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Research article

North Sea salt-marsh archives trace past storminess and climate variability

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ABSTRACT

Intertidal coastal wetlands are regularly exposed to storm surges and associated flooding, resulting in the recurrent accretion of reworked sediments on the salt-marsh surfaces. In this context, well-stratified salt-marsh sediment sequences provide an exceptional archive to evaluate the response of coastal wetlands to past storm-climate variability. Hence, this study focusses on the investigation of two sedimentary salt-marsh sequences from the south-eastern German North Sea coast (Bay of Tümlau and Friedrichskoog) to understand how and to which extent changes in the storm-surge climate are transferred into the sediment archive. This objective is particularly challenging as German mainland salt marshes have been greatly altered by human activities over the last century. To overcome this problem, this study combines different sedimentological and geochemical proxy data, using mean grain sizes together with ln(Br/Cl), Br/C_{org}, and ln(Zr/Rb) ratios, to allow for the identification of storm-surge layers. Local changes in the sedimentary organic matter supply are reflected by the ln(Br/Cl) ratio. There, abrupt drops in the ln(Br/Cl) data coincide with relatively coarser textured sand layers, indicating impacts by regional storm surges during winter, while intervals of comparable higher ln(Br/Cl) values may represent deposition during spring to fall. The Br/C_{org} record reflects the marine versus terrestrial organic matter input and reveals a long-term increase starting during the first half of the 20th century towards recent times, resembling the observed amplification in North Sea storminess. A similar trend is reflected by the ln(Zr/Rb) ratio (since 1950 CE), which can be used as a proxy for the grain-size distribution. Periodic fluctuations in the ln(Zr/Rb) ratio at inter-decadal timescales (10–19 years) suggest a close linkage between local sediment accretion and large-scale atmosphere-ocean climate oscillations over the North Atlantic and Europe, and thus related storm-surge frequency and intensity. Periodic variability on decadal scales was also identified in the ln(Br/Cl) record at the less human-modified and more naturally developed salt marsh at the Bay of Tümlau (12–22 years), likewise indicating a relation between North Sea storminess and associated shifts in the seasonal signal of the primary production and sediment texture to oscillations in the atmosphere-ocean system. On the contrary, similar periodicities are lacking for the intense modified salt marsh at Friedrichskoog. Apparently, the salt-marsh depositional system in the Bay of Tümlau reacts more sensitively to super-regional climatic changes, respectively, the natural depositional processes in the salt marsh at Friedrichskoog are superimposed by the more intense local human activities.

1. Introduction

Sedimentation in active salt marshes is mainly controlled by the complex dynamics of mean sea level (MSL), tides, and storm surges (e.g., Allen 2000; Davy et al. 2009; Stevenson and Kearney 2009; Haigh et al. 2010). These hydrodynamic processes are responsible for the local erosion, relocation, and re-deposition of sediments, and can therefore lead to the loss of salt marshes at some places, but at the same time provide the required sediment supply for the growth of salt marshes at other sites (Allen 1990; Temmerman et al. 2003; Mariotti and Fagherazzi 2010; Andersen et al. 2011; Schuerch et al. 2013, 2019; Kirwan et al. 2016). The mobilization of sediments further depends on the

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exposure of a salt marsh to wave energy, and its geomorphology (e.g., Allen 2000; Mariotti and Fagherazzi 2010). The composition of the reworked suspended sediments, which are introduced onto the salt marsh by recurrent floods, and thereby contribute to their vertical growth, reflects the availability of material originating from the adjacent tidal flats and eroded marshes (Müller-Navarra et al. 2019; Schuerch et al. 2019; Bunzel et al. 2020), as well as from rivers (Eisma and Irion 1988). The accretion of sediments on top of the marsh surface finally depends on the vegetation cover and structure (Nolte et al. 2013; Mariotti and Fagherazzi 2010; Fagherazzi 2014; Möller et al. 2014). Similar processes are also active along the North Sea coast, where specifically the recurrent flooding during storm surges results in the accumulation of well-stratified salt-marsh sequences, providing a potential high-resolution archive of past storm-surge dynamics and climate changes.

The North Sea coastline is exposed to annual storm surges, specifically during winter times (e.g., Gerber et al. 2016). The surge heights are either raised by local wind stress pushing the water towards the coastline (Weisse and von Storch 2010), or by strong atmospheric low-pressure centres that are formed over the North Atlantic and then move across the North Sea (e.g., Müller-Navarra and Giese 1999). During the last century, storm surges were additionally influenced by the long-term increase of regional MSL (2.4 ± 0.1 mm yr^{-1} between 1871 and 2008 CE) under the influence of global warming (Dangendorf et al. 2013a). Particularly in shallow coastal areas, such as the south-eastern North Sea, a rising MSL has significant impacts on the associated bottom-friction forces, which then change with increasing water depth (Davies and Jones 1995). Accordingly, model simulations for the German Bight documented an amplification in the intensity and range of the oscillating tidal currents during the past decades (Arns et al. 2015). It remains unclear, however, to which extend a rising MSL affects the height and impact of storm surges. Generally, the depth-limited storm-surge waves are attenuated with increasing water depth (Arns et al. 2017), but the surge generation itself preferentially occurs concomitant with rising tides (Horsburgh and Wilson 2007). Consequently, rising MSL and amplified tidal ranges likely result in a higher variability of storm-surge heights, complicating the associated flood-risk assessment (Familkhalili and Talke 2016). The assumed amplification in the storm-surge climate signature over the curse of the 20th century, however, can be tested in the well-stratified sediment sequences of modern foreland salt marshes along the German North Sea coast. Given the expected global sea-level rise (SLR) of 0.43–0.84 m by 2100 CE (IPCC, 2019), it further highlights the importance to obtain a better understanding on how changes in sea level and storminess affect the resilience of coastal salt marshes under ongoing global warming.

Salt-marsh sedimentation along the south-eastern North Sea coast is further influenced by local human impacts such as drainage measures, land reclamations, and shoreline modifications (Davy et al. 2009). As evaluated by Esselink et al. (2009), between 80% (Lower Saxony) and 90% (Schleswig-Holstein) of the mainland salt marshes that fringe the German North Sea coastline have been intensely modified during the past decades, specifically, by the construction and dredging of drainage ditches. Consequently, most of today's salt marshes are of anthropogenic origin, as their development has been favoured by the artificial drainage systems and their frequent upkeep (Esselink et al. 2009, 2017). Although human-modified salt marshes represent nowadays the majority of the intertidal wetlands along the German North Sea coast, they have undergone different land-use histories and degrees of modification (e.g., regarding the frequency of upkeep of the drainage ditches). Accordingly, each salt-marsh sediment sequences should reflect the specific management histories, whereas the natural influence of long-term climate changes and associated storm-surge statistics should leave a similar depositional imprint along the entire coast.

Hence, the overarching hypothesis of this study is that sedimentary salt-marsh sequences along the German North Sea coast archive past storm-climate signals, despite the influence of human coastal management. In order to test this hypothesis, this study explores how the present human-modified salt marshes have responded to climate changes during the past century, how the storm-climate signal is transferred into the sediment sequences, and how this signal can be distinguished from the anthropogenic signals. Commonly, discrete storm-surge layers are described as being dominated by siliciclastic coarser-grained sediments (e.g., Ehlers et al. 1993; Chaumillon et al. 2017), but vary in thickness and composition, often impeding a detailed evaluation based on classical sedimentological analyses. In this context, geochemical analyses by high-resolution X-ray fluorescence (XRF) scanning may add detailed information on salt-marsh sedimentation dynamics on short timescales and may provide additional proxies for the identification of storm-surge layers. Based on that, this study follows an integrated approach by evaluating different sedimentological and geochemical proxy data, including grain size, organic carbon, and XRF scanning data (Br, Cl, Rb, and Zr). These data were obtained from two sediment sequences originating from different salt-marsh environments at the south-eastern German North Sea coast and have undergone similar natural climate processes but experienced different degrees of anthropogenic interventions during the last century. The extracted climate component is used to explore the complexity of the regional storm-surge history and its linkage to underlying super-regional climate oscillations.

2. Regional setting

At present, coastal salt marshes of the Wadden Sea region extend from Denmark to the Netherlands, covering an area of around 400 km^2 along the south-eastern North Sea (Dijkema 1987; Bartholdy et al. 2004; Nolte et al. 2013; Wolff 2013). To promote land reclamation, these salt marshes and adjacent tidal flats were intensely managed during the last centuries, so that their development mainly occurred under human influences (Dijkema 1987; Davy et al. 2009; Esselink et al. 2009, 2000). In order to restore and sustain the natural ecosystem services of coastal salt marshes and instead promote their natural development, they are protected since 1985 CE as part of the Wadden Sea National Park. As a consequence, coastal management and land reclamation, i.e., draining and grazing was reduced or stopped in most salt marshes during the recent past (e.g., Esselink et al. 2009; Nolte et al. 2013; Wolff 2013; and literature therein).

The studied sites comprise two different salt-marsh systems (Fig. 1), which both were modified to different degrees by human activities during the past century. These alterations include networks of parallel trench systems, which were recurrently renewed and dredged every two to three (Friedrichskoog, Dithmarschen) and every three to seven years (Bay of Tümlau, Eiderstedt peninsula) (pers. comm. Schleswig-Holstein Agency for Coastal Defence, National Park and Marine Conservation, LKN.SH, 2017, 2020). However, since foundation of the Wadden Sea National Park, the northern site (Bay of Tümlau) belongs to a protected and restored salt-marsh area that is now dominated by natural processes, while the southern site (Friedrichskoog) is located in an area that is still intensely managed and influenced by anthropogenic interventions. Since the introduction of national nature protection measures, a return of a higher-diverse salt-marsh vegetation was documented for the Bay of Tümlau at least since 2001 CE, favouring plant-communities consisting of, i.a., the *Atriplex portulacoides/Artemisia*-type, *Atriplex portulacoides/Puccinella*-type, or *Festuca rubra* (Stock et al. 2005). In contrast, draining measures and intensive grazing by sheep stock resulted in a short-grazed vegetation cover dominated by only a few grass species such as *Festuca rubra* and *Puccinellia maritima* together with few patches of *Salicornia europaea* at Friedrichskoog (Stock et al. 2005; Bunzel et al. 2020). Nowadays, the Bay of Tümlau is fringed by several modern dikes, which were constructed in 1861 CE and 1933 CE, while Friedrichskoog was diked in 1853 CE (Fischer 1956, 1957; Ehlers 1988). The constructed embankments are defending the populated hinterland from frequently occurring storm surges (Esselink

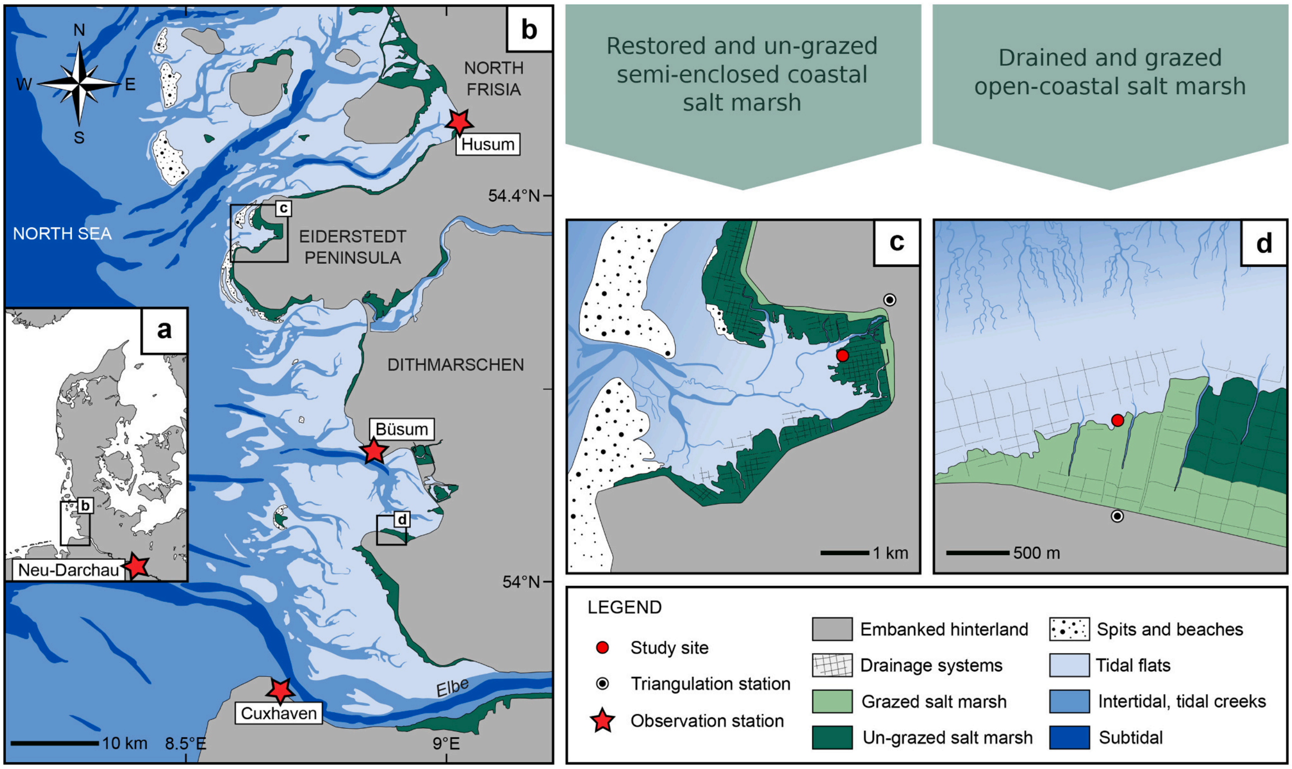

Fig. 1. South-eastern North Sea (a) and overview of the German North Sea coastline (b) with the location of the considered wind-signal stations (Husum, Büsum, and Cuxhaven), the Cuxhaven tide gauge, and the monitoring station for Elbe River discharges at Neu-Darchau (red stars), together with the present-day regional setting of the investigated sites at the Bay of Tümlau (c; TB13-1), and at Friedrichskoog (d; GeoHH-FK). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

et al. 2009; Davy et al. 2009), but they also prevent a natural landward migration of the salt marshes under rising sea level (Kirwan et al. 2016; Müller-Navarra et al. 2019; Bunzel et al. 2020). As a consequence of the embankments, both salt-marsh systems are exposed to lateral erosion at the seaward side of the dike during high tides or storm tides, and thus fringed by erosional cliffs between the tidal margins and the seaward edge of the marshes (Müller-Navarra et al. 2019; Bunzel et al. 2020). These cliffs were chosen for sediment sampling, generating sediment sequences TB13-1 (Bay of Tümlau, 54°21′51.07"N, 8°40′35.09″E; Müller-Navarra et al. 2019) and GeoHH-FK (Friedrichskoog, 54°2′35.02"N, 8°52′20.41″E; Bunzel et al. 2020).

3. Material, methods, and data sources

3.1. Field work

Field work was carried out in Dithmarschen (Friedrichskoog, site GeoHH-FK) in November 2016, while sediments of the Eiderstedt peninsula (Bay of Tümlau, site TB13-01) were recovered in August 2013 (Müller-Navarra et al. 2019). The marsh surfaces at the erosional cliffs are situated 2.09 m (TB13-1) to 2.80 m (GeoHH-FK) above NHN ('Normalhöhennull'), thus exceeding the local mean high water spring (MHWS) levels by 0.50 m (TB13-1) and 1.06 m (GeoHH-FK). As a result, the investigated salt-marsh systems are only flooded during times of extreme water levels that are exceeding the mean high water (MHW) by ≥1.5 m (Gerber et al. 2016). Tidal data were provided by the Federal Maritime and Hydrographic Agency of Germany (BSH), and are based on the nearest tide gauges Tümlauer Hafen (observation period: 2001–2013 CE) and Friedrichskoog Hafen (observation period: 1986–2018 CE).

The sediment sequences at both sites were sampled by 10–15 U-channels, which were pressed vertically into the previously cleaned erosional cliff face. Each U-channel has a maximum dimension of 1.75 cm width, 2.00 cm depth, and 200 cm length, and is open at one long side. Cliff-surface elevation and position was surveyed by using a Leica Geosystems GNSS field controller (Viva Uno CS10) and referred to triangulation stations number 1618 031 10 (Bay of Tümlau) and 1919 088 00 (Friedrichskoog). For further details, see Müller-Navarra et al. (2019) and Bunzel et al. (2020). Data for the triangulation stations were provided by the State Office for Surveying and Geoinformation Schleswig-Holstein (LVermGeo SH). Subsequent processing of the surveyed data was conducted with the Leica Geo Office 8.3 software.

3.2. Historical wind, tidal, and discharge data, and simulated water level extremes

To assess past salt-marsh responses to natural climate variability during the last century, historical wind and tide-gauge observation data, as well as river runoff data for the Elbe River were evaluated. Since long-term wind-observation data recorded at different signal stations along the German North Sea coast are often incomplete due to partly lacking high-resolution records, specifically during the first half of the 20th century, data of three stations near the two study sites were taken and compared, to compensate for times of sparse meteorological observations. From north to south, the stations comprise: Husum, Büsum, and Cuxhaven (Schleswig-Holstein and Lower Saxony) (Fig. 1). Data were provided by the German Meteorological Service (DWD). In order to take only severe wind conditions into account, which are directly facing the coastline, the daily means of winds with prevailing wind directions from ≥180° to 360° azimuth (westerly winds) and with a wind strength of ≥7 Beaufort (Bft), that equals a minimum wind speed of 13.9–17.1 m s^{-1} (e.g., DWD), were used for subsequent analyses. Historical water levels are based on the tide gauge in Cuxhaven, which covers the longest time period and provides the most complete data record for the south-eastern

North Sea region (data were provided by the BSH). For subsequent analyses, only tidal data with MHW $\geq$ 1.5 m were considered hereafter, which is the classification of the minimum water-level height for storm tides (Gerber et al. 2016). Yearly mean discharge data of the Elbe River were provided by the Global Runoff Data Centre (GRDC) for the monitoring station Neu-Darchau (Lower Saxony), which is the northern-most station close to the Elbe estuary (Fig. 1).

To further compare the salt-marsh sediment sequences with large-scale climate states, simulated extreme sea levels (ESL) and their long-term variability in the German Bight were considered in addition (data were provided by Lang and Mikolajewicz 2019). Extreme sea level indices were characterized by considering only the annual sea-level maxima. The ESL setup relies on a coupled high-resolution regional atmospheric model (REMO, Jacob and Podzun 1997) and a global ocean model (MPIOM, Marsland et al. 2004; Jungclaus et al. 2013), which enables an integration of both regional and super-regional signals (for further details, see Lang and Mikolajewicz 2019).

3.3. Sedimentological and geochemical analyses

Grain-size measurements on the siliciclastic sediment components were conducted choosing a 0.5 cm resolution for the sediment sequence at site GeoHH-FK. Data for TB13-1 were provided at a 1.0 cm resolution by Müller-Navarra et al. (2019). To remove the organic and inorganic carbon from the samples, they were treated with 10–30% H_2O_2 and 1 M CH_3COOH successively. Subsequent grain-size measurements were carried out on a HELOS KF Magic Laser particle-size distribution analyser. The accuracy of the analysis was achieved by measuring an intern silicon carbide (SiC) standard, which was regularly tested after every twentieth to fiftieth sample. Grain-size quantification was conducted by using the software GRADISTAT version 8.0 (Blott and Pye 2001), which is based on the applications described by Folk and Ward (1957).

Scanning X-ray fluorescence (XRF) spectroscopy was performed at an ITRAX Core Scanner with a chromium tube applying a generator setting of 30 kV (30 mA), step sizes of 260 μm (TB13-1) and 500 μm (GeoHH-FK), and a counting time of 15 s per step. The scanning uncertainty for element intensities is generally better than 5% (Jarvis et al. 2015). Further, the accuracy of the XRF scanning performance was regularly tested and confirmed by analysing a certified reference material (CRM), before and after the scanning procedure. Analyses were carried out at the Leibniz Institute for Baltic Sea Research Warnemünde (IOW). Relative changes in the down-core distribution of element intensities (i.e., Bromine, Br; Chloride, Cl; Rubidium, Rb; Zirconium, Zr) within sediment sequences TB13-1 and GeoHH-FK were expressed as logarithmic ratios, and used for environmental interpretations following Dypvik and Harris (2001), Thomson et al. (2006), and Weltje and Tjallingii (2008). The ln(Br/Cl) ratio was considered to provide information about local changes in the marine organic matter (MOC) supply. As Bromine is comparatively sparse in terrestrial organic matter, the Br/C_{org} ratio was then used to reflect the relative proportions of marine and terrestrial organic matter in the sediment, independent from the sediment texture (Mayer et al. 2007; Ziegler et al. 2008). In contrast, the ln(Zr/Rb) ratio was used as a high-resolution proxy for the relative grain-size distribution, since Zirconium (Zr) is enriched in the coarse-grained sediment fraction in form of zircon, while Rubidium (Rb) is mainly concentrated in clay minerals (e.g., Dypvik and Harris 2001; Weltje and Tjallingii 2008; Rothwell and Croudace 2015). Internal sedimentological down-core characteristics were generalized and expressed as light and dark layers, based on previously generated optical and x-ray images (Bunzel et al. 2020).

Organic carbon (C_{org}) was measured by using a EuroVector EuroEA3000 Analyser and a measurement time of 200 s per sample. Prior to the instrumental analysis, one sediment-filled U-channel per sites TB13-1 and GeoHH-FK was sampled at 1–2 cm spacing. Five mg sediment material per sample were separated, subsequently freeze-dried, ground, and three times acidified with 1 M hydrochloric acid (HCl) Merck Suprapure. The accuracy of the method is 0.05%, based on the averaged standard deviations of the analysed replicates after every tenth sample.

In a previous study, individual age models were generated for each sediment sequence based on the combination of different independent dating methods commonly used to date modern sedimentary deposits (Bunzel et al. 2020). This strategy enabled the establishment of an integrated stratigraphic framework for each site. Specifically, the down-core activity of natural (^{210}Pb) and artificial (^{137}Cs) radionuclides, together with the mercury (Hg) concentration was evaluated for both study sites, whereas artificial ^{241}Am was only measured in the Bay of Tümlau (Suppl. Fig. S1). Radionuclide data of TB13-1 (comprising the decay-corrected ^{210}Pb, ^{137}Cs, and ^{241}Am data only; see description below) were taken from Müller-Navarra et al. (2019). Analyses for GeoHH-FK were conducted with the CANBERRA's high-purity Germanium detector (HPGe) with a gamma-spectrometry analysis at the Laboratory for Radioisotopes (LARI), Georg-August-University of Göttingen. Uncertainties (counting errors of ^{210}Pb, ^{137}Cs, and ^{241}Am) were derived from the relative statistical counting error and the measured activity; however, uncertainties of the unsupported ^{210}Pb were calculated by applying the Gaussian-error propagation formula on the previously obtained ^{210}Pb counting errors. For further details, see Bunzel et al. (2020). Furthermore, radionuclide data were corrected to the time of sampling (decay-correction), from which the unsupported ^{210}Pb and ^{137}Cs were further corrected to the sum of organic carbon and portion of the <20 μm sediment fraction (Ackermann et al. 1983; Cundy and Croudace 1995; Milan et al. 1995; Kirchner and Ehlers 1998). At the Leibniz Institute for Baltic Sea Research Warnemünde (IOW), Hg measurements were conducted by using a Milestone Company's DMA-80 Direct Mercury Analyser; for further details, see Bunzel et al. (2020). There, precision of the Hg analyses was controlled by the recurrent measurement of a certified reference material (light sandy soil, Community Bureau of Reference, BCR-142R) and an intern Hg standard (Mecklenburg Bay sediment standard, MBSS-1) after every tenth sample. For further details, see Bunzel et al. (2020), and the description of the stratigraphic framework in the supplements.

3.4. Spectral analyses

For the evaluation of periodic signals in the proxy records, spectral analyses were carried out on the unevenly spaced time series of the ln (Br/Cl) and ln(Zr/Rb) records of sites TB13-1 and GeoHH-FK. The ln(Br/Cl) and ln(Zr/Rb) records were chosen for spectral analysis, since they provide the highest resolution of data points. Statistical significance is expressed with the χ^2 95% and χ^2 99% red-noise levels; however, subsequent data interpretation will build on the power spectra exceeding χ^2 99% as well as periods >2.5 years only. Spectral analyses were performed with the PAleontological STatistics (PAST) software package version 4.02 (Hammer et al. 2001), using the integrated REDFIT module with a Welch window (Schulz and Mudelsee 2002).

4. Results

4.1. Sediment composition and description

The total sediment recovery with the U-channels varied between 110 cm (TB13-1) and 116 cm (GeoHH-FK). Concerning the organic and inorganic carbon free sediment fraction, the investigated sediment sequences mainly consist of fine sand and silt, i.e., on average 55% sand and 43% silt for TB13-1, and between 61% sand and 38% silt for GeoHH-FK. The clay content can be neglected with low values ranging between 2% (TB13-1) and 0.5% (GeoHH-FK) on average (Fig. 2). The average mean grain size is 63.33 μm for TB13-1 and 70.84 μm for GeoHH-FK (Bunzel et al. 2020). The organic carbon (C_{org}) content is generally very low at both sites, showing mean values of 0.86% for TB13-1, and 0.57% for GeoHH-FK, however, maximum values occurred in the

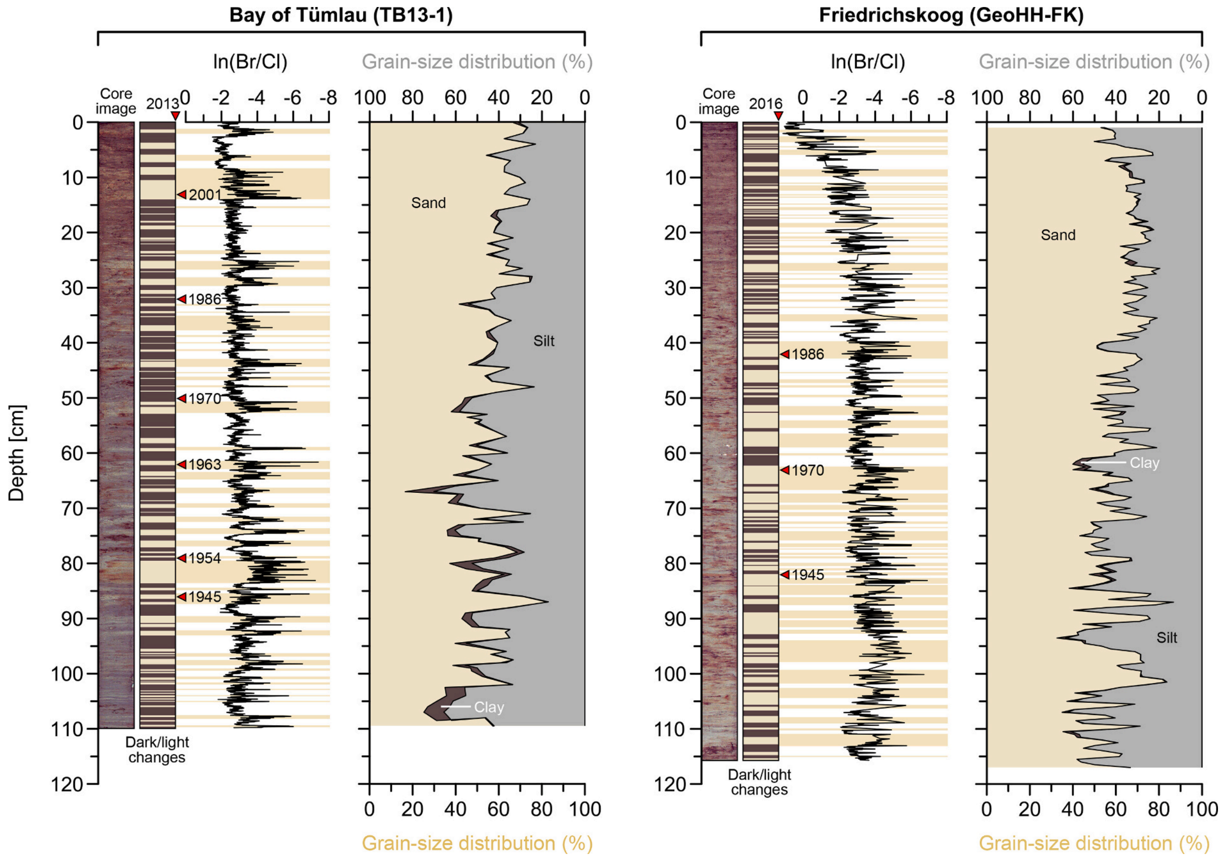

Fig. 2. Optical images of the two sediment sequences TB13-1 and GeoHH-FK together with simplified dark/light brown colour changes, representing the dark reddish-grey to light greenish-grey sediment colours, and reliable age markers given in years CE (red triangles; Bunzel et al. 2020). Prominent drops in the ln(Br/Cl) records are highlighted with light brown shaded bars. The relative sediment composition comprises the fractions sand (light brown), silt (grey), and clay (dark brown); note the inversely oriented x-axes. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

uppermost sediments. Furthermore, both sediment sequences are characterized by a prominent horizontal lamination of alternating light (greenish-grey) and dark (reddish-grey) coloured layers (Fig. 2) (Müller-Navarra et al. 2019; Bunzel et al. 2020). The light colour is likely caused by a reduced proportion of organic components being incorporated in the sediment matrix (Müller-Navarra et al. 2019). The thickness of the individual layers in the sediment sequences ranges from around one millimetre to a few centimetres, in which the layers are slightly thickening upward, accompanied by a gradual upward coarsening trend at both sites (Fig. 2). At site GeoHH-FK, a horizontal shell layer was observed in a depth of 24 cm, which could be continuously traced along the entire erosional cliff face (Suppl. Fig. S2). The bottommost intervals at both sites were defined as reduced horizons (below ca. 100 cm at site TB13-1 and below ca. 110 cm at site GeoHH-FK), which are temporarily to permanently affected by ground water, revealing a dark greyish to blackish sediment colour (Bunzel et al. 2020).

4.2. Geochemical and spectral analyses

Both ln(Br/Cl) records are characterized by strong and high-frequency fluctuations with the recurrent occurrence of sharp drops, which can be attributed either to Bromine (Br) decreases or Chloride (Cl) increases (Fig. 2). These drops clearly coincide with the light greenish-grey coloured sandy sediment intervals. At site TB13-1, the distinct drops in the ln(Br/Cl) record are displaying variations on multi-decadal to inter-decadal timescales with strong power at periods of 131.5, 21.9, and 12.0 years at the >99% χ^2 confidence level, as well as at periods of 6.6, 5.7, and 3.2 years (Fig. 3). In comparison, the ln(Br/Cl) record of site GeoHH-FK lacks any significant periodic variability, instead, this record is characterized by a prominent long-term increase towards today (Figs. 2, 3).

The ln(Zr/Rb) records reveal a variability on inter-decadal timescales with generally higher values occurring around 1930 CE (at ca. 98 cm depth) and between 1940 and 1950 CE (ca. 86 cm) (Suppl. Figs. S3, S4). From 1950 CE onwards, the decadal variability is superposed by a long-term increasing trend. At site TB13-1, the ln(Zr/Rb) record exhibits significant power (>99% χ^2 confidence level) centred at periods of 65.8, 16.4, 10.1, 6.9, and 4.5 years. At site GeoHH-FK, the ln(Zr/Rb) record shows significant power at the >99% χ^2 confidence level, centred at periods of 76.9 and 19.2, respectively (Fig. 3).

For the total recorded time span (1914–2013 CE), the Br/C_{org} ratio of sediments at site TB13-1 exhibits an overall increasing trend, with maximum values around the late 2010s (within the top 10 cm depth), and a transient depletion during the 1950s (ca. 80 cm) (Suppl. Figs. S3, S4). The Br/C_{org} record at GeoHH-FK partly resembles that of TB13-1, however, with lowest values around the early 1930s (at around 90 cm depth) and a subsequent increase, finally peaking around 1990 CE (ca. 35 cm). After 1990 CE, the Br/C_{org} ratio returns to low values, similar to those between 1930 and 1940 CE (Suppl. Figs. S3, S4).

5. Discussion

5.1. Salt-marsh depositional systems and their regional variations in sediment characteristics

The sediment sequences of the present study are generally dominated by fine sand (>63 μm; on average 55% at the Bay of Tümlau and 61% at Friedrichskoog) and silt (<63 μm; on average 43% at the Bay of

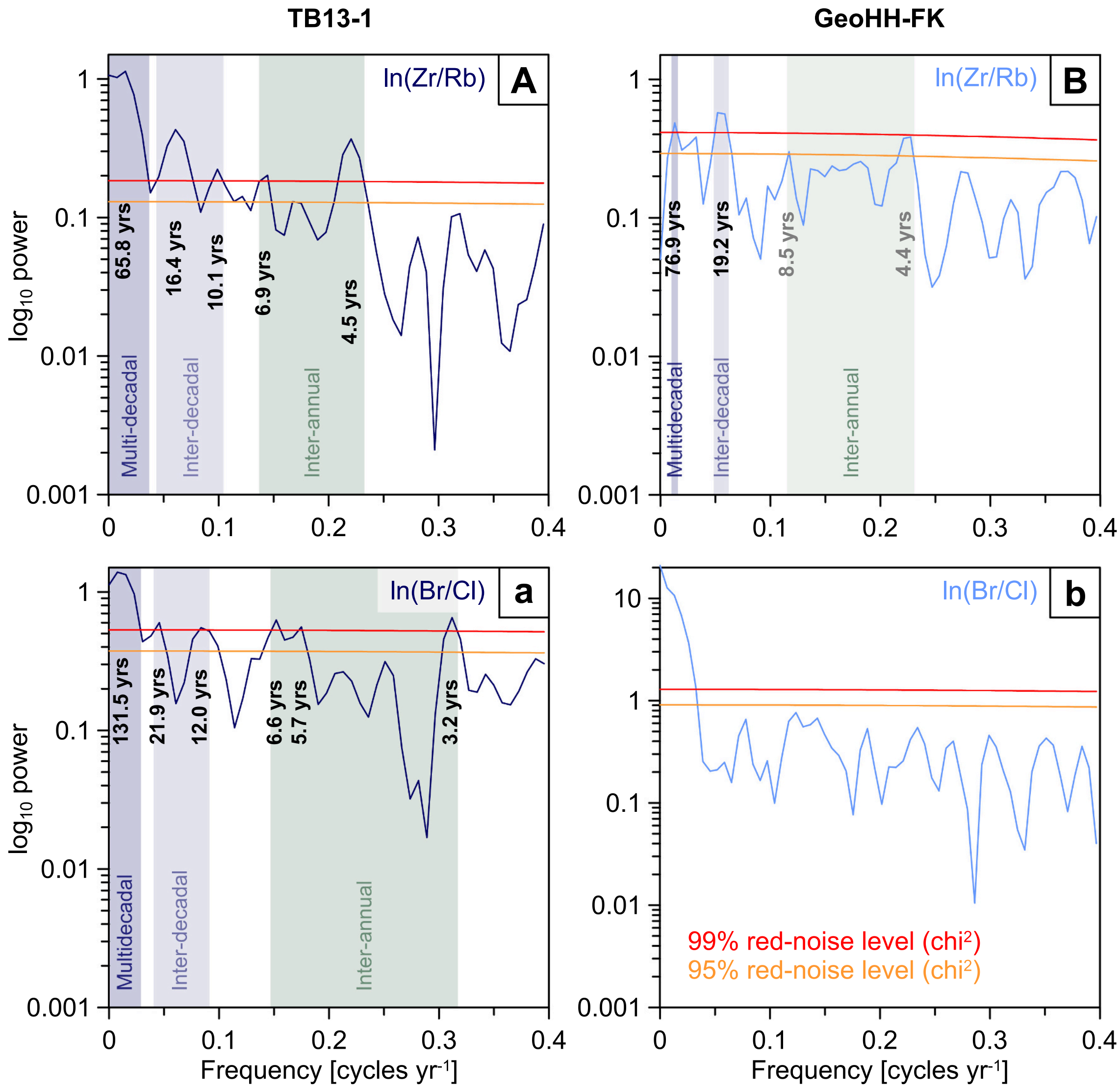

Fig. 3. REDFIT power spectra with 95% and 99% red-noise confidence levels (chi^2) of the ln(Zr/Rb) and ln(Br/Cl) ratios at sites TB13-1 (A, a; dark blue line) and GeoHH-FK (B, b; light blue line), using a Welch window. Black numbers indicate periods in which the corresponding power spectra is >99% red-noise level, grey numbers indicate periods which are significant at >95%. Shaded bands denote the relevant time intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Tümlau and 38% at Friedrichskoog), with rather moderate down-core variations (Fig. 2). The coarsening trends were observed by both the measured grain-size spectrum and the ln(Zr/Rb) ratio. In both sequences, however, changes in the sediment characteristics are indicated by a clearly distinct fine-scale stratification and lamination, which can be attributed to the recurrent influence of the hydrodynamic interaction between storm surges and tides (e.g., Reineck 1982). If, however, the allocation criteria are solely based on the grain-size spectrum of the different sediment layers, storm-surge events cannot be clearly discriminated within the studied salt-marsh deposits. In fact, sedimentation dynamics in coastal salt-marsh environments are rather highly complex. For this reason, there is often inconsistency about the characteristic composition of sediment particles transported onto the salt-marsh surface during a storm surge. In various German, Dutch, and UK salt marshes, the deposition of relatively coarse-grained layers, containing sand grains and/or shell fragments, have been associated with severe storm surges (e.g., Ehlers et al. 1993; de Groot et al. 2011; Schuerch et al. 2012; Swindles et al. 2018). In contrast, Eisma and Irion (1988) and Bartholdy (2000) related the deposition of fine-grained material (<63 μm) originating from the North Sea basin to storm surges. There, the mud of the adjacent tidal flats represents a mobile layer, which is re-suspended during the increasing shear stress of a storm event (Bartholdy and Aagaard 2001).

Correspondingly, the high-resolution ln(Br/Cl) records from the Bay of Tümlau and Friedrichskoog were used for a more detailed reconstruction of regional storm-surge impacts and the assessment of differences in sediment accretion in a high-frequently dredged and grazed versus a less-frequently dredged and un-grazed salt marsh. Since the light greenish-grey coloured and more sandy sediment intervals clearly coincide with abrupt drops in the ln(Br/Cl) values (Fig. 2), this coincidence suggests a loss of Bromine and/or supply of Chloride during deposition of the siliciclastic coarser-grained sediments, which may be directly related to single storm surges (Swindles et al. 2018). In intertidal coastal wetlands, Bromine is known to be incorporated by various marine primary producers such as phytoplankton, macroalgae, and seagrass, thus representing the marine organic carbon (MOC) (Mayer et al. 1981, 2007, and references therein). In addition, Bromine can indicate high sediment porosity accompanied by a high seawater content in the pore spaces (Thomson et al. 2006; Ziegler et al. 2008). In contrast, enrichments in Chloride are only found in the sedimentary pore water (Thomson et al. 2006), remaining almost constant with increasing sediment depth (Beck et al. 2008). Consequently, the ln(Br/Cl) ratio can provide information about changes in the marine organic matter supply. An enhanced transport of re-suspended material from the surrounding tidal flats during a storm-surge event (e.g., Eisma and Irion 1988), may then result in a concomitant increase of the MOC deposition on the adjacent salt marshes. However, North Sea ecosystems are characterized by strong seasonal contrasts in primary production and storm surge induced suspension, with maximum production rates during spring and summer, but maximum re-suspension of the sediment particles during winter (Skogen et al. 1995). These seasonally differing impacts seems to be archived by the stratified salt-marsh sequences, which show regular alternations between clayey-silty (dark reddish-grey coloured) and silty-sandy (light greenish-grey coloured) sediment layers across the depths. Accordingly, the stratification presumably reflects the different influences of storm surge-induced sediment accretion (Redfield 1972; Behre and Streif 1980; Ehlers et al. 1993; Chaumillon et al. 2017), in dependence of that times at which the suspended material of the water columns contains more MOC and finer-grained sediments, respectively, less MOC and coarser-grained sediments (e.g., Bartholdy and Anthony 1998). Based on these observations, the abrupt drops in the ln(Br/Cl) records in connection with the light greenish-grey coloured and more silty-sandy sediment intervals, particularly evident throughout the sediment sequence at the Bay of Tümlau, likely represent deposits evoked by regional storm surges in winter time. During winter, the MOC content of the total suspended matter is $\leq$20% (Eisma and Irion 1988), and the high sedimentary pore volume in the sand layers promotes an enrichment of Chloride (Thomson et al. 2006). Hence, pronounced drops in the ln(Br/Cl) ratio further represent the dilution of the re-suspended MOC by the concomitant high proportion of siliciclastic coarser-textured particles. Conversely, clayey-silty intervals revealing comparably higher ln(Br/Cl) values may then represent re-suspension in spring to fall under generally calm weather conditions with less intense storms, when the suspended material encompasses highest MOC contents together with finer-grained particles. This is in line with studies by Bartholdy and Anthony (1998), who documented the highest import of fine-grained sediments from the open North Sea to the Wadden Sea coast at times of fair weather conditions.

At Friedrichskoog, the observed small-scale variability in the ln(Br/Cl) ratio is less pronounced and rather superposed by the overall increasing values towards the sediment surface. Inspection of the XRF raw data reveals that this long-term ln(Br/Cl) increase is mainly caused by a concomitant decrease of the Chloride counts. Since the salt-marsh surface at Friedrichskoog is situated 2.80 m above NHN (1.06 m above mean high water spring, MHWS), while the salt marsh in the Bay of Tümlau is situated only 2.09 m above NHN (0.50 m above MHWS), the seawater induced Chloride supply likely decreased with increasing height of the salt-marsh surface at Friedrichskoog. This would be compatible with a long-term decrease in submergence time and frequency responding to the gradual elevation of the salt-marsh surface at Friedrichskoog during recent times. There, the increase in surface level was probably artificially promoted by the frequent dredging measures. As a consequence, the top soils at the more elevated erosional cliff became partly dehydrated (e.g., de Jong et al. 1994). In contrast, the more sheltered location of the lower salt marshes in the Bay of Tümlau favoured a more sensitive and persistent response of short-term depositional processes to seasonal changes in storminess. At this site, the response of the salt-marsh system to regional climate variability was further enhanced by a return of natural conditions when grazing and draining was persistently stopped after National Park foundation (Müller-Navarra et al. 2019).

When further taking the obtained mean accretion rates into consideration, slightly lower average accretion rates (1.16 cm yr^{-1}) appeared in the grazed and ditched salt marsh at Friedrichskoog when comparing to the less modified and more naturally developed salt marsh in the Bay of Tümlau (1.31 cm yr^{-1}) (Bunzel et al. 2020). This result is surprising since the salt-marsh surface at Friedrichskoog is much higher with 2.80 m NHN, and at this more wave-exposed open coastal site the general net transport and deposition of re-suspended sediments during storm surges should be expected to be higher than in the semi-enclosed salt marsh in the Bay of Tümlau. Apparently, the contrasting accretion rates can be partly attributed to the different anthropogenic land-use histories, including the establishment of different vegetation types. Particularly, interventions by intense grazing management affect the heterogeneity of the salt-marsh plant communities (Bakker et al. 2019). Consequently, a monotonous short-grazed sward cover (mainly consisting of *Puccinellia maritima*), as it is found at Friedrichskoog, can diminish the process of capturing suspended sediments from incoming waves during submergence (Kiehl et al. 1996; Nolte et al. 2013). In comparison, the development of a more natural vegetation in the Bay of Tümlau enhanced the accretion rate of sediment particles during storm surges (Schuerch et al. 2012; Möller et al. 2014; Leonardi et al. 2018; Müller-Navarra et al. 2019). However, due to the semi-enclosed position of the bay, storm-surge waves are attenuated and sediment deposition on the salt marsh occurs under relatively low-energy conditions (Müller-Navarra et al. 2019). This is underlined by the absence of shell fragments within the potential silty-sandy storm layers, but the occurrence of allochthonous calcareous foraminiferal tests originating from the surrounding tidal flats (Müller-Navarra et al. 2019). This finding is in accordance with results from sheltered Dutch salt marshes, where the deposition of sediments was associated with low-energy conditions of tides and waves (de Jong et al. 1994). Further, the estimated accretion rates at the Bay of Tümlau slightly decreased in recent times, which implies a naturally advanced stage of maturity of the local marsh system. In contrast, the potential storm layers deposited at Friedrichskoog contain comparatively more coarse particles, occasionally even larger shell fragments. This suggests an exposition of the studied salt-marsh sequence to rather high-energy conditions during a storm surge. Nevertheless, the overall sediment-accretion rate is lower at Friedrichskoog due to the combined effects of an altered vegetation by grazing, and a rather flat salt-marsh morphology, which is at the same time artificially elevated due to the intense dredging and drainage measures (e.g., de Jong et al. 1994; Müller-Navarra et al. 2016).

5.2. Salt-marsh archive of changes in storminess and regional sea level

The effects of changing extreme water levels on salt-marsh depositional processes were further evaluated by considering the sedimentary Br/C_{org} ratio. The similar appearing long-term trends in both Br/C_{org} records from the Bay of Tümlau and Friedrichskoog reveal lowest Br/C_{org} values during the first half of the 20th century, suggesting that the marine influence was likewise comparatively low during this time. Whereas, the subsequent increase in Br/C_{org} values from the mid-century towards recent times, with highest values occurring between 1990 CE (Friedrichskoog) and 2010 CE (Bay of Tümlau), reflect an increase in the marine contribution towards recent times (Fig. 4b, d) (e.g., Mayer et al. 1981). Consequently, both Br/C_{org} records are resembling the trends in North Sea storminess, which is reflected by the historical wind observation and tide-gauge data at Husum, Büsum, and Cuxhaven showing a gradual amplification in the wind strength and water-level height around 1920 CE and towards the 1990s (Fig. 4). In fact, North Sea storminess varies on timescales of decades and longer, in which periods of enhanced storminess mainly coincide with the beginning and the end of the 20th century, while a period of reduced storminess occurs during the mid-century centred around 1960 CE (Matulla et al. 2008; Weisse et al. 2012; Dangendorf et al. 2014). It remains unclear, however, why the highest Br/C_{org} values at the different sites appear with an offset of about 20 years, i.e., 20 years earlier at Friedrichskoog (1990 CE) than in the Bay of Tümlau (2010 CE). These contrasts may likewise reflect the land-use histories of the two salt marshes with differences in morphology, elevation, and corresponding vegetation communities affecting the local submergence frequencies. Furthermore, the different

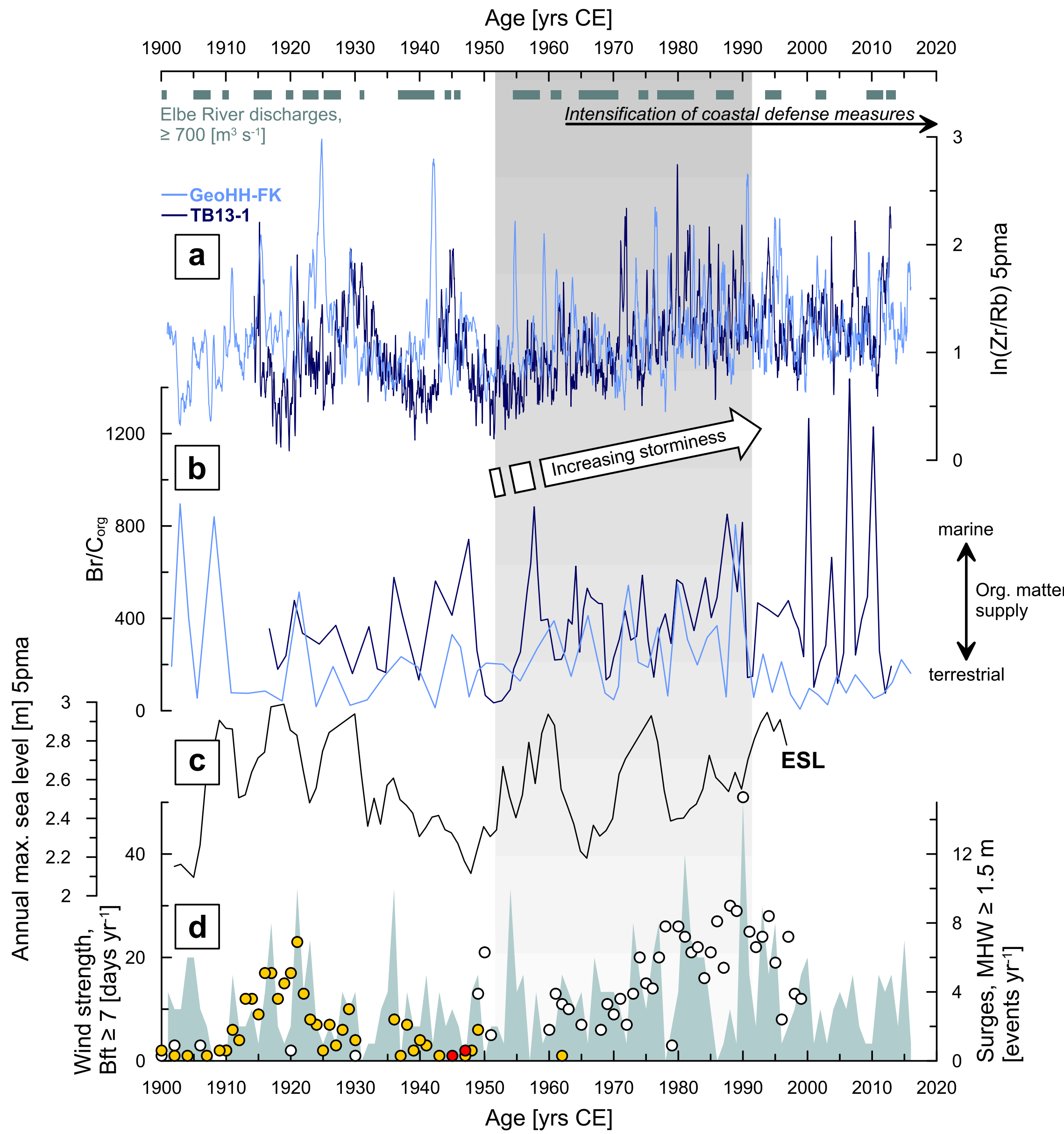

Fig. 4. Distribution patterns of the ln(Zr/Rb) ratios as a proxy for grain-size fluctuations at the Bay of Tümlau (TB13-1; dark blue) and Friedrichskoog (GeoHH-FK; light blue) (a), and Br/C_{org} ratios as indicator for changes in the marine organic matter supply (b). (c): Simulated times series of extreme sea levels (ESL) at Cuxhaven; data were provided by Lang and Mikolajewicz (2019). (d): Yearly number of recorded storm-surge days, which are exceeding the mean high water (MHW) with ≥1.5 m at the Cuxhaven tide gauge (light blue-green), and number of days with westerly winds exceeding ≥7 Beaufort (Bft) at Husum (yellow circles), Büsum (white circles), and Cuxhaven (red circles). The grey band marks the period of general amplified storm-climate conditions and concomitant increased flooding of the salt marshes. Dark green bars at the top show observed Elbe River discharges at Neu-Darchau, when the annual mean discharges are exceeding the total mean discharges of 700 $m^3 s^{-1}$. 5pma = 5-point moving average. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

and highly dynamic depositional environments at the North Sea coast may, most likely, account for ageing uncertainties within the salt-marsh stratigraphy, although the obtained age models appear relatively robust for the past ~70 years (Bunzel et al. 2020). Moreover, both Br/C_{org} records imply a storminess strengthening already starting in the first half of the 20th century, while the increasing coarsening of the sediments (as suggested by the ln(Zr/Rb) ratio) started to be decoupled from the previously prevailing inter-decadal variability since around 1950 CE, which is in line with model simulations (e.g., Matulla et al. 2008). However, the upward coarsening trends at both sites reflect rather indirectly the increase in marine influences, as the seaward edges of the salt marshes are progressively under erosion when sea level rises, leading to a retreat of the marsh-edge cliffs and increasingly proximal depositional conditions (e.g., Allen 1989; Ehlers et al. 1993).

The modern extreme water levels, and associated risks by flooding, started to increase from the mid-20th century onwards, outpacing the rate of regional sea-level rise (SLR) (e.g., Mudersbach et al. 2013; Arns et al. 2017). The reason is that mean sea level (MSL) and extreme sea levels rather seem to represent a non-linear feedback, i.e., a regional long-term MSL rise does not necessarily result in a comparable linear rise in extreme high-water levels (e.g., Dangendorf et al. 2013b; Mudersbach et al. 2013; Arns et al. 2015; and references therein). Indeed, the climate mechanisms being responsible for variations in the extreme water level and accompanied flooding likely differ from those causing background sea-level variations (Lang and Mikolajewicz 2019). Consequently, the North Sea storminess itself lacks a clear long-term trend (Weisse et al.

2012), as it was observed for the MSL (2.4 ± 0.1 mm yr^{-1}; Dangendorf et al. 2013a).

Commonly, shallow coastal environments are considered extremely vulnerable to the impacts of an accelerating SLR and possible changes in storminess (Dangendorf et al. 2013b; Arns et al. 2017). Assuming a maximum SLR scenario of 84 cm by 2100 CE (IPCC, 2019), up to 45% of the salt-marsh areas may vanish, at least along the south-eastern U.S. coast (Craft et al. 2009). Although those salt-marsh areas that receive high amounts of minerogenic sediment supplies may compensate for the SLR-evoked loss of coastal wetland habitats (French 2006; Stevenson and Kearney 2009). Accordingly, the recorded sediment-accretion rates of 1.16–1.31 cm yr^{-1} in Friedrichskoog and the Bay of Tümlau suggest that the different salt-marsh systems at the south-eastern North Sea coast are currently able to outpace the ongoing SLR, as long as the required sediment import and flooding dynamics are ensured (Bunzel et al. 2020). In addition to the direct consequences of climate-induced SLR and concomitant differences between MSL and extreme sea levels, coastal protection measures may have also contributed to a change in the storm-surge signal (Dangendorf et al. 2013b). Since there was no need to maintain the heights and efficiency of dikes between 1855 and 1962 CE, due to the period of reduced storminess, the severe storm-surge event in 1962 CE caused many dike failures, and thus a wide range of damages and casualties along the German North Sea coast (von Storch et al. 2008). As a consequence, extensive investments were subsequently initiated to improve coastal protection measures, i.a., by improving the dike bases and rising the dike levels up to 7.20 m above NHN, entailing persistent ecological and morphological impacts on the coastal ecosystems (Kelletat 1992; von Storch et al. 2008; Dangendorf et al. 2013b). Hence, the establishment and observed retreat of the erosional salt-marsh cliffs and accompanied coarsening trends, as mentioned above, likely have been further accelerated due to intensified coastal protection measures, as the dikes in the hinterland prevent a landward migration of the salt marshes with SLR.

5.3. North Atlantic climate control on salt-marsh sedimentation in the German Bight

The investigated sediment archives cover approximately the last 100 years. A similar long-term variability in both ln(Zr/Rb) records suggest comparable depositional processes in the Bay of Tümlau (TB13-1) and Friedrichskoog (GeoHH-FK), although the different exposures and land-use histories account for site-specific differences. The relative alternation of coarser- and finer-grained material on inter-decadal timescales, i.e., at periods of 10.1 and 16.4 years (TB13-1), and 19.2 years (GeoHH-FK), is particularly pronounced during the early 20th century until 1950 CE (Fig. 4). In comparison, the ln(Br/Cl) record of site TB13-1 exhibits similar variability with significant periods centred at 12.0–21.9 years, while site GeoHH-FK lacks comparable periodicities at the >99% confidence level (Fig. 3). Hence, the observed periodicities of the ln(Zr/Rb) and ln(Br/Cl) records suggest a close linkage of sediment accretion, changes in flooding dynamics, and related shifts in the primary production to super-regional oscillations in the atmosphere-ocean system. One of the major modes, forcing a recurrent atmospheric circulation pattern in the Northern Hemisphere, is the North Atlantic Oscillation (NAO) (Hurrell 1995; Hurrell et al. 2003), which exhibits an 11–25 year period related to the solar Hale cycles (Fairbridge and Krebs, 1961; Raspopov et al. 2004). The NAO dipole anomalies between the Arctic and subtropical Atlantic are responsible for a variety of climate changes concerning wind speed and direction, precipitation, and temperature (Hurrell 1995; Hurrell et al. 2003; Wakelin et al. 2003; Ionita et al. 2011). The occurrence of oscillating climate patterns on inter- to multi-decadal timescales is, however, often discussed as being the result of various interfering climatic teleconnections (e.g., Comas-Bru and McDermott 2014). Consequently, the observed periodic changes in salt-marsh sedimentation dynamics may be likewise the product of interfering decadal-scale shifts in the climate system.

Regional environmental responses to interfering climate modes were further postulated by Ionita et al. (2011) and Zanchettin et al. (2019), who documented periodic inter-decadal fluctuations in the discharge of the Elbe River, centred at a period of 14.2 years. As discussed above, salt-marsh sediments along the south-eastern North Sea coast mainly originate from the surrounded tidal flats and/or adjacent eroded salt marshes (Schuerch et al. 2019), in which the prevailing anti-clockwise sea-surface circulation and tidal currents are responsible for the required erosion, transportation, and deposition of the sediments (Postma 1981; Eisma and Kalf 1987; Eisma and Irion 1988; Winther and Johannessen 2006). Additionally, around 4.8 × 10^6 t yr^{-1} of suspended particulate matter are remobilized by the rivers and transported into the North Sea basin (Eisma and Kalf 1987; Eisma and Irion 1988; Allen 1990; Wolfstein and Kies 1999). Based on that, the sediment sequence at Friedrichskoog is likely affected by both tidal currents and the Elbe River discharge, due to its exposed location in an open coastal salt-marsh setting and its proximity to the Elbe Estuary (Bunzel et al. 2020). In contrast, the more sheltered salt marsh in the Bay of Tümlau located further north is expected to be less influenced by the latter, although its ln(Zr/Rb) record is similar to that at Friedrichskoog. Accordingly, high ln(Zr/Rb) values may at least partly reflect the enhanced availability of suspended material in the Wadden Sea during times of high river discharges, that are alternating on similar inter-decadal timescales.

Changes in the atmosphere-ocean climate oscillation over the North Atlantic and Europe are further generating shifts in the wind speed and direction, and corresponding MSL (e.g., Wahl et al. 2011; Dangendorf et al. 2013a), which may also have contributed to the observed changes on inter-decadal timescales in both ln(Zr/Rb) records (Fig. 4a). Specifically, dipole anomalies towards a positive NAO phase are associated with recurrent north-westerly winds and extreme sea-level high-stands in the German Bight (Lang and Mikolajewicz 2019). These conditions may have fostered the deposition of coarser textured particles in the salt marshes under high-energy conditions. The observed long-term increase of both ln(Zr/Rb) records and sand contents since 1950 CE onwards (Fig. 4a), which is partly superimposed on the decadal trends, corresponds to the concomitant increase in North Sea storminess (Fig. 4d), and is also reflected by the gradual Br/C_{org} increase (Fig. 4b). Apparently, the ln(Zr/Rb) and Br/C_{org} records specifically reflect the period of strengthened North Sea storminess since the mid-1950s towards recent times, when the long-term increase in rates of extreme water levels is decoupled from the MSL, as related to changes in the tidal regime (Mudersbach et al. 2013; Arns et al. 2015, 2017). While a direct comparison between individual recorded storm surges, extreme sea-level simulations from model experiments (Lang and Mikolajewicz 2019; Fig. 4c), and sedimentary proxy records may reveal inconsistencies, their long-term trends show similar variations on various timescales (Fig. 4), as described above. Accordingly, salt-marsh deposition along the south-eastern North Sea is likely driven by interfering large-scale climate variabilities and the combined effects of storminess and Elbe River discharge, and associated suspended matter availability.

In the ln(Zr/Rb) record originating from the Bay of Tümlau, strong spectral power was further observed for a period of 65.8 years, as well as for a period of 76.9 at Friedrichskoog. Despite the comparatively low statistical significance of these long periodicities, they may reflect a relation of sedimentation processes to the Altantic Multidecadal Oscillation (AMO), coinciding with changes in the North Atlantic sea-surface temperature (SST) on periods of 50–90 years (Enfield and Cid-Serrano 2010). Accordingly, the complex interaction of NAO and AMO and superposition of various periodicities in driving European hydroclimate (e.g., Enfield et al. 2001; Sutton and Dong 2012; Zanchettin et al. 2019), may account for a comparable long-term periodicity archived by sediments of salt marshes in the Bay of Tümlau and Friedrichskoog. However, any long-term fluctuations cannot be confidently proven, as data of the corresponding sediment sequences are limited by covering only the last ca. 100 years.

Variability on shorter timescales, comprising significant periods between 3.2 and 6.9 years (>χ^2 99%), as documented by the ln(Br/Cl) and ln(Zr/Rb) records in the Bay of Tümlau, and periods with comparatively weak power (>χ^2 95%) between 4.4 and 8.5 years at Friedrichskoog (Fig. 3), cannot be clearly linked to any climate modes either, as they are likely impacted by coastal management activities. Specifically, these small-scale changes may be attributed to human-induced dredging activities, in which the drainage systems are recurrently renewed by removing the previously accumulated sediments from the drainage trenches and by replacing the material onto the surrounding salt-marsh surfaces (Nolte et al. 2013; Müller-Navarra et al. 2019; Bunzel et al. 2020). Close to the Elbe estuary, these measures are carried out every two to three years, while the time intervals for dredging activities are increased further north (every three to seven years). This strategy considers the northward decrease in the amount of suspended particles in the water column, leading to a reduction of accumulated sediments in the drainage trenches of salt marshes in the North (pers. comm. Schleswig-Holstein Agency for Coastal Defence, National Park and Marine Conservation, LKN.SH, 2017, 2020). This management strategy was carried out in most salt-marsh systems of the south-eastern North Sea, before it was successively abandoned with establishment of the Wadden Sea National Park in 1985 CE in many areas, including the Bay of Tümlau (Nolte et al. 2013; Müller-Navarra et al. 2019). Nowadays, these dredging activities are mainly restricted to salt-marshes, which are still grazed, such as Friedrichskoog, accounting for the observed differences in the disturbance of the sediment sequences.

6. Conclusions

High-resolution geochemical and sedimentological proxy records from two different salt marshes of the south-eastern German North Sea coast document variations in regional storm-climate conditions and potential links to North Atlantic climate conditions during the past century. The studied salt marshes include the more naturally developed salt marsh at the Bay of Tümlau and the intensely anthropogenically modified salt marsh at Friedrichskoog. Despite different human management histories of ditching and grazing, storm-surge signals are archived in the sediment archive of both studied salt marshes. The main conclusions of this study are summarized below:

(1) Contrasting sediment-accretion rates in the Bay of Tümlau and Friedrichskoog reflect different anthropogenic land-use histories, which are accompanied by the establishment of deviating vegetation types. The less modified and more naturally developed salt-marsh vegetation in the Bay of Tümlau fostered sediment accumulation during storm surges, although the deposition on the salt marsh occurs under relatively low-energy conditions within the semi-enclosed position of the bay. In contrast, at the more wave-exposed open coastal salt marsh at Friedrichskoog, the deposited storm layers contain coarser particles, however, the overall sediment-accretion rate is lower due to the altered vegetation by grazing.

Pronounced drops in the ln(Br/Cl) records together with the occurrence of sandy sediment layers are likely owed by storm surges in winter, when extreme water levels and subsequent inland propagating storm waves are more frequent and intense. The associated suspended material contains less marine organic carbon (MOC), and the enhanced sediment porosity in the sand layers allows for an enrichment of Chloride. Hence, variations in the ln(Br/Cl) ratio are interpreted to reflect the seasonal differences in the effects of storm surges, but the specific exposure and land-use history of a salt-marsh system determines how well the signal is archived in the deposited sediments.

(2) Both salt-marsh sequences exhibit lowest Br/C_{org} values during the first half of the 20th century, suggesting that the marine influence was comparatively low during this time. The Br/C_{org} ratios started to increase from the mid-20th century towards recent times, with highest values occurring between 1990 and 2010 CE. This trend is accompanied by a concurrent increase of the ln(Zr/Rb) ratios, resembling the period of strengthened North Sea storminess since the mid-1950s onwards, when the long-term increase in rates of extreme water levels is decoupled from the MSL. The general coarsening-upward trends in the ln(Zr/Rb) ratios can then be attributed to the combined effects of the retreating erosional cliff face, increasing flooding frequency due to enhanced storminess, but also intensified coastal protection measures.

(3) The salt-marsh successions reflect changes in the regional storm climate, revealed by the ln(Zr/Rb) records alternating on inter-decadal (10–19 years) timescales at both study sites. In comparison, the ln(Br/Cl) record from the Bay of Tümlau varies on timescales of 12–22 years, while similar periodicities are lacking at Friedrichskoog. These periodicities suggest a close linkage of the North Sea storminess and associated shifts in the primary production to oscillations in the atmosphere-ocean system. The corresponding large-scale atmospheric circulation anomalies are the main drivers of the European hydroclimate, generating (multi-) decadal variability of precipitation and related river runoff, westerly winds and extreme water levels in the German Bight. Apparently, the salt-marsh depositional systems in the sheltered Bay of Tümlau responded particularly sensitive to super-regional climatic impacts.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.

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