

Editor  
Earth System Science Data

Dec 4, 2020

Dear Editor,

We would like to thank you for your rapid handling and response to our submission. Please find enclosed the revised manuscript for the *Earth System Science Data*, entitled “*Synchronized high-resolution bed-level change and biophysical data from ten marsh-mudflat sites in northwestern Europe*” [Paper # essd-2020-78], and detailed list of our point-by-point reply to the comments of the two reviewers. The line numbers of updated texts are marked according to the manuscript with changes tracked below.

We highly appreciated the comments made by the associate editor and reviewers, as they enabled us to improve our manuscript. In the attached letter below, we have detailed how their comments were used to revise the manuscript. If you have further suggestions for improvement, we will be willing to make additional modification.

Looking forward to your reply.

Yours sincerely,  
On behalf of all co-authors,  
Heng Wang

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**“Synchronized high-resolution bed-level change and biophysical data from ten marsh-mudflat sites in northwestern Europe” [Paper # essd-2020-78]**

Zhan Hu, Pim W.J.M. Willemsen, Bas W. Borsje, Chen Wang, Heng Wang, Daphne van der Wal, Zhenchang Zhu, Bas Oteman, Vincent Vuik, Ben Evans, Iris Möller, Jean-Philippe Belliard, Alexander Van Braeckel, Stijn Temmerman, Tjeerd J. Bouma

**Response to reviewers' comments**

**1. Response to Edward Anthony (Referee 1):**

**1.1** This is an interesting and useful paper that opens up on bed-level changes and their drivers in tidal flats in NW Europe. The paper basically presents high-resolution bed level data obtained from SED sensors, an innovative method of measuring short-term substrate variations on tidal flats, coupled with biophysical characteristics, and shows the potential link with drivers, notably storms. My main concern revolves around the wave-height measurements (data description and table 1).

**Response:**

We would like to thank the positive comments from the reviewer. We hope that the revised version responds adequately to your concerns and we remain available for further improvement. The concern related to the wave-height measurements is addressed in detail in point 1.7 below.

**1.2** The term bed level needs to be hyphenated throughout when used in the adjectival form of 'bed-level changes' (this is done in Fig. 4c!). I would consider data as being in the plural form: 'data are' instead of 'data is', etc.

**Response:**

We thank the reviewer for these linguistic suggestions. The suggested revisions are done for the whole manuscript. Data and dataset are both considered in the plural form.

**1.3** Title: Awkward title. High-resolution bed-level change is linguistically rather strange as I do not see how bed level change can be of high or low resolution. Measurements or data are of high or low resolution but not change. I suggest 'Synchronized high-resolution bed-level and biophysical data from .....

**Response:**

We thank this suggestion. The new title of the manuscript is: “Synchronized

high-resolution bed-level change and biophysical data from ten marsh-mudflat sites in northwestern Europe”.

**1.4 Abstract:** Line 73: deployment of labour; Line 76: delete 'rare' to read: providing an opportunity

**Response:**

We thank these suggestions from the reviewer and have revised these parts of the manuscript accordingly.

*“In light of these limitations, SED-sensors (Surface Elevation Dynamics sensors) have been developed to record daily bed-level dynamics with high accuracy, while reducing the unit cost and labour during deployment (Hu et al., 2015) ” (Line 88)*

**1.5 Site description:** Line 84: delete 'the' to read from northwestern Europe and use lettering when indicating the number of sites: seven sites, one site, etc. Site 1, 7 etc is OK as you are identifying your sites. Line 96: repetition of measuring. Maybe use: The coordinates of the monitoring stations as well as the bathymetry of the measuring transects...

**Response:**

We thank these suggestions for the reviewer and have revised these parts of the manuscript accordingly.

**1.6 Methods:** I know this is not a study on long-term net sedimentation-erosion rates but how do you account for subsidence from the SED data? Line 143: water-level data were obtained from nearby tidal gauge stations... Line 144: Diatoms act as biostabilizers...

**Response:**

We thank the reviewer for this comment. Indeed, our study is not on long-term net sedimentation-erosion rates, but it is focused on short-term bed-level changes. We did not account for deep subsoil subsidence as over the short-term periods considered here (typically 10-15 months) values of subsidence are mostly in the order of less than 1 or a few mm for the study areas, and therefore mostly much less than values of vertical bed-level changes recorded by the SED sensors:

*“We note that the SED technique does not include effects of deep subsoil subsidence on bed-level changes. For a typical deployment period of the SED sensors (10-15 months), subsidence in the study areas is mainly related to glacial isostatic adjustment after the last ice age, with values in the order of less than 1 or a few mm over the considered time periods (Vink et al., 2007), and therefore mostly much less than values of vertical bed-level changes recorded by the SED sensors.” (Line 167)*

The suggested revisions on the use of hyphen are adapted in the revised manuscript: ‘water level data’ to ‘water-level data’ and ‘bio-stabilizers’ to ‘biostabilizers’.

**1.7 Data description:** Line 173: I am highly surprised by mean Hs values of 0.1 cm and 0.008 cm? These are meaningless and tantamount to zero wave energy! How did you measure such values? A 1 mm-high wave!!! I would suggest you refrain from quoting these values (this also goes for the very low Hs values in Table 1), and focus more on the higher Hs values and their variations in Figure 3 which are more meaningful and pertinent to bed-level change.

**Response:**

We thank the reviewer for this comment. We apologize that the very low Hs values (0.1 cm and 0.008 cm) here were due to a mistake in the calculation. The corrected values should be 10.4 cm and 11.3 cm, respectively. We also checked the mean Hs values in the Table 1, which are correct. Similar values can be found in previous field studies at these sites (e.g. Callaghan et al., 2010; Hu et al., 2015). The very low mean Hs value (1 cm) at Site 3 Baarland in this table is because this site is sheltered by an offshore sandbar that blocks almost all the incident waves (see Figure 1). Additionally, we provide more details related to the data-processing method of Tucker and Pitt (2001) and the source of the processing routines:

*“Significant wave height (Hs) and peak wave period (Tp) were derived from the dynamic wave pressure signals. The attenuation of pressure signals with water depth was corrected using the standard calculations methods as described in Tucker and Pitt, (2001). The attenuation correction was only applied over the frequency range 0.05-0.4 Hz and the maximum correction factor was set as 5 to avoid over-amplification of high frequency signals (i.e. noise). A detailed description and source of the data-processing routines can be found at <http://neumeier.perso.ch/matlab/waves.html>.” (Line 204)*

**1.8 Conclusions** Line 22: Due to the lack of ‘relevant’ (instead of desired).

**Response:**

We thank the reviewer’s suggestion. The text is revised accordingly.

**1.9** Table and figures: Table 1: Surprised at the significant wave height data values! Figure 1: Please add geographical coordinates and scale. Figure 2: Please add a scale in (b) to show length of SED probe. Figure 3. Use black bar to indicate wave height in figure legend.

**Response:**

We thank reviewer's comments on the table and figures. The issue with significant wave height is addressed in point 1.7. All the suggestions with the figures are adapted in the revised manuscript. Please see the updated figures below.

**2. Response to Alvise Finotello (Referee 2)**

**2.1** The article is clear and well structured. Figures and tables are of good quality and appropriate to support the text. The dataset presented is most certainly new (even though some subsets of these data were already employed for individual studies on specific study-case), and I believe it has a strong potential for being useful in the future (also because the authors intend to further expand the dataset by adding new study cases and data).

Methods and material are described in sufficient detail (with some minor exceptions that I've listed here below), and the cited literature is appropriate in my view.

I encountered no issues in accessing the dataset, which I found is complete and well organized. I've only highlighted in my comments one minor suggestion regarding the format of geographic coordinates to improve data consistency throughout the dataset. Data are easy to read and ready-to-use.

**Response:**

We would like to thank the positive comments from the reviewer. We hope that the revised version responds adequately to your concerns and we remain available for further improvement.

**2.2** However, I share the concern of Referee 1 (see RC1 comments n.5 and n.7) regarding the reported low values of significant wave height ( $H_s$ ) equal to 0.1 and 0.08 cm (text line 173). The authors refer to the work of Tucker and Pitt (2001) for the calculation of  $H_s$  and wave period from dynamic wave pressure signals. I believe the text should be briefly expanded to provide an explanation regarding this procedure, which are the potential sources of error, and what is the physical limit – if any – below which the derived  $H_s$  values should be disregarded due to (e.g.) instrument accuracy.

## Response:

We thank the reviewer for this comment. This response was shared with that of the comment 1.7. We apologize that the very low Hs values (0.1 cm and 0.008 cm) were due to a mistake in the calculation. The corrected values should be 10.4 cm and 11.3 cm, respectively. We also checked the mean Hs values in the Table 1, which are correct. Similar values can be found in previous field studies at these sites (e.g. Callaghan et al., 2010; Hu et al., 2015). The very low mean Hs value (1 cm) at Site 3 Baarland is because this site is sheltered by an offshore sandbar that blocks almost all the incident waves (see Figure 1). Additionally, we provide more details related to the data-processing method of Tucker and Pitt (2001) and the source of the processing routines:

*“Significant wave height (Hs) and peak wave period (Tp) were derived from the dynamic wave pressure signals. The attenuation of pressure signals with water depth was corrected using the standard calculations methods as described in Tucker and Pitt, (2001). The attenuation correction was only applied over the frequency range 0.05-0.4 Hz and the maximum correction factor was set as 5 to avoid over-amplification of high frequency signals (i.e. noise). A detailed description and source of the data-processing routines can be found at <http://neumeier.perso.ch/matlab/waves.html>.”* (Line 204)

2.3 1.1: the wording chosen for the title is a bit strange, because it seems that “high resolution” is referred to bed level (hyphenation is missing, by the way). I would suggest changing it to “High-resolution synchronized data of bed-level changes and biophysical data from...”, or something similar. Reading the abstract, it becomes clear that the focus of the paper is also (if not mostly) on salt marshes, so I find the choice of using “tidal flats” in the title a bit odd. My impression is that making explicitly clear that the paper aims to investigate the dynamics of both tidal flats and marshes would be much better.

## Response:

We would like to thank the reviewer for this constructive comment. Now the title is revised as: “Synchronized high-resolution bed-level change and biophysical data from ten marsh-mudflat sites in northwestern Europe”

2.4 1.53-54: “The evaluation of...”, there’s something strange in this sentence. Perhaps “Evaluating the impact of changing sea level and increasing storminess on these valuable coastal ecosystems is of socioeconomic importance” is more clear.

**Response:**

We agree with the reviewer's comment, and the text is revised accordingly.

**2.5** l.118-120: how was the low-tide defined/measured? Directly by the SED sensor (if so, how) or rather by coupling SEDs with a pressure gauge to measure water elevation? Later in the text (l.133) it is specified that “we deployed pressure sensors 0.05 m 0.10 m above the bed in the vicinity of the SED-sensors at some of the sites (see Table 1)”. I think the use of pressure sensors should be mentioned in l.118-120 too.

**Response:**

We thank the reviewer for this suggestion. We have included the following sentence in this part of the manuscript:

*“The tidal fluctuation of water level was recorded by pressure sensors deployed close to SED sensors.”* (Line 176)

**2.6** l.105-115: it would be nice to add some information here (or in Fig.2) regarding the size (i.e., total length) of the SED sensors.

**Response:**

This suggestion is very helpful, and we have revised the Figure 2 to indicate the size of the SED sensors.

**2.7** DATA: in the “profile\_all\_Mar\_2020.xlsx” file, the coordinates (LAT, LON) for all sites are reported in decimal degrees except for sites 9 and 10. I believe it'd be better to keep the decimal degree format throughout the whole dataset. This should be an easy fix. Also, I've noticed that coordinates for site 10 are reported in red: is there a specific reason behind this color choice or is it just a misprint?

**Response:**

We would like to thank the reviewer for this comment. We have revised the file to keep the decimal degree format throughout the whole dataset. The red coordinates of site 10 was indeed a misprint of the geodetic coordinates (unit: meter). To keep the uniform style of coordinates (LAT, LON in decimal degree format), we have deleted

these red columns in the updated version. The revised file has been uploaded to together with the main dataset.

**2.8 FIGURE:** Figure 1: the use of blue color to highlight (some) land cover makes the figure a bit confusing I think. It would be probably better to lose such a color-code in favor of a much clearer one with gray=land and white=sea.

**Response:**

We thank the reviewer for this suggestion. We have revised the Figure using the suggested color scheme.

**2.9 MINOR COMMENTS**

1.31: “instrument cost” → “costly instruments” is perhaps better.

1.33: “salt marsh sites” → “salt-marsh sites”.

1.34-35: “bed level changes” → “bed-level changes” (please add hyphen throughout the whole manuscript).

1.36: D50 → D<sub>50</sub> (use subscript throughout the whole manuscript)

1.36: “some sites”, please specify how many.

1.46: “with” → “of” global importance.

1.61: a semicolon is missing after “(Bouma et al., 2016)”.

1.82: “the current” → “such”

1.84: lose “current”

1.94: “in 2013-2017” → “in the period 2013-2017”; also “from 9-20 months” → “from 9 to 20 months”

**Response:**

We thank the reviewer for all these comments, and we have revised the manuscript accordingly.



**Synchronized high-resolution bed-level change and biophysical data from ten marsh-mudflat sites in northwestern Europe**

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**Abstract.** Tidal flats provide valuable ecosystem services such as flood protection and carbon sequestration. Erosion and accretion processes govern the eco-geomorphic evolution of intertidal ecosystems (marshes and bare flats), and hence substantially affect their valuable ecosystem services. To understand the intertidal ecosystem development, high-frequency bed-level change data are thus needed. However, such datasets are scarce due to the lack of suitable methods that do not involve excessive labour and/or costly instruments. By applying newly-developed Surface Elevation Dynamics sensors (SED-sensors), we obtained unique high-resolution daily bed-level change datasets in the period 2013-2017 from ten marsh-mudflat sites situated in the Netherlands, Belgium and Britain in contrasting physical and biological settings. At each site, multiple sensors were deployed for 9-20 months to ensure sufficient spatial and temporal coverage of highly variable bed-level change processes. The bed-level change data are provided with synchronized hydrodynamic data, i.e. water level, wave height, tidal current velocity, medium sediment grain size (D<sub>50</sub>) and chlorophyll-a level at four sites. This dataset has revealed diverse spatial morphodynamic patterns over daily to seasonal scales, which are valuable to theoretical and model development. On the daily

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scale, this dataset is particularly instructive as it includes a number of storm events, the response to which can be detected in the ~~bed~~-level change observations. Such data are rare but useful to study tidal flat response to highly energetic conditions.

The dataset is available from the 4TU.Centre for Research Data (<https://doi.org/10.4121/uuid:4830dbc2-84b8-46f9-99a3-90f01ab5b923>, Hu et al., 2020), which is expected to expand with additional SED-sensor data from ongoing and planned surveys.

## 1 Introduction

Salt marshes and the adjacent tidal flats are co-evolving coastal ecosystems ~~of~~ global importance (Mcowen et al., 2017; Schuerch et al., 2018). They provide multiple ecosystem services such as carbon sequestration (McLeod et al., 2011; Duarte et al., 2013), hosting migratory birds (Van Eerden et al., 2005), and protecting coastal communities and infrastructures by attenuating waves (Temmerman et al., 2013; Möller et al., 2014; Vuik et al., 2016). These systems are known as dynamic biogeomorphic systems (Knox, 1972; Friedrichs, 2011; Fagherazzi et al., 2012). Their bed form is continuously shaped by the interactions between physical and biological processes, including tidal currents, wind waves, sediment delivery, as well as bioturbation/bioaggregation, which jointly determine the time evolution of these systems (Le Hir et al., 2000; Yang et al., 2008; Green and Coco, 2014; Dai et al., 2016, 2018; D'Alpaos et al., 2016). ~~Evaluating the impact of changing sea level and increasing storminess on~~ these valuable coastal ecosystems ~~is~~ of high socioeconomic importance (Mariotti and Fagherazzi, 2010; Temmerman and Kirwan, 2015; Schuerch et al., 2018). More researches are clearly needed to reveal the key biogeomorphic processes that control the persistence of these intertidal ecosystems to enable an accurate assessment of their resilience.

Recent studies have shown that short-term (daily to seasonal scale) hydrodynamic forcing and the related ~~bed~~-level changes exert a critical control on: i) the recruitment of marsh seedlings (Balke et al., 2014; Silinski et al., 2016; Cao et al., 2018) and benthic invertebrates (Bouma et al., 2001; Nambu et al., 2012); ii) initiation of marsh lateral erosion (Bouma et al., 2016), and iii) position and dynamics of the existing marsh edge (Willemsen et al., 2018; Evans et al., 2019). Large spatial (e.g. dense vegetation vs. bare) and temporal (e.g. stormy vs. calm) variation in ~~bed~~-level changes has been observed in intertidal systems (Spencer et al., 2016; Hu et al., 2017). Thus, to better understand intertidal ~~bed~~-level change and their impact on biogeomorphic evolution, ~~bed~~-level change data with high resolution and sufficient spatio-temporal coverage are needed. However, such data are scarce to support theory and model development. For instance, we are lacking the ability to model cyclic marsh expansion-retreat dynamics since the existing data ~~are~~ insufficient to derive tipping points that lead to the expansion-retreat phase shift. Existing measurements of intertidal ~~bed~~-level dynamics typically have limited temporal (e.g., 2–5 tidal cycles) or spatial resolution (e.g., 1–2 stations) (Whitehouse and Mitchener, 1998; Shi et al., 2014; Zhu et al., 2014; Hunt et al., 2016), as high-resolution datasets require excessive labour or high cost for instruments (Andersen et al., 2006).

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In light of these limitations, SED-sensors (Surface Elevation Dynamics sensors) have been developed to record daily bed-level dynamics with high accuracy, while reducing the unit cost and labour during deployment (Hu et al., 2015). These sensors have been applied in the field at ten sites in the Netherlands (Westerschelde and Wadden Sea), Belgium (Zeeschelde) and Britain (Thames and Humber Estuary) from a number of previous studies (Hu et al., 2017; Willemsen et al., 2018; Belliard et al., 2019). This paper presents a comprehensive collection of the existing SED-sensor dataset. It is expected to provide an opportunity to assist future studies on intertidal biogeomorphic processes as it offers: i) high temporal resolution (daily) bed-level changes; ii) long temporal coverage, i.e. 9-20 months depending on the site; iii) large spatial coverage, i.e. multiple sensors deployed in both marshes and bare tidal flats across ten sites; iv) synchronized biophysical measurements, i.e. hydrodynamic measurements (water level, flow velocity and significant wave height), sediment properties (grain size, chlorophyll-a level and organic matter content) and bathymetric/topographic profiles. In this paper, we present the full dataset from 10 sites, and briefly discuss the potential research questions that can be addressed by exploring such dataset.

## 2 Site description

The dataset includes ten observation sites from northwestern Europe: seven sites from the Netherlands, one site from Belgium and two sites from Britain (Figure 1). For all the seven Dutch sites, site 1-6 are in the Westerschelde estuary, and only site 7 is in the Wadden sea region. Near Zuidgors in the Westerschelde, there are two sites (site 1 and 2). At site 1 (Zuidgors A), only the bare tidal flat was monitored, whereas at site 2 (Zuidgors B), both the bare tidal flat and marsh area were included in the monitoring. The only Belgian site (site 8, Galgeschoor) is located in the Zeeschelde estuary, which is the upstream part of the Westerschelde estuary. Site 8 has two observational transects: north and south transects with different bathymetries. The two British sites, site 9 (Tillingham) and 10 (Donna Nook) are on the southeast coast of England (Figure 1).

Overall, these ten sites cover areas of differing tidal range, wave exposure, sediment grain size and marsh vegetation species (Table 1). Notably, site 10 (Donna Nook) has the largest tidal range (6.9 m), whereas site 9 (Tillingham) has highest wave exposure. The observations were conducted in the period 2013-2017. The duration of the observation at each site varies from 9 to 20 months (Table 1). At all the sites, bed-level changes were monitored daily with multiple SED-sensors. For all sites except site 1, 4 and 8, SED-sensors were deployed on both bare flat and marsh areas. The coordinates of the monitoring stations as well as the bathymetry of the measuring transects were measured by Real Time Kinematic Global Positioning Systems (RTK-GPS) to an accuracy of 15 mm in the vertical and 10 mm in the horizontal. Besides the daily bed-level observation, biophysical measurements were available at some sites, i.e. water level, wave height, current velocity, surface sediment grain size, chlorophyll-a level as well as organic matter content.

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### 3. Method

#### 3.1 ~~bed-level~~ change observation

The ~~bed-level~~ dynamics at each site were monitored using recently developed SED-sensors (Hu et al., 2015, see Figure 2). These sensors are standalone instruments with all the parts ~~for~~ measuring, data-logging and batteries enclosed in a transparent tube. The measuring part is an array of light sensitive cells that measure light intensity. When in use, a sensor is inserted vertically into the bed, leaving about half of the ~~measuring~~ array above the bed. The cells above/below the bed receive different amount of the day light, which will lead to different voltage outputs in the array of cells. By using an autonomous script, the noise in the raw signal is reduced, and the bed level is determined as where the large transition from high to low voltage occurred (Figure. 2d, and see Willemsen et al., 2018). When bed accretion or erosion occur, the transition point moves up or down in the measuring array. Thus, by recording the changes of the transition point, we can measure the ~~bed-level~~ changes. In some cases, scouring holes occurred around some of the deployed SED-sensors, with the maximum depth of 5 cm. They typically result in two transition points in the array, corresponding to the bottom and the top of the scouring holes. In such cases, bed level was determined as the vertical position at the top of the scouring holes. Details of SED-sensor data processing are included in Willemsen et al. (2018). [We note that the SED technique does not include effects of deep subsoil subsidence on bed-level changes. For a typical deployment period of the SED sensors \(10-15 months\), subsidence in the study areas is mainly related to glacial isostatic adjustment after the last ice age, with values in the order of less than 1 or a few mm over the considered time periods \(Vink et al., 2007\), and therefore mostly much less than values of vertical bed-level changes recorded by the SED sensors.](#)

As the sensor is dependent on the presence of daylight, the measuring window is day time during low tide. Data acquired while the sensors were submerged or during night were excluded from the analysis. ~~For most of the time, SED sensors provided at least one measurement per day, i.e. daily temporal resolution. To avoid recording ~~bed-level~~ data when sensors were submerged, an effective measuring window was set as two hours around low tide. [The tidal fluctuation of water level was recorded by pressure sensors deployed close to SED sensors.](#) In such a window, we used the averaged readings as a ~~bed-level~~ observation point.~~

The accuracy of the sensors has been compared to a precise manual method (i.e. Sedimentation Erosion Bar) (Hu et al., 2015). The manual measurements were conducted weekly from 13 June to 17 July 2014 at the second most seaward measuring station of site 1 (Zuidgors A). These observations serve as an independent quality control of our automatic SED-sensor measurements. Good agreement ( $R^2 = 0.89$ ) has been obtained between these two methods (detailed in Hu et al., 2015). The estimated operational accuracy of the SED-sensors is 5.0 mm with a 3.9 mm standard deviation. Additionally, good agreement between the SED-sensors and Sedimentation Erosion Bar measurements has been obtained at site 8 (Galgeschoor) over an 18-months parallel measurement (Belliard et al., 2019).

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### 3.2 Hydrodynamics measurements

Bed-level changes in the intertidal environment are closely related to the local hydrodynamic forcing. We measured hydrodynamic parameters of water level, wave height and tidal current velocity simultaneously with the bed-level measurement at some of our observation sites (Table 1). To measure the water level and wave height, we deployed pressure sensors 0.05 m-0.10 m above the bed in the vicinity of the SED-sensors at some of the sites (see Table 1). At site 1, 3, 4 and 6, OSSI-010-003C pressure sensors (Ocean Sensor Systems, Inc.) were used to measure pressure at a frequency of 5 Hz over a period of 7 mins, with a 15 mins interval. The mean water level is determined by the mean pressure in an interval. Significant wave height (Hs) and peak wave period (Tp) were derived from the dynamic wave pressure signals. The attenuation of pressure signals with water depth was corrected using the standard calculations methods as described in Tucker and Pitt, (2001). The attenuation correction was only applied over the frequency range 0.05-0.4 Hz and the maximum correction factor was set as 5 to avoid over-amplification of high frequency signals (i.e. noise). A detailed description and source of the data-processing routines can be found at <http://neumeier.perso.ch/matlab/waves.html>. At site 2, 5, 9, 10, PDCR 1830 pressure sensors were used. Pressure was recorded at 4 Hz for 4096 readings (~17 minutes) around high tide slack water, as determined by an on-board algorithm on the datalogger (Möller et al., 1999). This typically results in one set of wave parameters per tide. For site 8, both OSSI-010-003C and PDCR 1830 pressure sensors were used. The measuring frequency was 16 Hz for the PDCR sensors and 20 Hz for the OSSI-010-003C sensors. More details on the sensor deployments at site 8 are included in Belliard et al., (2019).

At sites without pressure sensor measurements, the water-level data were obtained by nearby tidal gauge stations operated by Rijkswaterstaat (Dutch department of waterways and public works) or the British Oceanographic Data Centre (BODC). These data were obtained from Terneuzen (for site 2 Zuidgors B and site 5 Paulina) and Eemshaven (for site 7 Uithuizen) with 10 mins interval. For site 9 (Tillingham) and site 10 (Donna Nook), water-level data were obtained at stations Sheerness and Immingham with 15 mins interval. Tidal current velocity was measured by Acoustic Doppler current profilers (ADCPs, Nortek Aquadopp) with a 5 or 10 mins interval at site 1, 3 and 8. Additionally, near-bed 3D current velocities were measured at site 8 using two acoustic Doppler velocimeters (ADV, Nortek vectors). All the hydrodynamic data are included in the current dataset.

### 3.3 Sediment grain size and Chlorophyll-a monitoring

To determine the median bed sediment grain size ( $D_{50}$ ), surface sediment samples (upper 2-3 cm) were collected at most of the sites (see Table 1).  $D_{50}$  of these samples was measured by Malvern laser particle sizer. Chlorophyll-a level in the sediment is an indicator for diatom biomass. Diatoms act as bio-stabilizers on tidal flats by producing Extracellular Polymeric Substances (EPS), and as such can affect sediment bed-level dynamics (Underwood & Paterson 1993; Austen et al., 1999; Andersen et al., 2005). At site 2, 5, 9 and 10, chlorophyll-a samples were collected from the upper 1 cm of the sediment using a small cut-off syringe. The processing procedures that were used to determine chlorophyll-a are described in Willemsen et al. (2018).

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245 Additionally, at site 8, organic matter content was determined for the upper 2 cm of surface sediment samples by Loss on Ignition – LOI.

4 Data description

4.1 Daily bed-level changes with storm events

250 At our study sites, daily bed-level observations were conducted for 9-20 months, which includes conditions with various hydrodynamic forcing. As an example, we show the daily bed-level change and the accompanying wave height at site 4 (Zimmerman) and site 6 (Hellegat) from Feb-2015 to May-2016 (Figure 3). Waves in front (5 m) of the marsh cliffs at the site 4 (Zimmerman) were generally smaller than at site 6 (Hellegat) (Figure 3b vs. 3d). Additionally, at both sites, there was a strong reduction in wave height from the bare tidal flats into the marshes (Figure. 3a vs. 3b and 3c vs. 3d). We observed that the bed-level fluctuation was more apparent on the bare tidal flats than in the marshes. Over the whole observation period, the bed-level fluctuation on the bare tidal flat was in the order of 5 cm at both sites, whereas bed level in the marshes stayed stable (site 6 station 1) or experienced mild accretion (station 1 of site 4).

260 Notably, a number of storm events with high incident waves were captured during our measurements. During the two storm events in Nov 2015, Hs (significant wave height) exceeded 0.6 m on the bare flat stations at both site 4 and site 6 (Figure 3g and 3h), whereas the mean Hs at the most seaward pressure sensors over the whole observation period was 0.104 m and 0.113 m at these two stations, respectively. During the two storm events, sudden erosion of 2-3 cm occurred on the two bare flat stations. However, bed-level changes at the two marsh stations remained small (0.025 m and 0.05 m in site 4 and 6, respectively). Across the ten sites, the most severe short-term erosion was observed at site 1 (Zuidgors A) on 27 and 28 October 2013 during the St. Jude storm (Hu et al., 2015). In that event, severe bed erosion of 10.5 cm depth was captured by our SED-sensor on one of the bare flat stations at site 1 (data not shown).

265 4.2 Seasonal bed-level changes and bio-physical changes

Our observations at most sites were longer than 12 months. Thus, seasonal bed-level changes were captured in our dataset. Examples of seasonal bed-level changes at site 2 (Zuidgors B), site 4 (Zimmerman) and site 6 (Hellegat) show complex spatiotemporal variations (Figure 4). Our data show that all the stations at these three sites have alternating erosion and accretion seasons. There is no consistent seasonal erosion-accretion pattern for all the stations. Winter is a typical season of bed erosion for stations on the bare flat, but not for the stations in marshes.

Spatially, bed-level variations were generally smaller at the landward stations in the marshes, and increased towards the seaward stations at all three sites. We further observed that the most seaward station at the site 4 (Zimmerman) experienced net erosion over an annual timescale, whereas stations at the other two sites were in equilibrium, i.e. the degree of erosion was

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comparable to accretion. Profile elevation data show that marsh cliffs were distinct at site 2 (Zuidgors B) and site 6 (Hellegat), with the cliff height being 0.88 m and 0.35 m, respectively, whereas a cliff was absent at site 4 (Zimmerman) (Figure 4).  
300 Notably, the magnitude of bed-level changes reduced from bare flat stations to the stations on the marsh plateaus at sites with  
305 marsh cliffs (site 2 and 6), whereas there was no clear difference between the bare flat station and the neighbouring marsh  
station at the site without cliff (site 4).

4.3 Surface sediment characteristics

305 Out of six sites with surface sediment grain size measurements, two sites (site 4 and 6) in the Westerschelde had the largest  
median sediment grain size (Figure 5). At these two sites,  $D_{50}$  of the surface sediment was in the range of 66.7-131.8  $\mu\text{m}$ ,  
which was significantly coarser than the rest of the shown sites ( $p=0 < 0.05$ ). Within each site, there was no apparent difference  
in  $D_{50}$  between the marsh and bare flat stations around the marsh edge (50 m seaward and landward to the marsh edge).  
However, there was a gentle trend of coarsening from the landward to the seaward stations on bare flats.

310 Chlorophyll-a levels in surface sediment, a proxy for the diatom biomass and their bio-stabilization effect, were also obtained  
at some of our observation sites (Table 1). The Chlorophyll-a levels at the site 2 (Zuidgors B) showed great temporal variability  
(Figure 6). For all the stations, the Chlorophyll-a levels were generally low in winter (January), but reached their maximum at  
the end of the spring (May). However, there was no clear spatial pattern in the Chlorophyll-a levels across different stations,  
as the marsh stations had similar levels compared to the bare flat stations.

315 5 Data availability and future observations

All data presented in this paper are available from the 4TU.Centre for Research Data (see Hu et al., 2020,  
<https://doi.org/10.4121/uuid:4830dbc2-84b8-46f9-99a3-90f01ab5b923>). The repository includes data as well as instructions  
in readme files. Additionally, we expect that the current repository will expand with additional SED-sensor data from ongoing  
as well as planned future observation programs including mangrove wetlands, e.g. ANCODE project  
320 (<https://www.noc.ac.uk/projects/ancode>).

6 Conclusions

By applying the novel high-resolution SED-sensors, we were able to perform long-term (e.g. a few months to a few years)  
monitoring of the bed elevation changes at daily frequency. Our observations have been carried out at ten sites in three countries  
in Western Europe for a long duration (9-20 months). To our knowledge, the current dataset is the most complete and  
325 comprehensive to date on high-resolution (daily) intertidal bed-level changes.

The SED-sensor data have been proven to be useful in revealing the relations between hydrodynamic forcing and intertidal  
bed-level dynamics (Hu et al., 2018; Belliard et al., 2019) and understanding the spatial variations in bed-level dynamics from

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tidal flats to salt marshes (Willemsen et al., 2018; Baptist et al., 2019). The presented dataset may be of further use to the scientific community for addressing several research questions: In particular, our dataset can be used to provide insights on storm impacts on intertidal morphology and post-storm recovery (Leonardi et al., 2018), as the dataset pinpoints a number of storm events with precise pre- and post-storm bed-level observations, which are otherwise difficult to measure by discontinuous manual methods. Furthermore, our dataset can be used to better understand biogeomorphic interactions in intertidal environments, which are important for marsh persistence, e.g. the control of short-term bed-level changes on marsh seedling establishment (Bouma et al., 2016; Cao et al., 2018), and the influence of marsh vegetation on sediment deposition (Yang et al., 2008; Schwarz et al., 2015; D' Alpaos and Marani, 2016). Lastly, our dataset may support morphodynamic model developments. Due to the lack of relevant data, existing intertidal morphological models rarely deal with daily morphological changes. The presented dataset contains high-resolution data across ten sites with various spatially (marsh vs. bare flat) and temporally (calm vs. stormy) varying conditions, which is valuable for model development and evaluation. In addition to process-based morphodynamic models (e.g. Delft3d, Lesser et al., 2004), this dataset can be of special interest to data-driven models based on machine learning techniques. Recent developments of the latter have shown great potential in resolving complex coastal morphodynamics (see a recent review in Goldstein et al., 2019). Therefore, the present dataset is expected to advance our understanding and prediction of tidal flat evolution and resilience.

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Author contribution

ZH, DV and TB developed the SED-sensor. ZH, PW, BB, DV, ZZ, BO, VV, BE, IM, JB, AB, ST, TB collected the raw data. PW and HW processed the data. ZH, CW and HW prepared the manuscript with contributions from all authors.

Competing interests

The authors declare that they have no conflicts of interest.

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## 380 References

- Andersen, T. J., Pejrup, M. and Nielsen, A. A.: Long-term and high-resolution measurements of bed level changes in a temperate, microtidal coastal lagoon, *Mar. Geol.*, 226(1–2), 115–125, doi:10.1016/j.margeo.2005.09.016, 2006.
- Balke, T., Herman, P. M. J. and Bouma, T. J.: Critical transitions in disturbance-driven ecosystems: Identifying windows of opportunity for recovery, *J. Ecol.*, 102(3), 700–708, doi:10.1111/1365-2745.12241, 2014.
- 385 Baptist, M. J., Gerkema, T., van Prooijen, B. C., van Maren, D. S., van Regteren, M., Schulz, K., Colosimo, I., Vroom, J., van Kessel, T., Grasmeijer, B., Willemsen, P., Elschot, K., de Groot, A. V., Cleveringa, J., van Eekelen, E. M. M., Schuurman, F., de Lange, H. J. and van Puijenbroek, M. E. B.: Beneficial use of dredged sediment to enhance salt marsh development by applying a “Mud Motor,” *Ecol. Eng.*, 127, 312–323, doi:10.1016/j.ecoleng.2018.11.019, 2019.
- Belliard, J.-P., Silinski, A., Meire, D., Kolokythas, G., Levy, Y., Van Braeckel, A., Bouma, T. J. and Temmerman, S.: High-resolution bed level changes in relation to tidal and wave forcing on a narrow fringing macrotidal flat: Bridging intra-  
390 tidal, daily and seasonal sediment dynamics, *Mar. Geol.*, 412, 123–138, doi:10.1016/j.margeo.2019.03.001, 2019.
- Bouma, H., Duiker, J. M. C., De Vries, P. P., Herman, P. M. J. and Wolff, W. J.: Spatial pattern of early recruitment of *Macoma balthica* (L.) and *Cerastoderma edule* (L.) in relation to sediment dynamics on a highly dynamic intertidal sandflat, *J. Sea Res.*, 45(2), 79–93, doi:10.1016/S1385-1101(01)00054-5, 2001.
- 395 Bouma, T. J., van Belzen, J., Balke, T., van Dalen, J., Klaassen, P., Hartog, A. M., Callaghan, D. P., Hu, Z., Stive, M. J. F., Temmerman, S. and Herman, P. M. J.: Short-term mudflat dynamics drive long-term cyclic salt marsh dynamics, *Limnol. Oceanogr.*, 61(6), 2261–2275, doi:10.1002/lno.10374, 2016.
- Callaghan, D. P., Bouma, T. J., Klaassen, P., van der Wal, D., Stive, M. J. F. and Herman, P. M. J.: Hydrodynamic forcing on salt-marsh development: Distinguishing the relative importance of waves and tidal flows, *Estuar. Coast. Shelf Sci.*, 89(1),  
400 73–88, 2010.
- Cao, H., Zhu, Z., Balke, T., Zhang, L. and Bouma, T. J.: Effects of sediment disturbance regimes on *Spartina* seedling establishment: Implications for salt marsh creation and restoration, *Limnol. Oceanogr.*, 63(2), 647–659, doi:10.1002/lno.10657, 2018.
- D’Alpaos, A. and Marani, M.: Reading the signatures of biologic–geomorphic feedbacks in salt-marsh landscapes, *Adv. Water Resour.*, 93, Part B, 265–275, doi:10.1016/j.advwatres.2015.09.004, 2016.
- 405 Dai, Z., Fagherazzi, S., Mei, X. and Gao, J.: Decline in suspended sediment concentration delivered by the Changjiang (Yangtze) River into the East China Sea between 1956 and 2013, *Geomorphology*, 268, 123–132, doi:10.1016/j.geomorph.2016.06.009, 2016.
- Dai, Z., Mei, X., Darby, S. E., Lou, Y. and Li, W.: Fluvial sediment transfer in the Changjiang (Yangtze) river-estuary depositional system, *J. Hydrol.*, 566, 719–734, doi:10.1016/j.jhydrol.2018.09.019, 2018.
- 410

- D'Alpaos, A., Toffolon, M. and Camporeale, C.: Ecogeomorphological feedbacks of water fluxes, sediment transport and vegetation dynamics in rivers and estuaries, *Adv. Water Resour.*, 93, Part B, 151–155, doi:10.1016/j.advwatres.2016.05.019, 2016.
- 415 Duarte, C., Losada, I. J., Hendriks, I., Mazarrasa, I. and Marba, N.: The role of coastal plant communities for climate change mitigation and adaptation, *Nat. Clim. Change*, 3, 961–968, doi:10.1038/nclimate1970, 2013.
- Evans, B. R., Möller, I., Spencer, T. and Smith, G.: Dynamics of salt marsh margins are related to their three-dimensional functional form, *Earth Surf. Process. Landf.*, 44(9), 1816–1827, doi:10.1002/esp.4614, 2019.
- Fagherazzi, S., Kirwan, M. L., Mudd, S. M., Guntenspergen, G. R., Temmerman, S., D'Alpaos, A., Van De Koppel, J., Rybczyk, J. M., Reyes, E., Craft, C. and Clough, J.: Numerical models of salt marsh evolution: Ecological, geomorphic, 420 and climatic factors, *Rev. Geophys.*, 50(1), doi:10.1029/2011RG000359, 2012.
- Folmer, E., Dekinga, A., Holthuijsen, S., Van der Meer, J., Mosk, D., Piersma, T. and van der Veer, H.: Species Distribution Models of Intertidal Benthos : Tools for Assessing the Impact of Physical and Morphological Drivers on Benthos and Birds in the Wadden Sea, NIOZ, Texel. [online] Available from: <http://www.vliz.be/imisdocs/publications/77/307577.pdf>, 2017.
- 425 Friedrichs, C. T.: Tidal Flat Morphodynamics: A Synthesis, in *Treatise on Estuarine and Coastal Science*, edited by E. Wolanski and D. McLusky, pp. 137–170, Academic Press, Waltham. [online] Available from: <http://www.sciencedirect.com/science/article/pii/B9780123747112003077> (Accessed 14 April 2014), 2011.
- Goldstein, E. B., Coco, G. and Plant, N. G.: A review of machine learning applications to coastal sediment transport and morphodynamics, *Earth-Sci. Rev.*, 194, 97–108, doi:10.1016/j.earscirev.2019.04.022, 2019.
- 430 Green, M. O. and Coco, G.: Review of wave-driven sediment resuspension and transport in estuaries, *Rev. Geophys.*, 52(1), 77–117, doi:10.1002/2013RG000437, 2014.
- Hu, Z., Lenting, W., van der Wal, D. and Bouma, T. J.: Continuous monitoring bed-level dynamics on an intertidal flat: Introducing novel, stand-alone high-resolution SED-sensors, *Geomorphology*, 245, 223–230, doi:10.1016/j.geomorph.2015.05.027, 2015.
- 435 Hu, Z., van der Wal, D., Cai, H., van Belzen, J. and Bouma, T. J.: Dynamic equilibrium behaviour observed on two contrasting tidal flats from daily monitoring of bed-level changes, *Geomorphology*, 311, 114–126, doi:10.1016/j.geomorph.2018.03.025, 2018.
- Hu, Z., Willemsen, P. W.J.M., Borsje, B. W., Wang, C., Wang, H., van der Wal, D., Zhu, Z., Oteman, B., Vuik, V., Evans, B., Möller, I., Belliard, J., Van Braeckel, A., Temmerman, S., Bouma, T. J.: Data from: High resolution bed level change and 440 synchronized biophysical data from 10 tidal flats in northwestern Europe, <https://doi.org/10.4121/uuid:4830dbc2-84b8-46f9-99a3-90f01ab5b923>, 2020.
- Hu, Z., Yao, P., van der Wal, D. and Bouma, T. J.: Patterns and drivers of daily bed-level dynamics on two tidal flats with contrasting wave exposure, *Sci. Rep.*, 7, 7088, doi:10.1038/s41598-017-07515-y, 2017.

- Hunt, S., Bryan, K. R., Mullarney, J. C. and Pritchard, M.: Observations of asymmetry in contrasting wave- and tidally-  
445 dominated environments within a mesotidal basin: implications for estuarine morphological evolution, *Earth Surf. Process. Landf.*, 41(15), 2207–2222, doi:10.1002/esp.3985, 2016.
- Knox, J. C., Valley Alluviation in Southwestern Wisconsin, *Ann. Assoc. Am. Geogr.*, 62(3), 401–410, doi:10.1111/j.1467-8306.1972.tb00872.x, 1972.
- Le Hir, P., Roberts, W., Cazaillet, O., Christie, M., Bassoullet, P. and Bacher, C.: Characterization of intertidal flat  
450 hydrodynamics, *Cont. Shelf Res.*, 20(12–13), 1433–1459, 2000.
- Leonardi, N., Camacina, I., Donatelli, C., Ganju, N. K., Plater, A. J., Schuerch, M. and Temmerman, S.: Dynamic interactions between coastal storms and salt marshes: A review, *Geomorphology*, 301, 92–107, doi:10.1016/j.geomorph.2017.11.001, 2018.
- Lesser, G. R., Roelvink, J. A., van Kester, J. A. T. M. and Stelling, G. S.: Development and validation of a three-dimensional  
455 morphological model, *Coast. Eng.*, 51(8–9), 883–915, doi:10.1016/j.coastaleng.2004.07.014, 2004.
- Mariotti, G. and Fagherazzi, S.: A numerical model for the coupled long-term evolution of salt marshes and tidal flats, *J. Geophys. Res.-Earth Surf.*, 115, F01004, doi:10.1029/2009JF001326, 2010.
- McLeod, E., Chmura, G. L., Bouillon, S., Salm, R., Bjork, M., Duarte, C. M., Lovelock, C. E., Schlesinger, W. H. and Silliman, B. R.: A blueprint for blue carbon: toward an improved understanding of the role of vegetated coastal habitats in  
460 sequestering CO<sub>2</sub>, *Front. Ecol. Environ.*, 9(10), 552–560, doi:10.1890/110004, 2011.
- Mcowen, C. J., Weatherdon, L. V., Van Bochove, J.-W., Sullivan, E., Blyth, S., Zockler, C., Stanwell-Smith, D., Kingston, N., Martin, C. S., Spalding, M. and Fletcher, S.: A global map of saltmarshes, *Biodivers. Data J.*, 5, UNSP e11764, doi:10.3897/BDJ.5.e11764, 2017.
- Möller, I., Spencer, T., French, J. R., Leggett, D. J. and Dixon, M.: Wave transformation over salt marshes: A field and  
465 numerical modelling study from north Norfolk, England, *Estuar. Coast. Shelf Sci.*, 49(3), 411–426, doi:10.1006/ecss.1999.0509, 1999.
- Möller, I., Kudella, M., Rupprecht, F., Spencer, T., Paul, M., van Wesenbeeck, B. K., Wolters, G., Jensen, K., Bouma, T. J., Miranda-Lange, M. and Schimmels, S.: Wave attenuation over coastal salt marshes under storm surge conditions, *Nat. Geosci.*, 7(10), 727–731, doi:10.1038/ngeo2251, 2014.
- Nambu, R., Saito, H., Tanaka, Y., Higano, J. and Kuwahara, H.: Wave actions and topography determine the small-scale  
470 spatial distribution of newly settled Asari clams *Ruditapes philippinarum* on a tidal flat, *Estuar. Coast. Shelf Sci.*, 99, 1–9, 2012.
- Schuerch, M., Spencer, T., Temmerman, S., Kirwan, M. L., Wolff, C., Lincke, D., McOwen, C. J., Pickering, M. D., Reef, R., Vafeidis, A. T., Hinkel, J., Nicholls, R. J. and Brown, S.: Future response of global coastal wetlands to sea-level rise,  
475 *Nature*, 561(7722), 231–+, doi:10.1038/s41586-018-0476-5, 2018.

Schwarz, C., Bouma, T. J., Zhang, L. Q., Temmerman, S., Ysebaert, T. and Herman, P. M. J.: Interactions between plant traits and sediment characteristics influencing species establishment and scale-dependent feedbacks in salt marsh ecosystems, *Geomorphology*, 250, 298–307, doi:10.1016/j.geomorph.2015.09.013, 2015.

Shi, B. W., Yang, S. L., Wang, Y. P., Yu, Q. and Li, M. L.: Intratidal erosion and deposition rates inferred from field observations of hydrodynamic and sedimentary processes: A case study of a mudflat-saltmarsh transition at the Yangtze delta front, *Cont. Shelf Res.*, 90, 109–116, doi:10.1016/j.csr.2014.01.019, 2014.

Silinski, A., van, B., Fransen, E., Bouma, T. J., Troch, P., Meire, P. and Temmerman, S.: Quantifying critical conditions for seaward expansion of tidal marshes: A transplantation experiment, *Estuar. Coast. Shelf Sci.*, 169, 227–237, doi:10.1016/j.ecss.2015.12.012, 2016.

Spencer, T., Möller, I., Rupprecht, F., Bouma, T. J., Wesenbeeck, B. K. van, Kudella, M., Paul, M., Jensen, K., Wolters, G., Miranda-Lange, M. and Schimmels, S.: Salt marsh surface survives true-to-scale simulated storm surges, *Earth Surf. Process. Landf.*, 41(4), 543–552, doi:10.1002/esp.3867, 2016.

Temmerman, S. and Kirwan, M. L.: Building land with a rising sea, *Science*, 349(6248), 588–589, doi:10.1126/science.aac8312, 2015.

Temmerman, S., Meire, P., Bouma, T. J., Herman, P. M. J., Ysebaert, T. and De Vriend, H. J.: Ecosystem-based coastal defence in the face of global change, *Nature*, 504(7478), 79–83, doi:10.1038/nature12859, 2013.

Tucker, M. J. and Pitt, E. G.: *Waves in Ocean Engineering*, 1 edition., Elsevier Science, Amsterdam ; New York., 2001.

Van Eerden, M. R., Drent, R. H., Stahl, J. and Bakker, J. P.: Connecting seas: western Palaearctic continental flyway for water birds in the perspective of changing land use and climate, *Glob. Change Biol.*, 11(6), 894–908, doi:10.1111/j.1365-2486.2005.00940.x, 2005.

Vink, A., Steffen, H., Reinhardt, L. and Kaufmann, G.: Holocene relative sea-level change, isostatic subsidence and the radial viscosity structure of the mantle of northwest Europe (Belgium, the Netherlands, Germany, southern North Sea), *Quat. Sci. Rev.*, 26(25–28), 3249–3275, doi:10.1016/j.quascirev.2007.07.014, 2007.

Vuik, V., Jonkman, S. N., Borsje, B. W. and Suzuki, T.: Nature-based flood protection: The efficiency of vegetated foreshores for reducing wave loads on coastal dikes, *Coast. Eng.*, 116, 42–56, doi:10.1016/j.coastaleng.2016.06.001, 2016.

Whitehouse, R. J. S. and Mitchener, H. J.: Observations of the morphodynamic behaviour of an intertidal mudflat at different timescales, *Geol. Soc. Lond. Spec. Publ.*, 139(1), 255–271, doi:10.1144/GSL.SP.1998.139.01.21, 1998.

Willemsen, P. W. J. M., Borsje, B. W., Hulscher, S. J. M. H., Van der Wal, D., Zhu, Z., Oteman, B., Evans, B., Moller, I. and Bouma, T. J.: Quantifying Bed Level Change at the Transition of Tidal Flat and Salt Marsh: Can We Understand the Lateral Location of the Marsh Edge?, *J. Geophys. Res.-Earth Surf.*, 123(10), 2509–2524, doi:10.1029/2018JF004742, 2018.

Yang, S. L., Li, H., Ysebaert, T., Bouma, T. J., Zhang, W. X., Wang, Y. Y., Li, P., Li, M. and Ding, P. X.: Spatial and temporal variations in sediment grain size in tidal wetlands, Yangtze Delta: On the role of physical and biotic controls, *Estuar. Coast. Shelf Sci.*, 77(4), 657–671, 2008.

Zhu, Q., Yang, S. and Ma, Y.: Intra-tidal sedimentary processes associated with combined wave–current action on an exposed, erosional mudflat, southeastern Yangtze River Delta, China, *Mar. Geol.*, 347, 95–106, doi:10.1016/j.margeo.2013.11.005, 2014.

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**Table 1: An overview of the observation sites in the NL, Be and, UK**

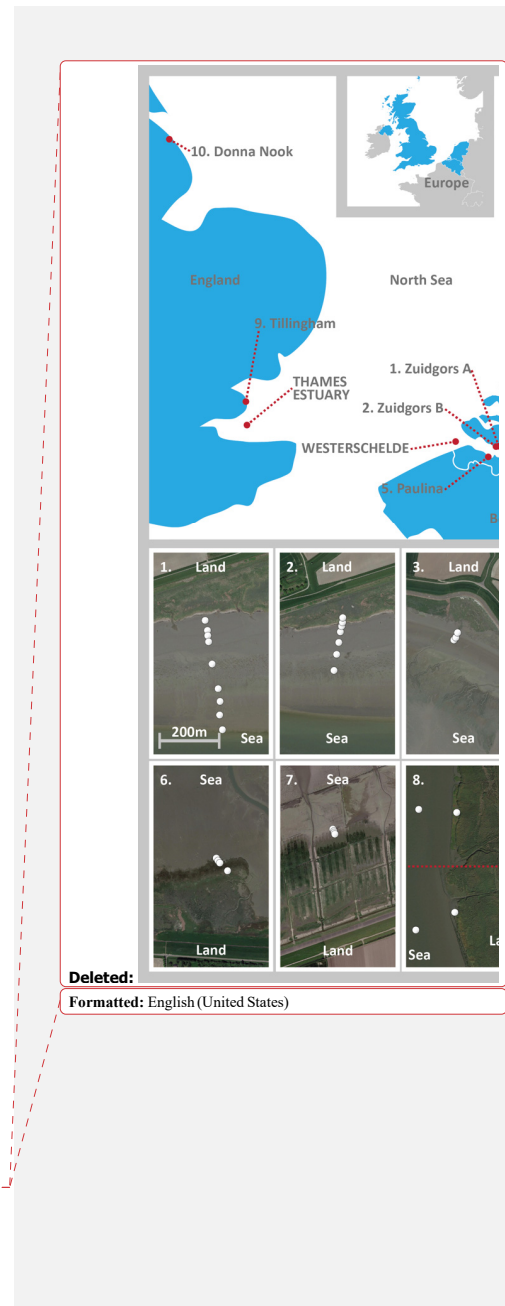
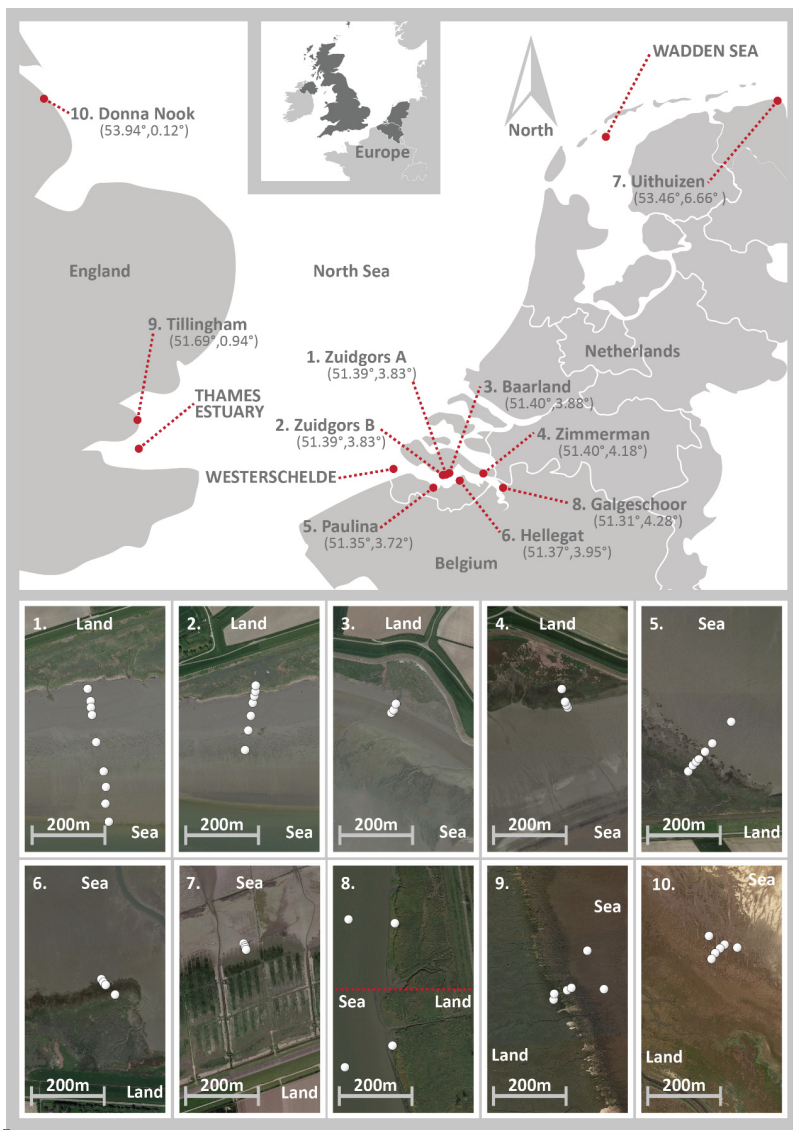
Country	Site name/ estuary	Latitude/longitude	SED sensor time period	D <sub>50</sub> mean and [spatial variations] (µm)	Tidal range (m)	Significant wave height mean and [standard deviation] (cm)	SED-sensor deployments relative to the marsh edge (m) <sup>a</sup>	Vegetation species	Bio-physical measurements <sup>b</sup>
NL	1. Zuidgors A/ Westerschelde	51°23'15.61"N, 3°49'43.46"E	2013.10- 2015.1	72.1 [23.4- 202.1]	4.3	8 [8]	15, 64, 109, 150, 233, 308, 329, 346, 379	<i>Spartina anglica</i> , <i>Salicornia spp</i>	D <sub>50</sub> , Hs, WL, Vel
	2. Zuidgors B/ Westerschelde	51°23'21.95"N, 3°50'7.51"E	2015.9- 2016.9	[23.4-48.8]	4.3	8 [8]	-20, -,5, 5, 25, 60, 100, 155	<i>Spartina anglica</i> , <i>Salicornia spp</i>	D <sub>50</sub> , chl-a
	3. Baarland/ Westerschelde	51°23'49.56"N, 3°52'51.63"E	2013.10- 2015.1	26.8 [12.9- 49.4]	4.1	1 [1]	12, 29, 38	<i>Spartina anglica</i> , <i>Salicornia spp</i>	D <sub>50</sub> , Hs, WL, Vel
	4. Zimmerman/ Westerschelde	51°24'8.05"N, 4°10'32.15"E	2015.1- 2016.5	[66.7-99.5]	4.9	10 [7]	-50, -15, -,5, 5	<i>Spartina anglica</i> , <i>Salicornia spp</i>	D <sub>50</sub> , Hs, WL
	5. Paulina/ Westerschelde	51°20'59.73"N, 3°43'3.37"	2014.12- 2015.8	[27-42.4]	4.1	5 [3] <sup>c</sup>	-42.5, -25.5, - 17.5, -2.5, 22.5, 47.5, 127.5	<i>Spartina anglica</i> , <i>Salicornia spp</i>	D <sub>50</sub> , chl-a
	6. Hellegat/ Westerschelde	51°21'59.33"N, 3°56'44.67"E	2015.1- 2016.5	[113.4- 131.8]	4.2	11 [8]	-50, -15, -,5, 5	<i>Spartina anglica</i> , <i>Salicornia spp</i>	D <sub>50</sub> , Hs, WL
	7. Uithuizen/ Wadden Sea	53°27'24.57"N, 6°39'32.07"E	2015.3- 2016.4	87 <sup>d</sup>	4.0	7 [8]	-15, -10, -,5, 2.5	<i>Salicornia europaea</i> , <i>Puccinellia maritima</i> , <i>Spartina anglica</i> , <i>Phragmites australis</i>	WL
BE	8. Galgeschoor/ Zeeschelde	51°19'6.41" N, 4°16'51.22" E (North transect) 51°18'32.21" N, 4°16'54.82" E (South transect)	2015.10- 2017.5	[28.6- 259.1]	5.2	7 [2]	10, 150 (North transect) 9, 135 (South transect)	<i>Puccinellia maritima</i> , <i>Spartina anglica</i> , <i>Salicornia europaea</i>	D <sub>50</sub> , Hs, WL, Vel, <del>OC</del>
UK	9. Tillingman/ Thames	51°41'40.37"N, 0°56'32.80"E	2015.7- 2016.7	22.0 [5.5- 70.3]	4.8	17 [8]	-5, 7.5, 40, 52.5, 125, 130	<i>Puccinellia maritima</i> , <i>Spartina anglica</i> , <i>Salicornia europaea</i>	D <sub>50</sub> , WL, chl- a, Hs
	10. Donna Nook/ Humber	53°29'28.20"N 0° 6'56.85"E	2015.1- 2015.10	153.8 [33.1- 258.2]	6.9	6 [5]	-2.5, 17.5, 35, 40, 45, 50	<i>Puccinellia maritima</i> , <i>Spartina anglica</i> , <i>Atriplex portulacoides</i>	D <sub>50</sub> , WL, chl- a, Hs

<sup>a</sup> Positive/ negative values mean the deploy locations are in the seaward/ landward direction of the marsh edges. The exact GPS coordinates of the SED sensor deployment are included in the data file.

<sup>b</sup> Bio-physical measurements include: water level (WL), significant wave height (Hs), tidal current velocity (Vel), medium grain size (D<sub>50</sub>), ~~organic carbon in sediment (OC)~~ and chlorophyll-a level (chl-a) of the surface sediment.

<sup>c</sup> ~~These data are~~ from Callaghan et al., (2010).

<sup>d</sup> ~~These data are~~ from Folmer et al., (2017).

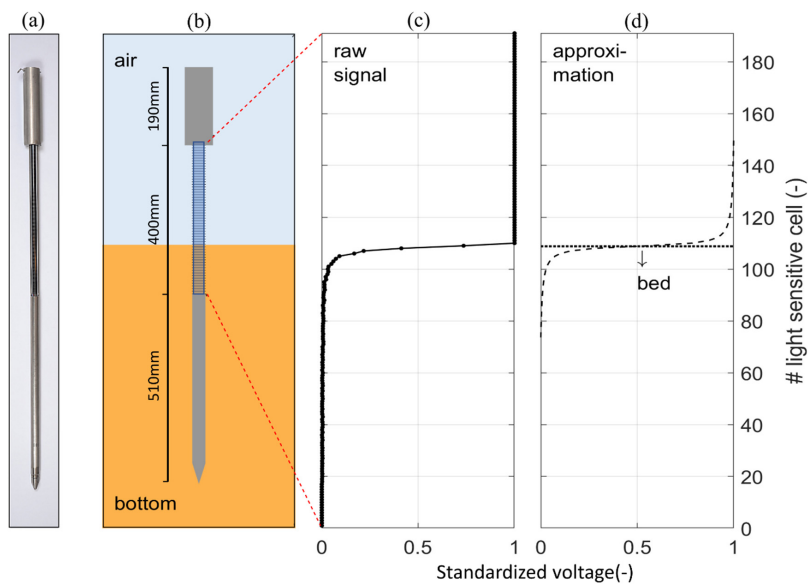


535 **Figure 1.** Locations and an overview of the observation sites in the Westerschelde and Wadden Sea in the Netherlands, Zeeschelde in Belgium, Thames Estuary and Humber Estuary in Britain. The lower 10 panels are the deployments of the SED-sensor stations (white dots) at the observation sites. The GPS coordinates of all the SED-sensor stations are included in the data file. In panel 8, the maps of the north and south measuring transects at the site 8 (Galgeschoor) are bordered by a red dot line. Source of aerial imageries: Google earth.

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**Figure 2.** A photo (a) and schematization (b) of a SED-sensor in operation. The sensor uses an array of light-sensitive cells to determine the position of the bed level, resulting in a transection in the raw voltage output of the array (c). The noise in the raw signal is reduced, and the bed level is obtained by approximating the signal by an autonomous script (d). Details of SED-sensor data processing are included in Willemsen et al. (2018).

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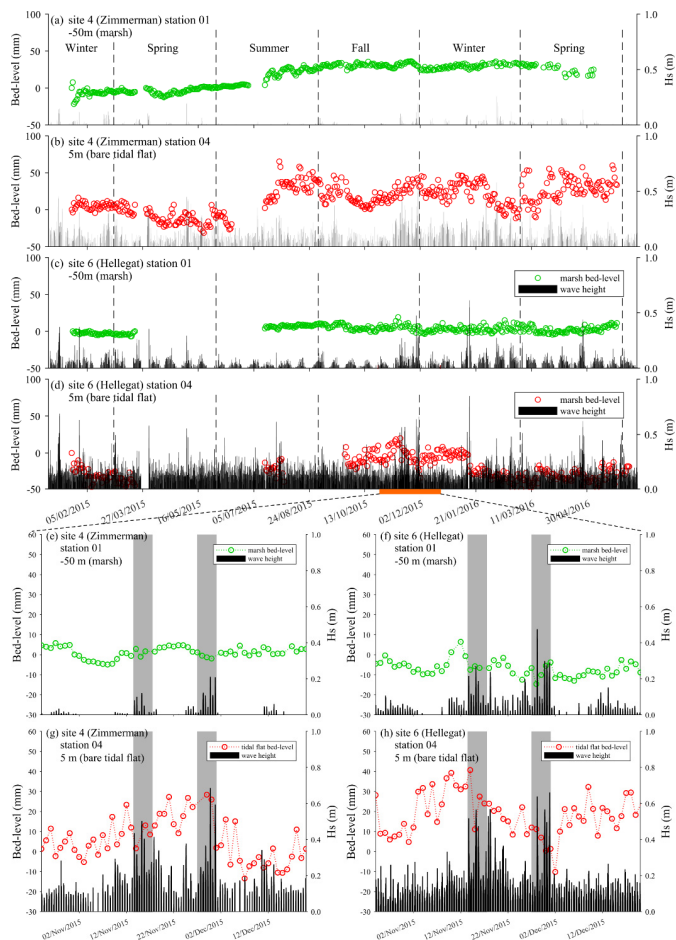


Figure 3. Time series of bed-level change and significant wave height (Hs) at site 4 (Zimmerman, a, b, e, g) and site 6 (Hellegat, c, d, f, h). The top four planes (a-d) are the entire dataset of four measuring stations from these two sites. Stations 4s are on bare tidal flat (5 m seaward of the marsh edge), whereas station 1s are in the marsh (50 m landward of the marsh edge). The gaps in the bed level time series were due to temporary sensor failures. The lower four planes are the enlarged plots of the stormy period in Nov 2015-Dec 2015. The dark grey shaded areas indicate bed-level changes during two storm events (13–17 Nov and 27 Nov–1 Dec in 2015).

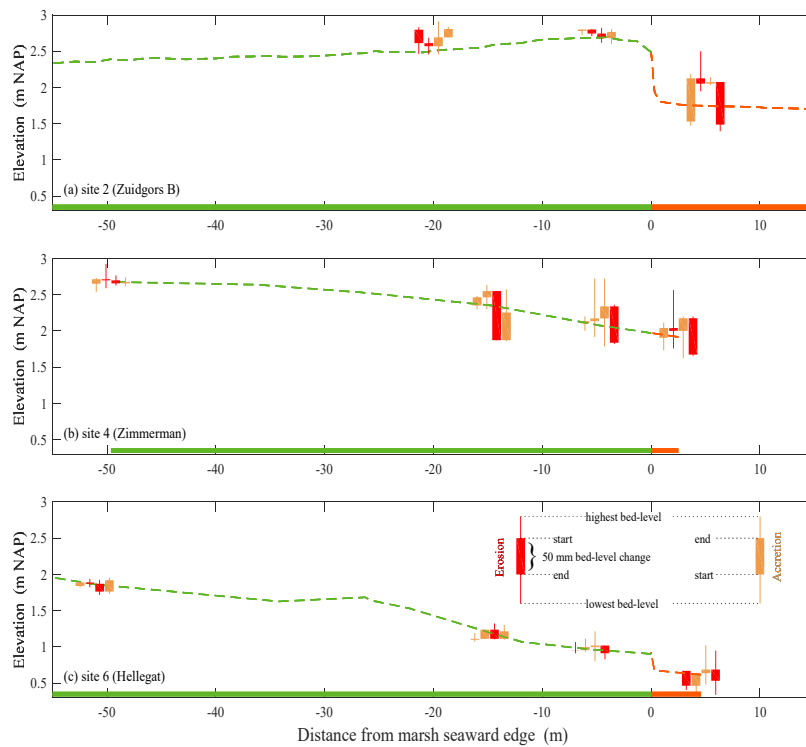
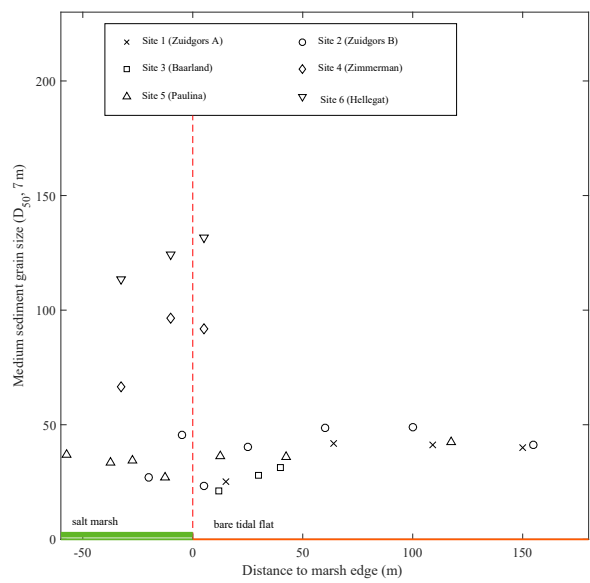


Figure 4. Seasonal **bed-level changes** at (a) site 2 (Zuidgors B), (b) site 4 (Zimmerman) and (c) site 6 (Hellegat) with bathymetry data (dash green line). At each SED-sensor station, the four bars from left to right indicate **bed-level changes** in spring (Mar–May), summer (Jun–Aug), fall (Sep–Nov) and winter (Dec–Feb). The red bars indicate net erosion and the yellow bars indicate net accretion. The observed highest and lowest bed levels in a season are indicated by the high and low tips of the bars.

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580 **Figure 5. Median grain size of surface sediment ( $D_{50}$ ) measured along cross-shore transects of six study sites in the Westerschelde estuary.**

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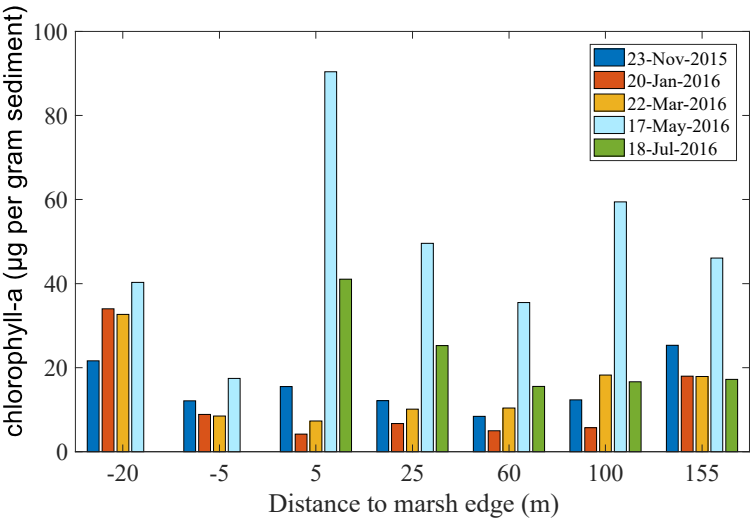


Figure 6. Spatiotemporal variation of chlorophyll-a level in surface sediment (top 1 cm) at site 2 (Zuidgors B)