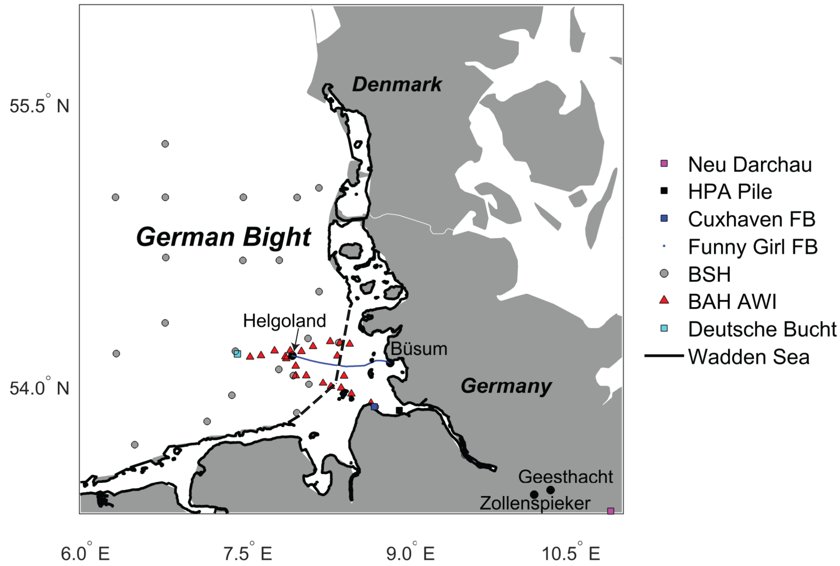

Figure 1. Map of German Bight, Elbe estuary, Wadden Sea and the continental regions around them. Stations are indicated with different symbols: Neu Darchau discharge gauging station (magenta square), operated by the German Federal Waterways and Shipping Administration (WSV); HPA pile (black square), operated by Bundesamt für Seeschifffahrt und Hydrographie (BSH) and Helmholtz-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.

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 November 1874–31 August 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), 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 (53.87° N, 8.72° 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 (53.877° N, 8.705° W) since 2010, measuring temperature, salinity, DO (Aanderaa optode), chlorophyll fluorescence (Chl; Turner Designs, Sunnyvale, CA), pH (Clark electrode) and turbidity (Turner Designs, Sunnyvale, CA) approximately every 10 min (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 us 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 (53.859° N, 8.944° W), about 15 km upstream of the Cuxhaven FerryBox, during 2012 and 2013 (March–November). Every 10 min a variety of biogeochemical parameters, including temperature, salinity, DO, Chl, 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, Chl, 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 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; six discrete samples (in duplicates) for Winkler titration were collected when the ferry was in Büsum between 2012 and 2015, and only two 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 (53.167° N, 7.45° 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 Seeschifffahrt und Hydrographie (BSH)) since 1989, as part of the Marine Environmental Monitoring Network in the North and Baltic Seas (MARNET). 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, 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.

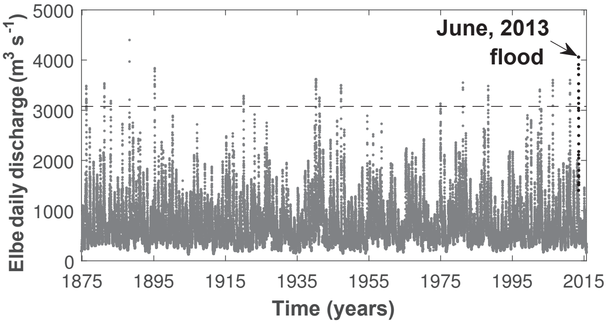

Figure 2. Daily discharge from the Elbe River between 1874 and 2015. The dashed black line indicates the level of 10-year flood, as listed in Table 2. The June 2013 flood is highlighted in black and indicated with an arrow.

3 Results

3.1 Discharge analysis

The average daily discharge for the entire Elbe record (Fig. 2) was $708 \pm 446\,m^3\,s^{-1}$. However, there were distinct seasonal differences, and summer was typically the driest season (Fig. S1 in the Supplement). 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 11 and 12 June 2013. The highest overall daily discharge ($4400\,m^3\,s^{-1}$) was recorded on 25 March 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 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 flood. 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 h 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 h periods (Voynova et al., 2015). In addition, a lower-frequency peak is resolved at the 24–25 h period, most likely associated with the day–night cycles and the O_1 and K_1 lunar diurnal tidal constituents. The 24 h 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 h 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 Chl) at the identified positions were extracted to represent the flood and ebb water mass end members at Cuxhaven and HPA pile (Fig. 5). About 4 to 5 days after the peak discharge (12–13 June 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 18 June. The elevated discharge shifted the entire salinity gradient seaward, so that around HPA pile (Elbe, 710 river km), salinity dropped 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

Table 2. Number of daily discharges ($m^3\,s^{-1}$) above a threshold, for two 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

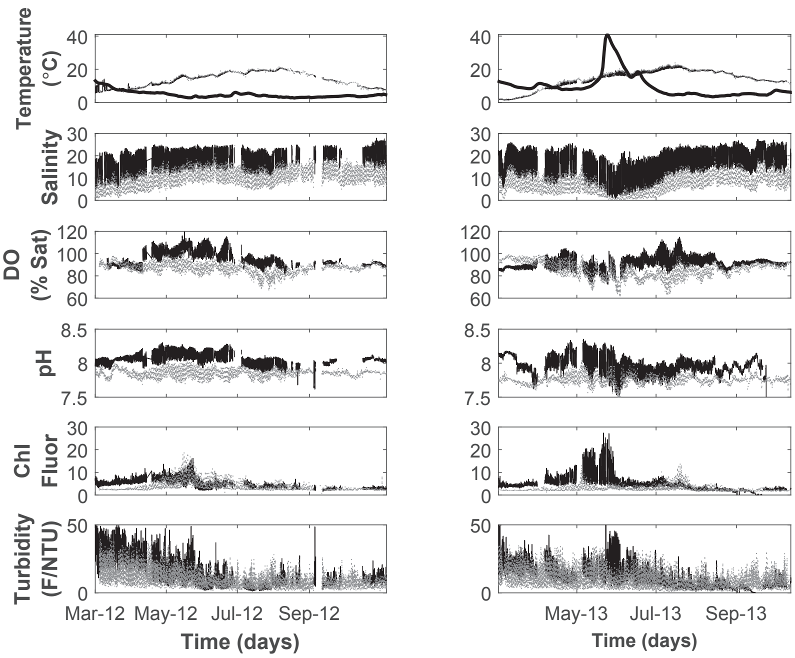

Figure 3. Hourly measurements of temperature, salinity, DO (% saturation), pH, chlorophyll (fluorescence) and turbidity (F/NTU), measured at Cuxhaven (725 river km, black line) and HPA pile (710 river km, gray line) in the Elbe estuary, for 2012 (left panels) and 2013 (right panels). As a reference, 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.

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 24 and 28 June, 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

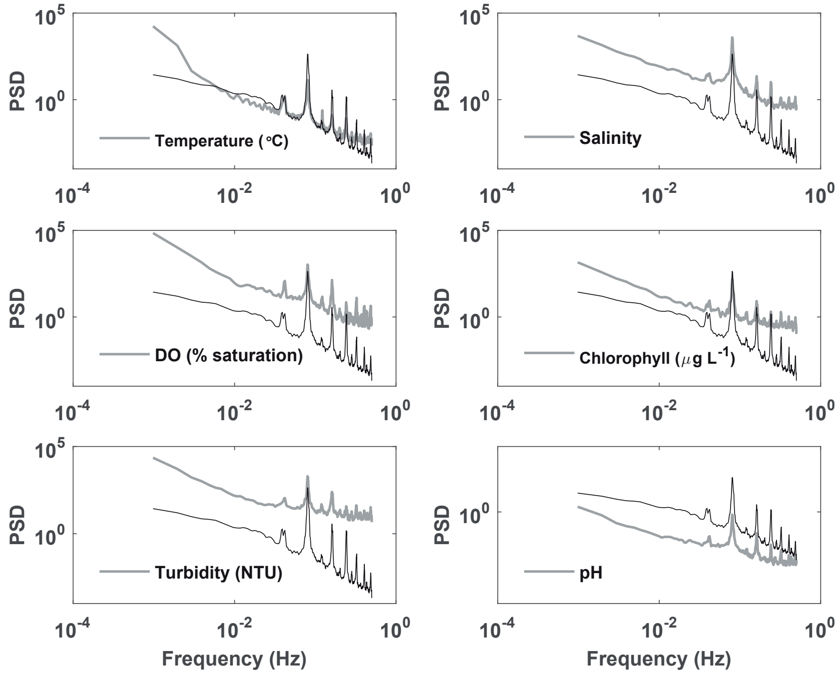

Figure 4. Power spectral density (PSD) plots (gray) of six parameters measured at the Cuxhaven FerryBox station (temperature, salinity, DO, chlorophyll, turbidity and pH). Also shown on each panel in black is the PSD for sea level measured at a station near Cuxhaven.

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

12 Jun–8 Jul 2013	NO_3 (tons day^{-1})	NH_4 (tons day^{-1})	PO_4 (tons day^{-1})	Si (tons day^{-1})
Min	200	5	3	400
Max	1100	28	15	1300
June average (1996–2005)	105	NA	2.3	24

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 and 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 5–6 June 2013 (not shown) along the BAH AWI stations (Fig. 1). The highest chlorophyll concentrations ranging between 6 and 16 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 southwest Wadden Sea (Fig. 1). After the onset of the June flood (12–13 June), 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 salin-

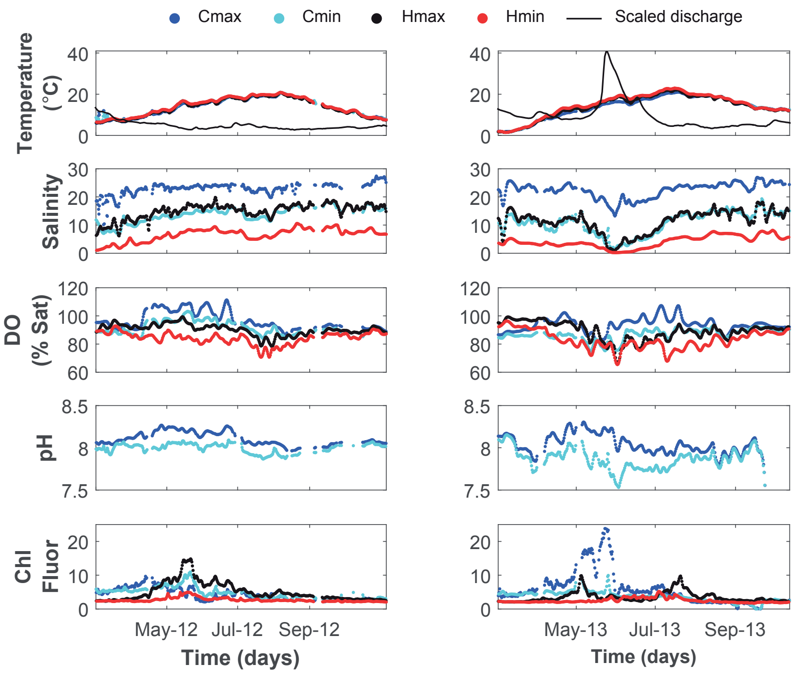

Figure 5. Temperature, salinity, DO (% saturation), pH and chlorophyll (fluorescence) measured at Cuxhaven and HPA pile in the Elbe estuary, for 2012 (left panels) and 2013 (right panels). The colors represent the data identified for each parameter, and at each station, at the times of salinity maxima (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.

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

Source	Mar	Jul	Aug	Sep
BSH	15–16	9–11	10–12	11–13
BAH AWI	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

ity 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.

3.3 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, Chl, DO, colored dissolved organic matter (CDOM) fluorescence and pH (two Clark

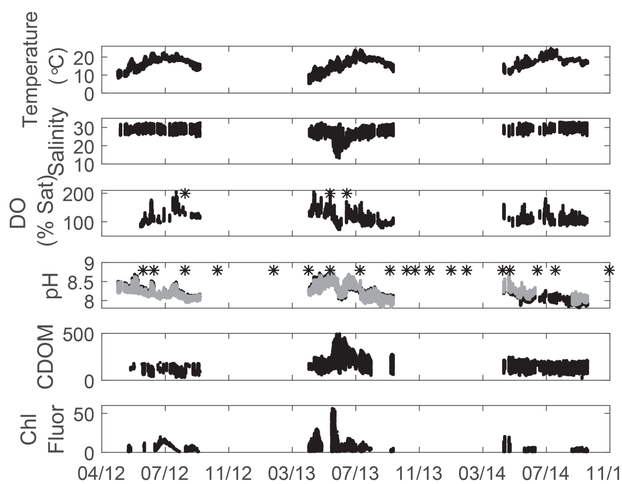

Figure 6. FerryBox data from M/V *Funny Girl* for temperature, salinity, dissolved oxygen (DO, % saturation), pH, CDOM and chlorophyll fluorescence between May 2012 and October 2015. For pH, there were two electrodes, one in black and the other in gray. The ferry data are a compilation of all transects 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.

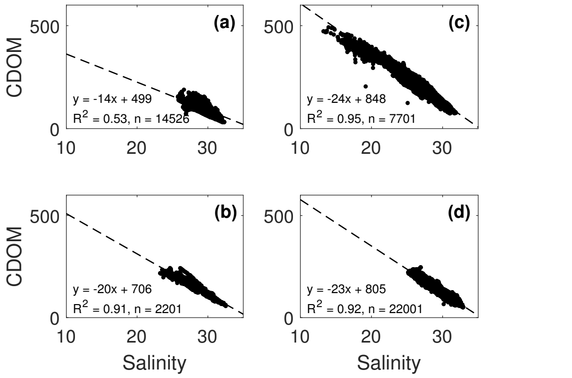

Figure 7. Salinity vs. CDOM fluorescence from M/V *Funny Girl* for the period between 2012 and 2014 (summer seasons): **(a)** 2012, **(b)** before the 2013 flood, **(c)** during and after the 2013 flood and **(d)** 2014.

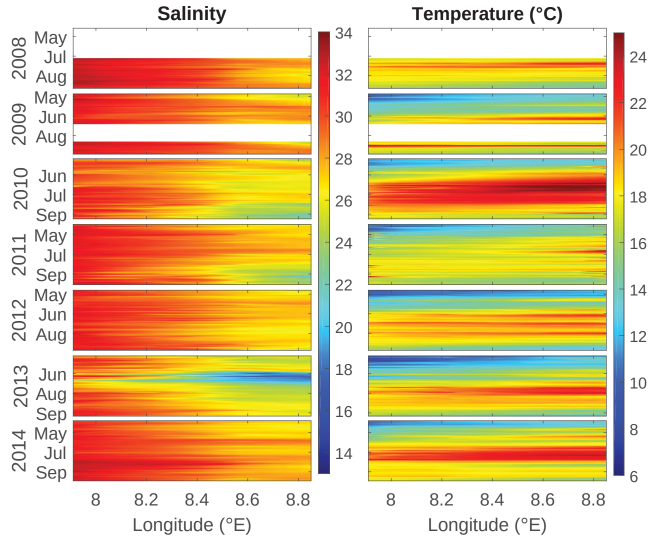

Figure 8. Salinity (left) and temperature (right) between Büsum and Helgoland for each summer between 2008 and 2014, collected by the M/V *Funny Girl* FerryBox. The ferry transect is shown in Fig. 1.

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° 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 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 allochthonous 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 floods 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 flood 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 2013, about 2 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 has salinity <25 throughout the whole 2013 season, and surface water temperatures during May and into June were unusually cold (5–15 °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 and 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

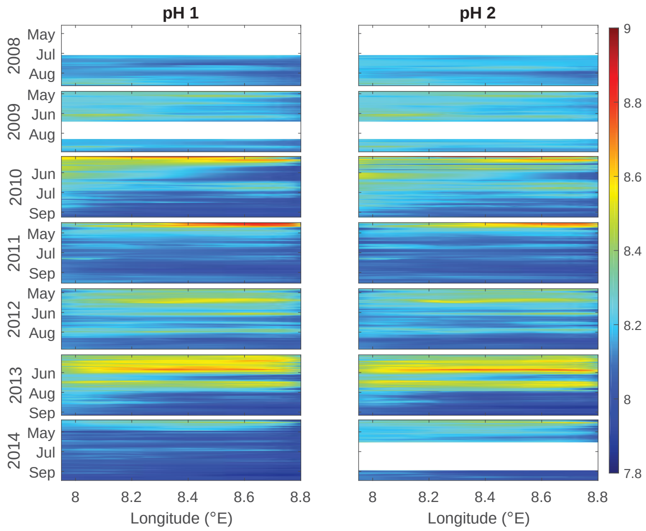

Figure 9. pH ferry data between Büsum and Helgoland for each summer between 2008 and 2014. There were two pH probes available on the ferry M/V *Funny Girl*. The white sections represent times when data were not available.

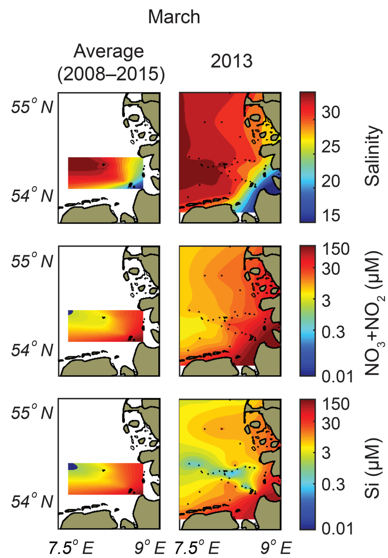

Figure 10. Maps of interpolated (Kriging method of interpolation) salinity, nitrate + nitrite ($NO_3 + NO_2$, µM) and silicate (Si, µM) for the month of March. The left panels show average parameter distributions in March, based on 7 years of data (2008–2015, excluding 2013) from BAH AWI stations (Table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

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 southeastern 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 (4–6 June), 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 2 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.

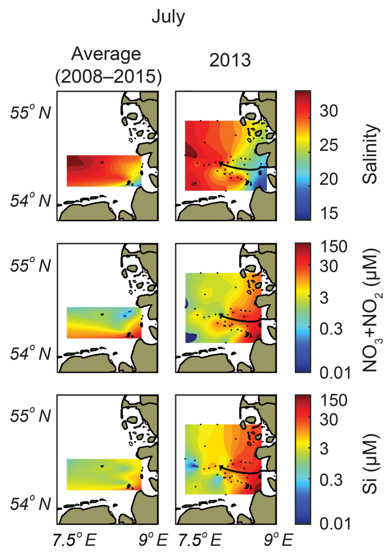

Figure 11. Same description as in Fig. 10, for the month of July. The left panels show average parameter distributions in July, based on 7 years of data (2008–2015, excluding 2013) from BAH AWI stations (Table 1); the right panels show interpolated parameters from 2 to 11 July 2013, measured at BAH AWI,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

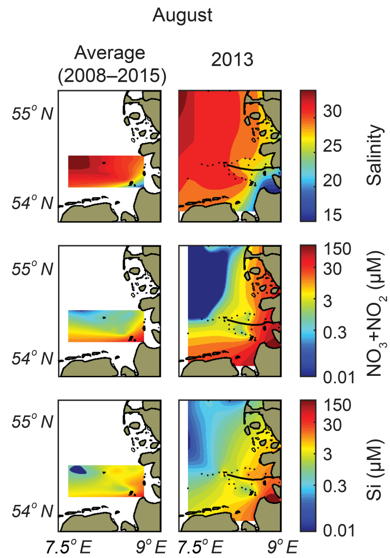

Figure 12. Same description as in Fig. 10, for the month of August. The left panels show average parameter distributions in August, based on 7 years of data (2008–2015, excluding 2013) from BAH AWI stations (Table 1); the right panels show interpolated parameters from 6 to 12 August, 2013, measured at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

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 southeastern 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 southeastern 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 southeastern 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, as well as 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 flod. 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 car-

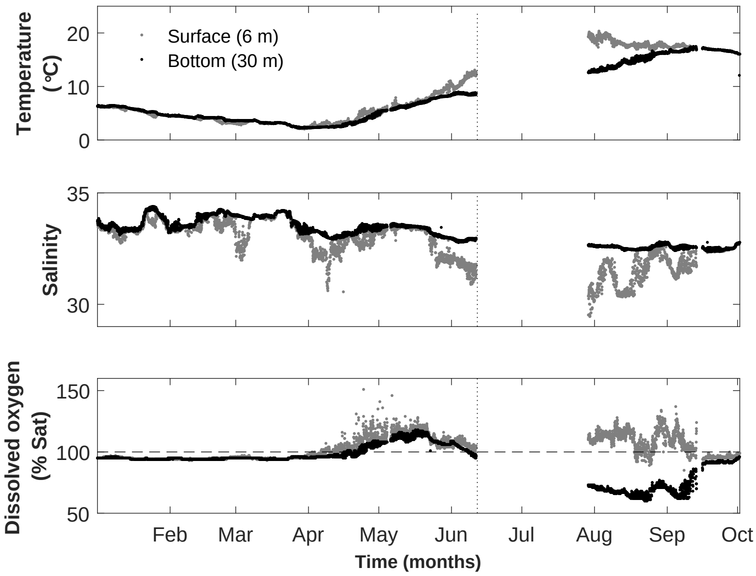

Figure 13. Surface (6 m, gray) and bottom (30 m, black) temperature, salinity and dissolved oxygen (% saturation) measured at the Deutsche Bucht station (Fig. 1, Table 1), part of the MARNET monitoring network. The data cover a time frame between January and October 2013. The onset of the June flood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

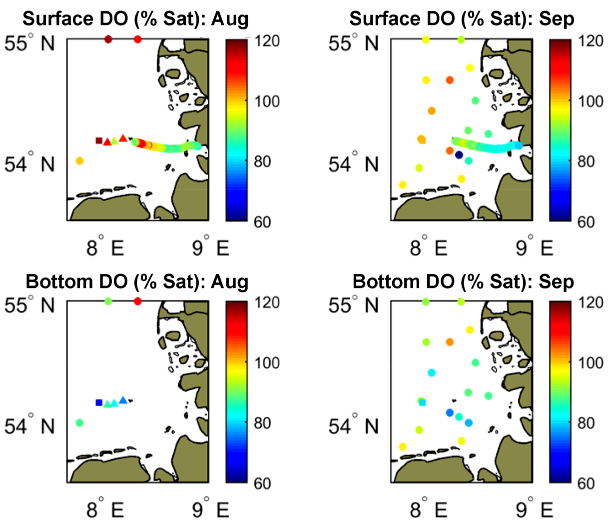

Figure 14. Dissolved oxygen (% saturation) in surface and bottom waters measured in August and September 2013. The surface and bottom dissolved oxygen were measured at available discrete stations from AWI and BSH stations, along with FerryBox (M/V *Funny Girl*) and Deutsche Bucht MARNET station. The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

bon 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 Beusekom 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 particulate organic carbon (POC) loading on the coast was high after the flood despite the lack of POC 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 eastern 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 allochthonous 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, 2011). The observed oxygen depletion after the flood (Fig. 8), for example, may have resulted from increased respiration of both allochthonous and autochthonous 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 southeastern 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 ($> 150\,\mu$M 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 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 (Figs. 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 allochthonous 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 autochthonous 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 three 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 autochthonous and allochthonous 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 southeastern 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 southeastern 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 1987–1988).

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 serve 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, 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; Allan 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, as well as 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 southeastern 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 Data availability

The transect data from BAH AWI have been archived in the Pangaea databank (http://www.pangaea.de; e.g., Helen, 2009). Transect data from BSH have been archived by the Deutsches Ozeanographisches Datenzentrum (DOD, German Oceanographic Data Bank, http://www.bsh.de/en/index.jsp) and are available per request (contact friedrich.nast@bsh.de). Data from FerryBoxes M/V *Funny Girl* and Cuxhaven, as well as HPA Pile and BSH Deutsche Bucht station, are available for download on the COSYNA website (www.cosyna.de, doi:10.17616/R3K02T). The FerryBox data are also available on the FerryBox data website (http://ferrydata.hzg.de). The BSH Deutsche Bucht data are also available on the Marnet Monitoring Network website http://www.bsh.de/en/Marine_data/Observations/MARNET_monitoring_network/index.jsp).

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