Modeling the influence of changing storm patterns on the ability of a salt marsh to keep pace with sea level rise

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Abstract

Previous predictions on the ability of coastal salt marshes to adapt to future sea-level rise (SLR) neglect the influence of changing storm activity that is expected in many regions of the world due to climate change. We present a new modeling approach to quantify this influence of changing storm activity on the ability of salt marshes to survive projected SLR. Namely we investigate the separate influence of storm frequency and storm intensity. Applied for a salt marsh on the German island of Sylt, the model is run for a simulation period from 2010 to 2100 for a total of 13 storm scenarios and 48 SLR scenarios. The critical SLR rate for marsh survival, being the maximum rate at which the salt marsh survives until 2100, lies between 19 and 22 mm yr^{-1}. Model results indicate that an increase in storminess can increase the ability of the salt marsh to accrete with sea level rise by up to 3 mm yr^{-1}, if the increase in storminess is triggered by an increase in the number of storm events (storm frequency). Meanwhile, increasing storminess, triggered by an increase in the mean storm strength (storm intensity), is shown to increase the critical SLR rate by up to 1 mm yr^{-1} only. Based on our results, we suggest that the relative importance of storm intensity and storm frequency for marsh survival strongly depends on the erodibility of the sediment on the tidal flats and in the tidal basins adjacent to the salt marsh.

1 Introduction

Coastal salt marshes are ecosystems forming at the interface between the land and the sea [*Bakker et al.*, 2005]. Their ecological, economical, and coastal protection functions are of high value for various bird and invertebrate species as well as for the local coastal communities [*Barbier et al.*, 2011; *Mitsch and Gosselink*, 2000]. Projected SLR is known to threaten the survival of today's salt marshes all over the world [*Craft et al.*, 2008; *Kirwan et al.*, 2010]. Modeling vertical salt marsh accretion in response to sea level rise is therefore conducted using empirical [*Bartholdy et al.*, 2004; *French et al.*, 1995; *Morris et al.*, 2002; *Temmerman et al.*, 2003b] or numerical models [e.g. *D'Alpaos et al.*, 2007; *French*, 1993; *Kirwan and Murray*, 2007; *Krone*, 1987; *Marani et al.*, 2010; *Mariotti and Fagherazzi*, 2010; *Mudd et al.*, 2010; *Temmerman et al.*, 2003a] in order to improve our understanding about the processes connected to salt marsh accretion and to further improve predictions for marsh survival. Results indicate that the survival of salt marshes in the future is crucially dependent on the rate of local SLR, tidal range, and the availability of suspended sediment [*Kirwan et al.*, 2010]. For a given local tidal range and sediment availability, a critical rate for SLR can be estimated by salt marsh modeling [*Kirwan et al.*, 2010; *D'Alpaos et al.*, 2011]. The critical rate of SLR is thereby defined as the maximum SLR rate at which the elevation of the salt marsh is just above the critical elevation for vegetation growth. However, the stochastic character of salt marsh evolution is not included in most of the existing salt marsh models [*Fagherazzi et al.*, 2012], although infrequently occurring storm events are known to significantly contribute to vertical accretion rates of salt marshes [*Bartholdy et al.*, 2004;

Bellucci et al., 2007; *Kolker et al.*, 2009; *Schuerch et al.*, 2012]. This can be explained by the fact that during storms there is an increased sediment supply to the marshes due to deep flooding of the marshes and due to the resuspension of sediment on the tidal flats and in the subtidal areas of the tidal basin. Besides increased vertical accretion rates, lateral erosion of salt marshes may occur during severe storm surges, initiating substantial loss of salt marsh areas on the one hand and an increased sediment supply for vertical marsh accretion on the other hand (*Callaghan et al.* [2010], *Törnqvist et al.* [2009]).

Increasing storminess as a consequence of climate change is expected in many regions of the world [*Emanuel*, 2005; *Webster et al.*, 2005]. While these changes are known to vary regionally, they also depend on whether the frequency of severe storm events or their intensity is analyzed [*Knutson et al.*, 2010]. In the area of the Wadden Sea, one of the largest unbroken systems of intertidal wetlands in the world [*Reise et al.*, 2010] located in the southeastern North Sea, long-term observations showed a significant increase of 3 to 5 mm yr^{-1} of the 90-percentile high water (HW) level during the last decades [*Weisse and Plüß*, 2006]. Regional model projections for the coming century indicate a further increase of extreme storm surges [*Kaas et al.*, 2001; *von Storch and Weisse*, 2008; *Woth et al.*, 2006] triggered by an increase in the number and the intensity of extreme extratropical cyclones [*Knippertz et al.*, 2000; *Leckebusch and Ulbrich*, 2004]. This increase of storm events will be overlaid by SLR that is projected to accelerate during the coming century [*Wahl et al.*, 2010]. The current SLR acceleration, derived from global tide gauge data from 134 years, is estimated to be 0.013 ± 0.006 mm yr^{-2} [*Church and White*, 2006]. Considering that salt marsh accretion would always lag behind sea level rise in case of a continuous SLR acceleration [*Kirwan and Temmerman*, 2009], the effects of storm activity on the ability of salt marshes to adapt to future SLR may be of great importance for the survival of the salt marshes in the Wadden Sea and elsewhere in the world.

This paper introduces a new approach for long-term salt marsh modeling in response to SLR which accounts for the effects of changes in storm patterns. Model simulations are conducted in order to quantitatively assess the influence of different storm scenarios on the ability of the marsh to survive future SLR. For this purpose a wide variety of linear and accelerating SLR scenarios and a total of 13 different storm scenarios are employed. The simulations specifically aim to investigate (i) how increases in future storm frequency and storm intensity affect the marsh accretion within a simulation period of 90 years (up to 2100), (ii) how the critical SLR rate, for which the salt marsh would just survive until 2100, is affected by different combinations of increasing storm frequency and increasing storm intensity, (iii) how different future storm patterns may influence the ability of the marsh to adapt to accelerated SLR, and (iv) if it is possible to define a critical SLR acceleration for marsh survival, following the concept of the critical SLR rate.

2 Methods

2.1 Study area

The salt marsh for which the model is calibrated and validated is located in the southern part of the German island of Sylt (54°47’18’’ N, 008°17’30’’ E). Sylt is an elongated barrier island in the Northern part of the Wadden Sea, stretching about 40 km from North to South (Fig. 1). Barrier-connected salt marshes [*Dijkema*, 1987] are found on the leeward side of the island’s extensive dune system (Fig. 1). The specific salt marsh, which the model is applied for, is characterized by a rather homogeneously sloping marsh platform with a typical vegetation zonation ranging from the pioneer zone to the high marsh zone (Fig. 1). Salt marsh vegetation is found at elevations between 0.7 and 1.5 m above mean sea level (MSL) [*Schuerch et al.*, 2012], while the mean high water (MHW) level is 1 m above MSL [*WSA*, 2007]. The historic evolution and a detailed description of the investigated marsh are given by *Schuerch et al.* [2012]

2.2 Definition of storm parameters

In the field of storm surge research, storminess is usually parameterized as the value of a certain percentile of measured wind speeds, air pressures, or sea levels, and the frequency as the number of events exceeding this percentile [*von Storch and Weisse*, 2008; *Woth et al.*, 2006]. However these definitions of storm intensity and storm frequency are statistically not independent from each other, because both a larger number and a higher intensity of storms result in an increase of a certain percentile value. Therefore the commonly used definitions for describing storm patterns are modified in order to statistically disentangle storm intensity and storm frequency. For our study, we use the approach applied by *Schuerch et al.* [2012], who define storm frequency as the number of events exceeding a predefined storm level, and storm intensity as the mean height of the peak water levels of these events.

2.3 The salt marsh model

A zero-dimensional point model, assuming the marsh to be a uniform platform, is utilized in the context of the study. The model was firstly described by *Krone* [1987] and further modified by *Temmerman et al.* [2003a]. The growth of the marsh platform (ΔE, mm yr^{-1}) is thereby described as the sum of mineral sedimentation (ΔS_{min}), organic sedimentation (ΔS_{org}), and autocompaction (ΔP, negative growth rate) [*Allen*, 1990; *French*, 1993].

$$\Delta E = \Delta S_{\min} + \Delta S_{org} + \Delta P \qquad \text{(equation 1)}$$

Mainly developed for mineralogenic marshes the model assumes the mineral sedimentation to be the main driver for salt marsh accretion, while the organic sedimentation and the autocompaction are kept constant, being derived from data presented by *Schuerch et al.* [2012]. The mineral sedimentation is modeled separately for every tidal cycle (T) as a function of the suspended sediment concentration (SSC, kg m^{-3}) of the water flooding the marsh surface ($C(t_T)$).

$$\frac{dS_{\min}}{dt} = \int_T \frac{\omega_s C(t_T) dt_T}{\rho} \qquad \text{(equation 2)}$$

where S_{min} is the depth of the accreted sediment (m), ω_s is the settling velocity (m s^{-1}), t_T is the time relative to HW (s), and ρ is the dry bulk density of the deposited sediment (kg m^{-3}). To describe the SSC during one tidal cycle ($C(t_T)$), a simple mass balance equation is used, including the inflow of inorganic matter with the flooding water as source term and the settlement of sediment to the marsh surface as sink term:

$$\frac{d[h(t_T) - E] * C(t_T)}{dt_T} = -\omega_s * C(t_T) + C(0) * \frac{dh(t_T)}{dt_T} \qquad \text{(equation 3)}$$

where $h(t_T)$ is the height of the water level during one tidal cycle (m above MSL), E is the marsh elevation relative to MSL (m), and $C(0)$ is the SSC of the incoming water (SSC within the tidal basin) during the flood phase. This term is replaced by $C(t_T)$, during the ebb phase, since no new material is transported onto the marsh from the tidal basin.

As shown by various authors [*Bartholdy and Aagaard*, 2001; *Bartholomä et al.*, 2009; *Fagherazzi and Priestas*, 2010; *Mueller et al.*, 2008], the SSC in a tidal basin is strongly related to meteorological forcing. Strong storms inducing extreme HW levels increase the hydrodynamic energy, including higher current velocities and increased wave heights, which in turn resuspend sediments from the tidal flat and the subtidal areas in the tidal basin and increase the SSC in the tidal basin. *Temmerman et al.* [2003a] found a significant linear relationship between $C(0)$ and the inundation height of the marsh:

$$C(0) = k * (h_{HW} - E) \quad \text{(equation 4)}$$

where h_{HW} is the HW level (m above MSL), which varies between individual tidal inundation events, and k is the linear regression coefficient (kg m^{-4}).

The effects of increased HW levels on the suspended sediment concentrations (*C(0)*) are parameterized by the model parameter *k*, which is a combined parameter for the increased sediment resuspension due to higher current velocities and due to increased wave heights during storm surges. It should, however, be noticed that the linear representation of these complex effects is highly simplified and cannot explain all the observed variations of SSC [*Temmerman et al.*, 2003a].

The temporal variation of the water level during a tidal cycle ($h_{tide}(t_T)$) is modeled using a tidal curve of a fixed shape, which follows the form of the mean tidal curve and is applied for all simulated tidal cycles by adapting the HW level [*Temmerman et al.*, 2003a, modified]:

$$h_{tide}(t_T) = a * \frac{1}{1+\left(\frac{t_T - X_0}{b}\right)^2} + c + h_{HW} - h_{MHW} \qquad \text{(equation 5)}$$

where a, b, c, and X_0 are constants and h_{MHW} is the MHW level (m above MSL). The curve is adjusted to the height of the specific HW level (h_{HW}) of every simulated tidal cycle.

An important assumption made for the model is that no resuspension occurs on the marsh platform due to the presence of a dense vegetation canopy. The vegetation canopy in turn is assumed to be present only if the marsh elevation is above the predefined critical height for vegetation growth. In case the marsh elevation falls below that critical height, the marsh is considered as being drowned and the model is stopped. Also, it must be noted that the employed salt marsh model is a zero-dimensional point model and cannot represent the lateral development of salt marshes, including possible erosion processes at the salt marsh edge during storm surges.

2.4 Estimation of model parameters

The model parameters are estimated for the salt marsh on the island of Sylt (Germany) that was studied intensively by *Schuerch et al.* [2012]. Existing elevation data derived from Light

Detection And Ranging (LIDAR) [*LVermGeoSH*, *2010*] as well as an elevation profile perpendicular to the shoreline are used to derive the current marsh topography and are combined with existing vegetation data [*TMAP*, 2006] in order to derive the critical height for vegetation growth (h_{crit}; table 1).

The model is calibrated and run for one specific site on the marsh located in the low marsh zone at an initial elevation (IE) of 1.34 m above MSL, where a reliable long-term time series of historic marsh elevations is available for calibration and validation purposes (core location S2, Fig. 1) [*Schuerch et al.*, 2012]. Measurements of local bulk densities (ρ) are available for that site and used for the calculation of the local autocompaction (ΔP) [*Schuerch et al.*, 2012], while the organic sedimentation (ΔS_{org}) is calculated by multiplying the mean local organic carbon content (5.5%) from below the rooting zone, located in the upper 10 cm of the marsh, with the measured long-term accretion rates of 2.8 mm yr^{-1} [*Schuerch et al.*, 2012] (table 1).

2.5 Model calibration

The mathematical minimization algorithm 'Trust-region-reflective' [*Coleman et al.*, 1999] is used to optimize the model parameters k (equation 4) and ω_s (equations 2 and 3) by minimizing the model-to-data misfit of the historic marsh elevations. The radiometric measurements for the core location S2 (Fig. 1), spanning from 1953 to 2010 [*Schuerch et al.*, 2012], are therefore split into a calibration period from 1953 to 1983 and a validation period from 1983 to 2007. Driven by the HW levels measured at the harbor of Hoernum during the respective time periods, the model is calibrated utilizing the root mean square error (RMSE) for measuring the performance of the model runs. However, the parameter optimization, based on the historic marsh elevations during the calibration period, does not reveal a unique solution for the two model parameters, but shows a dependency on the starting value of the parameter optimization procedure. Therefore additional SSC measurements are employed to derive an initial estimate for model parameter k, which is then utilized as starting value.

The SSC of the water flooding the investigated salt marsh were therefore measured during a time period of 22 days from 16 February until 10 March 2011. Water samples were taken from different depths at a maximum of three different inundation heights during the flooding phase using a siphon sampler [*FISP*, 1961; *Graczyk et al.*, 2000] within the pioneer zone of the salt marsh at an elevation of about 0.7 m (above MSL). The SSC of the water samples were measured using a 'Laser in situ scattering and transmissometry' (Sequoia LISST-100X) in the laboratory and converted to mass concentrations using additional filter measurements [*Sequoia Scientific*, 2010].

From all measured tidal cycles, the first measurement is assumed to be an approximation for the initial suspended sediment concentration ($C(0)$), whereas this value in combination with the average inundation height is used to estimate the starting value of the model parameter k for the mathematical minimization algorithm 'Trust-region-reflective'. Since no value for the model parameter ω_s could be derived from the measured SSC, the starting value is chosen to be 1E-4 m s^{-1}, as reported by *Temmerman et al.* [2003a]. Further details about the procedure of the parameter optimization are given in appendix 1.

Employing the historic HW levels at the harbor of Hoernum for the model validation runs [*Wahl et al.*, 2011] the performance of the model is evaluated during the validation period 1983-2007. Model outputs are therefore compared to the historic marsh elevations derived from the radiometric measurements performed at the study site [*Schuerch et al.*, 2012]. The root mean square error (RMSE) is thereby used as a quantitative measure for the performance of the model.

2.6 Long-term modeling approach

In contrast to *Temmerman et al.* [2003a] who used a statistical probability function to simulate the heights of the HW levels over time, we develop a continuous water level function allowing the user to investigate how specific scenarios for SLR and changes in storm frequency and storm intensity influence the marsh accretion and its ability to adapt to future SLR. This continuous time series of modeled water levels serves as input for the salt marsh accretion model (equation 3), which in turn is applied to all inundation events flooding the marsh platform. The marsh elevation is thereby updated after every inundation event. The model is run for a total of 624 scenarios, including 30 linear and 18 accelerating SLR scenarios, while each of these scenarios is run for 13 different storm scenarios in order to investigate how different storm patterns affect the accretion rates and the ability of the marsh to survive the 90-year simulation period (2010-2100).

2.7 The water level function

For the simulation of future water levels, a new water level function is developed aiming at (i) simulating storm water levels independent of tides, (ii) enabling the user to manipulate storm frequency and storm intensity independently, (iii) creating storm water levels that follow the statistical distribution of the reference period (1999-2009), and (iv) reproducing the stochastic character of storm events. It is important to note that the water level function does not aim to predict future water levels, since this would require the incorporation of complex climate-ocean modeling and is beyond the scope of this study.

The ten-year tide gauge dataset from 1999 to 2009 with a temporal resolution of 6 minutes is used as a reference dataset to modify the parameters storm frequency and storm intensity. For every ten-year period of the simulation, the reference dataset is modified according to the user input regarding the changes of storm frequency and storm intensity and is appended to the previous ten-year simulation period. All changes of storm patterns are performed on the residuals, defined as the difference between the observed water levels and the predicted astronomical tide. These residuals are assumed to be triggered by meteorological forcing [*Boon*, 2004]. In the region of the German Bight, we assume that positive residuals (i.e. observed water levels are higher than the predicted ones) are triggered by strong westerly winds, while negative residuals (i.e. observed water levels are lower than the predicted ones) originate from strong easterly winds [*Müller-Navarra and Giese*, 1999]. The modeled water level ($h(t)$) is therefore described as follows:

$$h(t) = h_0(t) + h_{tide}(t) + h_{wind}(t) \qquad \text{(equation 6)}$$

where $h_0(t)$ is the mean sea level (MSL), possibly changing through time (t, days) due to SLR, $h_{tide}(t)$ is the water level fluctuations due to the astronomical tide (m above MSL), and $h_{wind}(t)$ is the wind-induced residual water level (m above MSL).

2.7.1 Tide analysis and tide prediction

Harmonic tide analysis [*Boon,* 2004] is employed to (i) assess the harmonic constants (amplitude and phase) of the eight tidal constituents with the highest amplitudes for the reference dataset (M2, S2, N2, μ2, O1, K1, 2MN2, M4), (ii) calculate the residual water levels, and (iii) perform tide predictions for the simulation period [*Boon*, 2004]. A linear interpolation algorithm between every HW and LW is implemented for smoothing the resulting residual water levels, which are assumed to represent the wind-forcing and are therefore defined as the baseline dataset for all modifications of storm frequency and storm intensity within the water level function.

2.7.2 Modeling changes of storm patterns

Modifications of storm patterns within the water level function are implemented by changing the parameters storm frequency and storm intensity. These parameters can be modified by the user for every 10-year period within a simulation. Storm frequency and storm intensity, derived from the baseline dataset, are defined as the baseline values. All changes in storm intensity and storm frequency are given as relative changes (in percent) to these baseline values and shall always be positive.

Besides these input parameters, the definition of a storm level is crucial for the application of the water level function. The storm level for the purpose of this study is defined as the height of the residual water level (relative to MSL) above which it is considered as a storm water level. Storm water levels in turn are only considered as a storm, if they exceed the storm level for a minimum time period (minimum storm duration).

An increase in storm frequency, in the context of the water level function, is implemented as an increase in the number of storms during the respective 10-year period. Given the user input, the number of additional storms to be created is calculated based on the number of storms during the baseline period. A synthetic storm is created at a random time, when the residual water level is calm (between -0.2 and +0.2 m (MSL)). The heights and the durations of the synthetic storms follow the statistical distribution of the storm heights (Fig. 2a) and the storm durations (Fig. 2b) within the baseline dataset. The synthetic storm, parameterized as a parabolic curve is added to the original water levels.

Increases in storm intensities are parameterized as an increase of the mean height of the peak water levels that are classified as storms. Based on the user input for increasing storm intensities, the mean storm heights are increased, while their statistical distribution follows the distribution of the baseline dataset (Fig. 2a). For a detailed description of how increasing storm frequencies and storm intensities are implemented, see appendices 2 and 3.

Given the stochastic character of the water level function, a statistical evaluation with regard to the cumulative distribution of the modeled storm heights (two-sample Kolmogorov-Smirnoff (K-S-) test) and the mean storm heights (two-sample T-test) is performed for every modeled 10-year period, before using the newly created dataset for model simulations. The level of significance for both statistical tests is set to 5% (table 1). If the modified water level time series does not pass both statistical tests, the water level function is rerun.

2.8 Storm scenarios

Trends for the development of storm surges are usually analyzed on percentiles of continuous water level measurements [e.g. *Woth et al.*, 2006]. Depending on the study objectives, higher or lower percentiles are employed for the analysis of storm patterns. *Woth et al.* [2006], for example, have modeled the future storm patterns of extreme storm surges along the North Sea coast, using the 99.5-percentile of all water levels measured during the winter months (DJF), thereby including the most severe one or two storms per year. For the purpose of this study we utilize the 96-percentile since this corresponds to a residual water level of about 1 m, which is chosen as the storm level (SL) for the present model application.

Three scenarios for increases of the general storminess are parameterized by an increase of the 96-percentile of all water levels measured during the winter months (DJF). The numbers for the three scenarios are derived from modeling results presented by *Woth et al.* [2006]. Calculating the 96-percentile water levels from these modeling results reveals an increase of the 96-percentile by 0.04, 0.08, and 0.12 m between 1999-2009 and 2091-2100. These values were therefore defined to be the low, moderate, and high storm scenarios respectively (table 2). For a detailed description of the derivation of the storm scenarios, see appendix 4.

Performing a Monte-Carlo simulation using the water level function and employing different values for increases in storm intensity and storm frequency, each of the three increase scenarios for the 96-percentile is reproduced by the following four different combinations of increasing storm intensity and storm frequency (table 2):

1) Increase of the 96-percentile is only triggered by an increase in storm frequency (frequency only: freq_only).
2) Increase of the 96-percentile is only triggered by an increase in storm intensity (intensity only: int_only).

3) Increase of the 96 percentile is mainly triggered by an increase in storm frequency (frequency dominated: freq_dom).
4) Increase of the 96-percentile is mainly triggered by an increase in storm intensity (intensity dominated: int_dom).

Including the zero-scenario (no increase in storm frequency and no increase in storm intensity), a total of 13 storm scenarios is produced (table 2).

It should be considered that the relative influence of storm intensity on the 96-percentile is 6.12 times higher than the influence of the storm frequency. This means that a 10% increase of storm intensity increases the 96-percentile 6.12 times more than a 10% increase in storm frequency and is the reason why the increase in storm frequency for the 'int_dom'-scenario is larger than the increase in storm intensity (table 2).

2.9 Sea level rise scenarios

48 different SLR scenarios are employed for the presented model application in order to assess the critical SLR rate and the "critical SRES-scenario" for marsh survival under conditions of changing storm patterns. For investigating the critical SLR rate, a series of linear SLR scenarios with rates ranging from 1 to 30 mm yr^{-1} is used. The maximum SLR rate at which the final marsh elevation is just higher than the critical height for vegetation growth after the simulation period of 90 years is considered as the critical SLR rate. For investigating the "critical SRES-scenario" 18 exponential SLR curves presented by *Vermeer and Rahmstorf* [2009] are employed. For each SRES-scenario, the lower boundary, the model average, and the upper boundary are considered as distinct SLR-scenarios (table 3). A 2nd degree polynomial is fit through each of the scenarios in order to derive a constant acceleration, besides the averaged SLR rate (table 3).

3 Results

3.1 Model calibration and validation

The calculation of historic marsh elevations is described in detail by *Schuerch et al.* [2012]. SSC measurements for water samples collected during a total of six tidal cycles in February 2011 are used to derive the starting value for the minimization algorithm 'Trust-region-reflective' employed to calibrate the model parameters k and ω_s. The measured SSC of these samples range from 18 to 52 mg l^{-1}, averaging 34 mg l^{-1}. During the course of the tidal inundation events in February the SSC is observed to continuously decrease, thus confirming the model assumption of no resuspension on the marsh platform. Analyzing the first SSC measurements during each of the six tidal cycles results in concentrations ranging from 34 mg l^{-1} to 52 mg l^{-1}, averaging 41 mg l^{-1}. Meanwhile, the average inundation height during the measured inundation events is 0.33 m. Considering that this inundation height closely corresponds to the MHW level at the study site (1 m above MSL), we conclude that the resulting k-value of 0.125 can be used as an initial approximation for the model parameter k and as a starting value for the mathematical minimization procedure.

Utilizing the historic marsh elevations from 1953 to 1983 as well as the marsh characteristics presented in table 1, the calibration of the model parameters k and ω_s results in values of 0.1062 kg m^{-4} and 6.98E-05 m s^{-1} respectively. The performance of the model during the calibration process is assessed for both the marsh elevations from 1953 to 1983 (Fig. 3) as well as for the SSC measurements. The RMSE of the modeled marsh elevations (compared to the ^{210}Pb-derived marsh elevations) is 0.0064 m, while the RMSE of the modeled SSC (compared to the measured data) is 0.0184 kg m^{-3}.

For the calibration period (1953-1983), the mean and the maximum SSC (occurring at the highest tide during that time period) are calculated in order to obtain the storm-related resuspension simulated by the model. The average SSC of all tidal cycles inundating the salt marsh during the calibration period is 0.0336 g l^{-1}, whereas the maximum SSC is 0.2997 g l^{-1}.

The calibrated model is able to reproduce the measured ^{210}Pb data during the validation period between 1983 and 2007 (Fig. 3). The associated RMSE is 0.009 m, which corresponds to 32.1% of the measurement's standard deviation (0.028 m) and allows for the conclusion that the model is able to sufficiently reproduce the measured accretion patterns.

3.2 Influence of storms on accretion rates

In order to assess the separate influence of storm frequency and storm intensity on marsh accretion, sensitivity analyses are carried out for a 10-year period (2010-2020) for the different storm scenarios neglecting any influence of SLR. The calibrated model with the input parameters as shown in table 1 is used for these runs. Starting from the baseline scenario, the storm frequency is increased in 6-percent steps up to the maximum storm frequency of 216%, while the increase of storm intensity is kept zero. The sensitivity runs for the storm intensity are conducted in one-percent steps ranging from zero to 36%, while keeping the storm frequency at zero percent.

The modeled accretion rate for the baseline scenario is about 3.5 mm yr^{-1}. Increasing storm frequencies result in considerably higher accretion rate, reaching a maximum of about 5.8 mm yr^{-1} for a 216%-increase in storm frequency (Fig. 4). The marsh accretion thereby seems to follow a linear relationship with storm frequency, indicating increasing accretion rates by about 0.010 mm yr^{-1} for one percentage increase in storm frequency (R^2=0.95; Fig. 4). A similar linear relationship can be observed for increasing storm intensities, showing an increase of marsh accretion rates by about 0.032 mm yr^{-1} for one percentage increase in storm intensity (R^2=0.90; Fig. 4).

Taking into account that storm intensity is 6.12 times more effective in increasing the 96-percentile, the storm frequency is 1.94 times more effective in increasing marsh accretion rates as the storm intensity (Fig. 4). For example an 215.71% increase in storm frequency results in an increase of the 96-percentile by 0.12 m, while an increase in storm intensity of only 35.25% reveals the same increase of the 96-percentile (table 2). Meanwhile, the storm-related accretion rate for a 215.71% increase in storm frequency is 2.25 mm yr^{-1}, while the storm-related accretion rate for a 35.25% increase in storm intensity is only 1.16 mm yr^{-1}.

3.3 Critical sea level rise rates

Critical SLR rates, assessed from linear the SLR experiments (see section 2.9), are found to lie between 19 mm yr^{-1} and 22 mm yr^{-1}. Increasing storminess is generally found to increase marsh accretion (Fig. 4), thereby increasing the critical SLR rate by up to 3 mm yr^{-1} (Fig. 5). However, this effect strongly depends on the simulated storm patterns. An increase in storm frequency seems to be the main driver for increasing the critical SLR rate, while an increase in storm intensity shows a considerably weaker influence on the critical SLR rate.

The SLR critical rate for the baseline scenarios (i.e. no increase in storminess) is found to be 19 mm yr^{-1}. An increase in storm intensity for the low, moderate, and high storm scenarios shows an increase of the critical rate by 1 mm yr^{-1} (Fig. 5). The same pattern is found for the intensity dominated storm scenario (Fig. 5). If the increase in storminess is predominantly triggered by an increase in storm frequency, the critical rate is also increased by 1 mm yr^{-1} for the low and moderate storm scenario, while the high storm scenario shows an increase of the critical rate by 2 mm yr^{-1} (Fig. 5). The most efficient storm scenario, however, is if an increase in storminess is triggered by an increase in storm frequency only. In this case the highest storm scenario results in a critical SLR rate of 22 mm yr^{-1}, which is 3 mm yr^{-1} (or 14%) higher than the baseline scenario (Fig. 5).

3.4 Critical accelerating sea level rise scenarios

18 different accelerating SLR scenarios [*Vermeer and Rahmstorf*, 2009] are run in combination with 13 different storm scenarios. For a low increase in storminess the average accretion rate for all SLR scenarios increases by 3.1% (±1.3%) compared to the scenario with no increase in storminess. For a moderate increase in storminess, accretion rate increases by 5.6% (±1.6%), while for a high increase in storminess, accretion rate increases by 8.1% (±2.0%).

The 18 accelerating SLR scenarios used for this study differ regarding their averaged SLR rate and their acceleration. Model results indicate that for all scenarios with a mean SLR rate below 16 mm yr^{-1} and an acceleration of less than 0.22 mm yr^{-2}, the salt marsh is able to survive during the simulation period of 90 years. Namely these scenarios are the following: B1 (low, medium, high), B2 (low, medium, high), A1T (low, medium), A1B (low, medium), A2 (low, medium), A1FI (low) (Fig. 6).

Within this group of SLR scenarios the marsh elevations at the end of the 90-year simulation period vary between 5 and 34 cm above the critical height for vegetation growth. The SLR scenario A1FI (medium), a scenario with a high acceleration (0.29 mm yr^{-2}), and a mean rate of only 15 mm yr^{-1} appears to be the 'critical SLR-scenario' for the baseline storm scenario (i.e., no increase in storminess) (Fig. 6). Marsh elevations at the end of the simulation period are only about 0.9 cm above the critical height for vegetation growth. However, for the critical SLR scenario A1FI (medium) an increase in storminess could increase the mean accretion rates up to about 1 mm yr^{-1} and therefore increase the ability of the marsh to withstand higher and faster SLR scenarios.

Similarly to the model simulations, discussed earlier, it is generally observed that an increase in storm frequency is most efficient in increasing the ability of a marsh to survive higher SLR scenarios. A low increase in storminess solely triggered by an increase in storm frequency already enables the marsh to survive the scenarios A1T (high), A1B (high), and the second highest SLR scenario A2 (high). In contrast, even a high increase in storminess only triggered by an increase in storm intensity cannot sufficiently increase marsh accretion rates to survive the A1B (high) and A2 (high) scenario (Fig. 6). The general pattern found in the model simulations is that a stronger increase in storm frequency results in a better ability of the marsh to survive exponential SLR scenarios.

3.5 Variability and reliability of model outputs

The stochastic character of the water level function, namely the randomly created storm heights (as described in the sections 2.7.2) result in differences of the model output, even if all input parameters are kept constant. Setting the level of significance for the statistical tests to 5% considerably decreases the introduced variability, although it remains unknown how large the variability is regarding the modeled marsh elevations. In order to estimate the variability and the reliability of the modeled marsh elevations, the critical SRES scenario A1FI (medium) is run ten times for each of the 13 storm scenarios.

For the simulated 90-year period, the baseline scenario (no increase in storminess) clearly results in the lowest accretion of all storm scenarios (Fig. 7). The resulting average final marsh elevation of the ten model runs is 2.067 m in the year 2100. This is about 8.3 cm lower than the highest modeled final marsh elevation (highest scenario for increase in storm frequency only). Being about 7 mm above the critical height for vegetation growth on average and associated with a standard deviation of 0.7 mm it is confirmed that the final marsh elevation for the baseline scenario is significantly higher than the critical height for vegetation growth (Fig. 7). Generally it can be seen that for all three scenarios of increased storminess, the scenario in which only the storm frequency is increased results in the highest values for marsh accretion, followed by the “frequency dominated”, the “intensity dominated”, and the “intensity only” scenarios (Fig. 7).

Analyzing the variability of the model outputs shows that the variations of marsh elevations assessed for each storm scenario range from 2 mm (baseline) to 10 mm (freq_only, high). For each of the storm scenarios, the variability of the model outputs compared to the overall accretion is between 0.3 and 1.2%. The mean relative uncertainty is about 0.7%. Higher relative uncertainties are found in model runs resulting in higher accretion rates. However the simulated accretion rates/marsh elevations for the different storm patterns within one storm scenario are significantly different from each other (Fig. 7), thus allowing a clear interpretation of the effects of the different storm scenarios on marsh survival.

3.6 Sensitivity analysis of model parameters

Sensitivity runs for the model parameters k and ω_s are performed for the baseline scenario (i.e. no increase in storminess) during a 10-year simulation period from 2010 to 2020 for k-values ranging from 0.1 to 0.15 kg m^{-4}, while keeping the settling velocity constant (ω_s $=1.25*10^{-4}$ m s^{-1}). Values between $1*10^{-4}$ and $1.5*10^{-4}$ m s^{-1} are tested for the settling velocity, while the parameter k is kept constant at 0.125 kg m^{-4}.

In accordance with *Temmerman et al.* [2004a], our results indicate that variations of k have a larger influence on marsh accretion than variations of ω_s. During the 10-year simulation period, a 50% increase of k results in an increase of marsh accretion by 16.6 mm (43.6%), while a 50% increase of ω_s increases the marsh elevation by 3.5 mm (7.8%) only.

4 Discussion

4.1 Critical sea level rise rates

The determination of a critical SLR rate for salt marshes has been subject to various field and modeling studies throughout the past decades [*Bartholdy et al.*, 2010; *French*, 2006; *French*, 1993; *Kirwan et al.*, 2010; *van Wijnen and Bakker*, 2001]. Generally there are two different approaches of defining the critical SLR rate. The first is to define the critical SLR rate as the rate at which marsh accretion equals the SLR rate. For the Dutch part of the Wadden Sea, a critical rate of 5 mm yr^{-1} has been suggested [*Dijkema*, 1997], while for the Danish part of the Wadden Sea, *Bartholdy et al.* [2010] suggested a considerably lower critical SLR rate between 0.5 and 1 mm yr^{-1}. However, the alternative approach for assessing the critical SLR rate is to define it as the maximum rate at which a salt marsh just survives for a given period of time [*Kirwan et al.*, 2010]. Many modeling studies thereby concentrate on the time period of the 21st century, since this is the characteristic time frame for which climate and SLR scenarios are usually available [*Meehl et al.*, 2007; *Vermeer and Rahmstorf*, 2009]. An early modeling experiment, conducted on a macrotidal salt marsh in the eastern part of the UK revealed a critical rate of 15 mm yr^{-1} [*French*, 1993]. In contrast, *Bartholdy et al.* [2010] have reported a critical rate of only 4-6 mm yr^{-1} for a microtidal salt marsh in the Danish Wadden Sea.

The critical SLR rates for the investigated salt marsh on the island of Sylt reveal values between 19 and 22 mm yr^{-1}. These seem to be relatively high, compared to the above mentioned values. However, *Kirwan et al.* [2010] suggested the critical rate to be a function of SSC and of tidal range in the tidal basin. While *Kirwan et al.* [2010] present critical SLR rates for tidal ranges of 1, 3, and 5 m, our results, based on a tidal range of 2 m indicate a critical SLR rate of 19 mm yr^{-1} (for the baseline scenario) with a measured sediment supply of 34 mg l^{-1}. Interpolating the critical SLR rates for different sediment supply values reveals that our critical SLR rate is located in the middle between the 1 and the 3 m regression line, presented by *Kirwan et al.* [2010] (Fig. 8). The relationship drawn from our results also compares very well with the critical SLR rates, presented by *D'Alpaos et al.* [2011] (Fig. 8). Taking into account that the actual rate of SLR is about 3.7 (±0.8) mm yr^{-1} [*Wahl et al.*, 2011], we conclude that our salt marsh is presently not in danger to be drowned (Fig. 8).

Investigating the results for the different storm patterns indicates that the maximum increase scenario for storm frequency elevates the critical rate by about 3 mm yr^{-1} and therefore increases the ability of a marsh to adapt the future SLR. In contrast, the effect of increasing storm intensities is considerably weaker, increasing the critical rate by a maximum of 1 mm yr^{-1}. This result can be explained by the fact that inundation frequency has been identified as one of the major driving factors for salt marsh accretion [*Bellucci et al.*, 2007; *Morris et al.*, 2002; *van Wijnen and Bakker*, 2001]. We assume that the relative importance of storm frequency and storm intensity generally depends on how much more sediment is brought into suspension with increasing storm heights. Within the present model, this process is described as a linear relationship between SSC and the inundation height, whereas the model parameter *k* can be interpreted as a measure for the availability of erodible fine grained material in the tidal area being controlled by the erodibility of the tidal flats and the subtidal areas in the tidal basin and the wave exposure of investigated study area. However, it appears that even the most extreme scenarios for storm intensities do not increase the sediment supply on the marsh sufficiently to have a comparable effect on marsh accretion and the critical SLR rate as an increase in storm frequency. Given a rather coarse grain size on the sandy tidal flats adjacent to the investigated salt marsh we suspect that the erodibility of the sediment and the model parameter *k* are lower when the fraction of fine grained sediments is higher. This behavior is probably the reason for the weak influence of the storm intensity on marsh accretion rates. Also, it should be considered that a change in the exposure of the study site to increased wave activity could enhance sediment resuspension on the tidal flats and therefore increase the *k*-value.

4.2 Critical accelerating sea level rise scenarios

It is generally shown that the modeled salt marsh is likely to survive most of the investigated exponential SLR scenarios. Similar to previous studies [*French*, 1993; *Kirwan et al.*, 2010], conducted in other study areas, we conclude that only the highest projections for accelerated

SLR are likely to endanger the survival of the investigated salt marsh. Considering the baseline storm scenario, SLR scenarios with an average rate of more than 16 mm yr^{-1} and an acceleration of more than 0.22 mm yr^{-2} are shown to result in drowning of the salt marsh within the coming 90 years. The critical accelerating SLR scenario for the 90-year simulation period is shown to be the A1FI (medium) scenario resulting in a marsh elevation only a few millimeters above the critical height for vegetation growth. Although the average rate of this scenario is relatively low (15 mm yr^{-1}), the quick acceleration (0.28 mm yr^{-2}) additionally stresses the salt marsh system. In contrast, the B2 (high) scenario, showing the same average rate, but a much lower acceleration (0.2 mm yr^{-2}) results in a final marsh elevation of about 4.1 cm higher than for the A1FI (medium) scenario. A further indication for the importance of the acceleration term is given by the comparison of the critical rates derived from the linear experiments with the averaged rates of the critical accelerating SLR scenarios. We show that the critical rate of SLR with no acceleration is about 4 mm yr^{-1} higher than the averaged SLR rate of the critical SRES-scenario.

Analyzing the model results for the accelerating SLR scenarios regarding changes of storm patterns with respect to marsh survival reveals similar results as presented for the linear experiments. Increasing storminess is generally shown to increase the ability of the marsh to survive more extreme SLR scenarios, although this effect is more pronounced for higher storm frequencies than for storm intensities. While all accelerating SLR scenarios with an average SLR rate of 16 mm yr^{-1} or more are drowned for the baseline scenario, changes in storm patterns are shown to have an influence on the ability of the marsh to survive higher SLR scenarios. However even the highest scenarios for increasing storm frequencies are shown to result in drowning of the investigated salt marsh, if the highest and fastest SLR scenario (A1FI (high)) is applied.

Even if the salt marsh is found to survive most of the SLR scenarios presented by *Vermeer and Rahmstorf* [2009] for the period 2010-2100, it should be noted that the marsh elevation is continuously decreasing for all accelerating SLR scenarios, indicating that the marsh might not reach an equilibrium state and may ultimately be drowned in the longer term future beyond 2100. Nevertheless, we should emphasize that the SLR scenarios presented by *Vermeer and Rahmstorf* [2009] are high compared to the IPCC scenarios [*Meehl et al.*, 2007]. Comparing the differences between the scenarios presented by *Vermeer and Rahmstorf* [2009] and the scenarios presented by the IPCC [*Meehl et al.*, 2007] with the development of the marsh elevation during the performed model runs, it seems likely that the modeled salt marsh would survive all IPCC scenarios. However, as shown in earlier studies, any continuous acceleration of SLR may result in lower marsh elevations, because sedimentation rates lag behind accelerating rates of SLR by 20-30 years [*French*, 1993; *Kirwan and Temmerman*, 2009].

4.3 Temporal and spatial implications

Sensitivity analyses show that the model outputs are highly sensitive to model parameter k, which is a measure of the availability of erodible fine grained material in the tidal area. Outputs are, however, less sensitive to model parameter ω_s. As suggested by recent empirical field studies [e.g. *Shi et al.*, 2011], we therefore conclude that the resuspension of sediment on the tidal flats and in the subtidal areas of the tidal basin are important processes that need to be considered when modeling salt marsh accretion. Saying this, it should also be mentioned that the k-value is not only controlled by the resuspension of sediment on the adjacent tidal flats and the subtidal areas of the tidal basin, but also by the erosion of the marsh edge, possibly initiating lateral marsh loss during severe storm surges. Depending on the local hydrodynamic conditions and the sediment characteristics, severe storm surges could result in lateral erosion, thereby reducing the area of the salt marsh and at the same time increasing the sediment supply for vertical marsh accretion [*Callaghan et al.*, 2010]. Considering the zero-dimensional character of our model, we cannot conclude on the net sediment addition for the whole marsh, but only on the effect of storm events on vertical accretion rates for the parts of marsh that are not affected by lateral erosion [*Törnqvist et al.*, 2007].

For our study site, these vertical accretion rates are shown to be affected by increasing storm intensities to a limited extent only. However, a higher erodibility of the tidal flat and the subtidal areas in the tidal basin adjacent to the salt marsh (resulting in a higher *k*-value) could increase the influence of storm intensity and the ability of the marsh to adapt to future SLR, since the sediment supply for the salt marsh would increase. As it was shown by *Temmerman et al.* [2004b], the model parameter *k* may be subject to high spatial variability. Comparing our *k*-value (0.1062) with *k*-values for various study sites along the Scheldt estuary (in The Netherlands and Belgium), we find that the *k*-value for our study site is higher than the *k*-values found towards the mouth of the Scheldt estuary, but lower than the *k*-values found in the freshwater part of the estuary [*Temmerman et al.*, 2004b].

Such spatial variability may be controlled by the prevailing hydrodynamic conditions and by the sediment characteristics. Tidal and wind-driven currents as well as wave activity are thereby considered as the most important hydrodynamic controls, whereas the erodibility of the sediment is the most important sediment property. Erodibility of the tidal flat sediments was shown to strongly vary on different temporal and spatial scales [*Lanuru*, 2004] and seems to be controlled by parameters such as grain size, elevation of the tidal flats, exposure of the study site to wave action [*Shi et al.*, 2011], and the presence of benthic organisms [*Andersen et al.*, 2010; *Mitchener and Torfs*, 1996]. Due to seasonal and long-term variations of all those parameters, it could be necessary to vary the model parameter *k* with time in order to further improve the modeling of salt marsh accretion [*Andersen et al.*, 2011].

However, in contrast to the weak influence of storm intensities on salt marsh accretion, increasing storm frequencies are shown to significantly enhance salt marsh accretion and the ability of the marsh to keep pace with SLR. Given the fact that storm frequency is a parameter which is highly variable in time and closely linked to changes of the tidal range [*Andersen et al.*, 2011; *Töppe and Führböter*, 1994], we conclude that analyzing the potential of marshes in a specific area to survive projected SLR, requires to include temporal variations of the tidal range, triggered by changing storm frequencies. This effect may be especially relevant for study sites with a low tidal range, while it may be less important for study sites with a high tidal range.

5 Conclusions

Given that coastal salt marshes are highly sensitive to projected accelerating rates of SLR, we investigated the ability of these marshes to survive future SLR accounting for the influence of changing storm patterns. The developed model proved to be able to reproduce the measured historic marsh elevations and was in accordance with previous modeling studies with regard to the critical SLR rates for marsh survival. Simulation runs using various scenarios of SLR and storm patterns for the simulation period from 2010 to 2100 highlighted that increasing storminess has the potential to increase the ability of a marsh to adapt to SLR, when assuming that lateral erosion processes are negligible. Increases in storm frequency appeared to be more important than increases in storm intensity in doing so.

A relatively low erodibility of the sediment on the tidal flat adjacent to the study site is suspected to be the main reason for the weak influence of storm intensity on salt marsh accretion. The erodibility on the tidal flats in turn is known to be subject to strong spatial and temporal variability, suggesting that the influence of storm intensity may increase or decrease in other areas or as a consequence of temporal changes of the sediment characteristics.

Storm frequency on the other hand was shown to have the potential to considerably increase the ability of a marsh to adapt to future SLR. Taking into account that the storm frequency strongly influences the local tidal range, this finding is in accordance with previous modeling studies, but further suggests that the tidal range cannot be parameterized as a constant parameter, when modeling the response of salt marshes to future SLR.

The presented modeling approach was shown to be able to address some of the open questions regarding the influence of climate change on salt marsh accretion and has shown that for a better understanding of the temporal and spatial variations of salt marsh accretion, we need to further account for the sediment dynamics within the tidal basins into the salt marsh accretion models.

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References

Allen, J. R. L. (1990), Salt-marsh growth and stratification: A numerical model with special reference to the Severn Estuary, southwest Britain, *Mar. Geol., 95(2)*, 77-96, doi:10.1016/0025-3227(90)90042-I.

Andersen, T. J., M. Lanuru, C. van Bernem, M. Pejrup, and R. Riethmueller (2010), Erodibility of a mixed mudflat dominated by microphytobenthos and Cerastodermaedule, East Frisian Wadden Sea, Germany, *Estuar. Coast. Shelf S., 87(2)*, 197-206, doi:10.1016/j.ecss.2009.10.014.

Andersen, T. J., and M. Pejrup (2001), Suspended sediment transport on a temperate, microtidal mudflat, the Danish Wadden Sea, *Mar. Geol., 173(1-4)*, 69-85, doi:10.1016/S0025-3227(00)00164-X.

Andersen, T. J., S. Svinth, and M. Pejrup (2011), Temporal variation of accumulation rates on a natural salt marsh in the 20th century - The impact of sea level rise and increased inundation frequency, *Mar. Geol., 279(1-4)*, 178-187, doi:10.1016/j.margeo.2010.10.025.

Bakker, J. P., J. Bunje, K. Dijkema, J. Frikke, N. Hecker, B. Kers, P. Körber, J. Kohlus, and M. Stock (2005), Salt marshes, in *Wadden Sea Quality Status Report 2004, Wadden Sea Ecosystem, No. 19*, edited by K. Essink et al., pp. 163-179, Trilateral Monitoring and Assessment Group, Common Wadden Sea Secretariat, Wilhelmshaven, Germany.

Barbier, E. B., S. D. Hacker, C. Kennedy, E. W. Koch, A. C. Stier, and B. R. Silliman (2011), The value of estuarine and coastal ecosystem services, *Ecol. Monogr., 81(2)*, 169-193, doi:10.1890/10-1510.1.

Bartholdy, A. T., J. Bartholdy, and A. Kroon (2010), Salt marsh stability and patterns of sedimentation across a backbarrier platform, *Mar. Geol., 278(1-4)*, 31-42, doi:10.1016/j.margeo.2010.09.001.

Bartholdy, J., and T. Aagaard (2001), Storm surge effects on a back-barrier tidal flat of the Danish Wadden Sea, *Geo.-Mar. Lett., 20(3)*, 133-141, doi:10.1007/s003670000048.

Bartholdy, J., C. Christiansen, and H. Kunzendorf (2004), Long term variations in backbarrier salt marsh deposition on the Skallingen peninsula - the Danish Wadden Sea, *Mar. Geol., 203(1-2)*, 1-21, doi:10.1016/S0025-3227(03)00337-2.

Bartholomä, A., A. Kubicki, T. Badewien, and B. Flemming (2009), Suspended sediment transport in the German Wadden Sea - seasonal variations and extreme events, *Ocean. Dynam., 59(2)*, 213-225, doi:10.1007/s10236-009-0193-6.

Bellucci, L. G., M. Frignani, J. K. Cochran, S. Albertazzi, L. Zaggia, G. Cecconi, and H. Hopkins (2007), Pb-210 and Cs-137 as chronometers for salt marsh accretion in the Venice Lagoon - Links to flooding frequency and climate change, *J. Environ. Radioactiv., 97(2-3)*, 85-102, doi:10.1016/j.jenvrad.2007.03.005.

Boon, J. D. (2004), *Secrets of the tide: Tide and tidal current analysis and predictions, storm surges and sea level trends*, Woodhead Publishing Limited, Cambridge.

Callaghan, D. P., T. J. Bouma, P. Klaassen, D. van der Wal, M. J. F. Stive, and P. M. J. Herman (2010), Hydrodynamic forcing on salt-marsh development: Distinguishing the relative importance of waves and tidal flows, *Estuar. Coast. Shelf S.*, *89(1)*, 73-88, doi:10.1016/j.ecss.2010.05.013.

Church, J. A., and N. J. White (2006), A 20th century acceleration in global sea-level rise, *Geophys. Res. Lett., 33(1)*, L01602, doi:10.1029/2005gl024826.

Coleman, T., Branch, M.A., and Grace, A. 1999. *MATLAB Optimization Toolbox User's Guide*. Third edition, Math Works, Natick.

Craft, C., J. Clough, J. Ehman, S. Joye, R. Park, S. Pennings, H. Guo, and M. Machmuller (2008), Forecasting the effects of accelerated sea-level rise on tidal marsh ecosystem services, *Front. Ecol. Environ., 7(2)*, 73-78, doi:10.1890/070219.

D'Alpaos, A., S. Lanzoni, M. Marani, and A. Rinaldo (2007), Landscape evolution in tidal embayments: Modeling the interplay of erosion, sedimentation, and vegetation dynamics, *J. Geophys. Res.-Earth Surf.*, 112(F1), 17, doi:10.1029/2006JF000537.

D'Alpaos, A., M. S. Mudd, and L. Carniello (2011), Dynamic response of marshes to perturbations in suspended sediment concentrations and rates of relative sea level rise, *J. Geophys. Res.-Earth Surf.*, 116(F4), F04020, doi:10.1029/2011jf002093

Dijkema, K. S. (1987), Geography of salt marshes in Europe, *Z. Geomorphol., 31(4)*, 489-499.

Dijkema, K. S. (1997), Impact prognosis for salt marshes from subsidence by gas extraction in the Wadden Sea, *J. Coastal Res., 13(4)*, 1294-1304.

Emanuel, K. (2005), Increasing destructiveness of tropical cyclones over the past 30 years, *Nature, 436(7051)*, 686-688, doi:10.1038/nature03906.

Fagherazzi, S., et al. (2012), Numerical models of salt marsh evolution: Ecological, geomorphic, and climatic factors, *Rev. Geophys., 50(1)*, RG1002, doi:10.1029/2011rg000359.

Fagherazzi, S., and A. M. Priestas (2010), Sediments and water fluxes in a muddy coastline: interplay between waves and tidal channel hydrodynamics, *Earth Surf. Processes, 35(3)*, 284-293, doi:10.1002/esp.1909.

FISP - Federal Interagency Sedimentation Project (1961), The single-stage sampler for suspended sediment. A study of methods used in measurement and analysis sediment loads in streams. *Rep. No. 13*, Government Printing Office, Washington, D.C.

French, J. (2006), Tidal marsh sedimentation and resilience to environmental change: Exploratory modelling of tidal, sea-level and sediment supply forcing in predominantly allochthonous systems, *Mar. Geol., 235(1-4)*, 119-136, doi:10.1016/j.margeo.2006.10.009.

French, J. R. (1993), Numerical simulation of vertical marsh growth and adjustment to accelerated sea-level rise, North Norfolk, U.K., *Earth Surf. Processes, 18(1)*, 63-81, doi:10.1002/esp.3290180105.

French, J. R., T. Spencer, A. L. Murray, and N. S. Arnold (1995), Geostatistical analysis of sediment deposition in two small tidal wetlands, Norfolk, U.K., *J. Coastal Res., 11(2)*, 308-321.

Graczyk, D. J., D. M. Robertson, W. J. Rose, and J. J. Steuer (2000), Comparison of water-quality samples collected by siphon samplers and automatic samplers in Wisconsin, *U.S. Geological Survey Fact Sheet 067–00*, U.S. Geological Survey, Middelton, Wisconsin.

Kaas, E., U. Andersen, R. A. Flather, J. A. Williams, D. L. Blackman , P. Lionello, F. Dalan, E. Elvini, A. Nizzero, P. Malguzzi, A. Pfizenmayer, H. von Storch, D. Dillingh, M. Philippart, J. de Ronde, M. Reistad, K. H. Midtbø, O. Vignes, H. Haakenstad, B.

Hackett, I. Fossum, and L.Sidselrud (2001), Synthesis of the STOWASUS-2100 project, in *Regional storm, wave and surge scenarios for the 2100 century, Final project report ENV4-CT97-0498*, Danish Meteorological Institute, Copenhagen.

Kirwan, M. L. and A. B. Murray (2007), A coupled geomorphic and ecological model of tidal marsh evolution. *Proc. Nat. Acad. Sci. USA, 104(15)*, 6118-6122, doi:10.1073/pnas.0700958104.

Kirwan, M., and S. Temmerman (2009), Coastal marsh response to historical and future sea-level acceleration, *Quarternary Sci. Rev., 28(17-18)*, 1801-1808, doi:10.1016/j.quascirev.2009.02.022.

Kirwan, M. L., G. R. Guntenspergen, A. D'Alpaos, J. T. Morris, S. M. Mudd, and S. Temmerman (2010), Limits on the adaptability of coastal marshes to rising sea level, *Geophys. Res. Lett., 37(23)*, L23401, doi:10.1029/2010gl045489.

Knippertz, P., U. Ulbrich, and P. Speth (2000), Changing cyclones and surface wind speeds over the North Atlantic and Europe in a transient GHG experiment, *Clim. Res., 15(2)*, 109-122, doi:10.3354/cr015109.

Knutson, T. R., J. L. McBride, J. Chan, K. Emanuel, G. Holland, C. Landsea, I. Held, J. P. Kossin, A. K. Srivastava, and M. Sugi (2010), Tropical cyclones and climate change, *Nat. Geosci., 3(3)*, 157-163, doi:10.1038/ngeo779.

Kolker, A. S., S. L. Goodbred Jr, S. Hameed, and J. K. Cochran (2009), High-resolution records of the response of coastal wetland systems to long-term and short-term sea-level variability, *Estuar. Coast. Shelf S., 84(4)*, 493-508, doi:10.1016/j.ecss.2009.06.030.

Krone, R. (1987), A method for simulating historic marsh elevations, paper presented at Coastal Sediments, American Soc. of Civil Engineers, New Orleans, Lousiana.

Lanuru, M. (2004), The spatial and temporal patterns of erodibility of an intertidal flat in the East Frisian Wadden Sea, Germany, GKSS-Forschungszentrum.

Leckebusch, G. C., and U. Ulbrich (2004), On the relationship between cyclones and extreme windstorm events over Europe under climate change, *Global Plant. Change, 44(1-4)*, 181-193, doi:10.1016/j.gloplacha.2004.06.011.

LVermGeoSH - Landesamt für Vermessung und Geoinformation Schlewig-Holstein (2010), Digitale Geländemodelle, in *Produktkatolog*, edited by LVermGeoSH, p. 34, Kiel, Germany.

Marani, M., A. D'Alpaos, S. Lanzoni, L. Carniello, and A. Rinaldo(2010). The importance of being coupled: Stable states and catastrophic shifts in tidal biomorphodynamics. *J. Geophys. Res., 115(F4)*, F04004, doi:10.1029/2009JF001600.

Mariotti, G., and S. Fagherazzi (2010), A numerical model for the coupled long-term evolution of salt marshes and tidal flats, *J. Geophys. Res., 115(F1)*, F01004, doi:10.1029/2009jf001326.

Meehl, G.A., T.F. Stocker, W.D. Collins, P. Friedlingstein, A.T. Gaye, J.M. Gregory, A. Kitoh, R. Knutti, J.M. Murphy, A. Noda, S.C.B. Raper, I.G. Watterson, A.J. Weaver, and Z.-C. Zhao (2007), Global climate projections, in *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, edited by S. Solomon et al. pp. 747-846, Cambridge University Press, Cambridge, UK and New York, USA.

Mitchener, H., and H. Torfs (1996), Erosion of mud/sand mixtures, *Coast. Eng., 29(1-2)*, 1-25, doi:10.1016/S0378-3839(96)00002-6.

Mitsch, W. J., and J. G. Gosselink (2000), The value of wetlands: Importance of scale and landscape setting, *Ecol. Econ, 35(1)*, 25-33, doi:10.1016/S0921-8009(00)00165-8.

Morris, J. T., P. V. Sundareshwar, C. T. Nietch, B. Kjerfve, and D. R. Cahoon (2002), Responses of coastal wetlands to rising sea level, *Ecology, 83(10)*, 2869-2877, doi:10.1890/0012-9658(2002)083[2869:ROCWTR]2.0.CO;2.

Mudd, S. M., A. D'Alpaos, and J. T. Morris (2010), How does vegetation affect sedimentation on tidal marshes? Investigating particle capture and hydrodynamic controls on biologically mediated sedimentation, *J. Geophys. Res, 115(F3)*, F03029, doi:10.1029/2009jf001566.

Mueller, J.-M., R. Riethmueller, and R. Onker (2008), Multiple time scale analysis of suspended sediment concentration in the Wadden Sea, paper presented at Coastal Engineering, World Scientific Publishing Co, Hamburg.

Müller-Navarra, S., and H. Giese (1999), Improvements of an empirical model to forecast wind surge in the German Bight, *Ocean. Dynam., 51(4)*, 385-405, doi:10.1007/bf02764162.

Nakicenovic, N., and R. Swart (Eds.) (2000), *Special Report on Emission Scenarios*, Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK.

Pejrup, M. (1988), Flocculated suspended sediment in a micro-tidal environment, *Sediment. Geol., 57(3-4)*, 249-256, doi:10.1016/0037-0738(88)90032-2.

Pejrup, M., and O. A. Mikkelsen (2010), Factors controlling the field settling velocity of cohesive sediment in estuaries, *Estuar. Coast. Shelf S., 87(2)*, 177-185.

Reise, K., M. Baptist, B. P., N. Dankers, L. Fischer, B. Flemming, A. P. Oost, and C. Smit (2010), The Wadden Sea - A universally outstanding tidal wetland, in *The Wadden Sea 2010*, *Wadden Sea Ecosystem No. 29*, edited by H. Marencic, and de Vlas, J., 7-24 pp, Trilateral Monitoring and Assessment Group, Common Wadden Sea Secretariat (CWSS), Wilhelmshaven, Germany.

Schuerch, M., J. Rapaglia, V. Liebetrau, A. Vafeidis, and K. Reise (2012), Salt marsh accretion and storm tide variation: An example from a barrier island in the North Sea, *Estuar. Coast., 35(2)*, 486-500, doi:10.1007/s12237-011-9461-z.

Sequoia Scientific, Inc. (2010), Converting LISST volume concentrations to mass concentrations, on *http://www.sequoiasci.com/Articles/ArticlePage.aspx?pageid=197*, accessed 9 April 2012, Bellevue, Washington, USA.

Shi, B. W., S. L. Yang, Y. P. Wang, T. J. Bouma, and Q. Zhu (2011), Relating accretion and erosion at an exposed tidal wetland to the bottom shear stress of combined current wave action, *Geomorphology, 138(1)*, 380-389, doi:10.1016/j.geomorph.2011.10.004.

Temmerman, S., G. Govers, P. Meire, and S. Wartel (2003a), Modelling long-term tidal marsh growth under changing tidal conditions and suspended sediment concentrations, Scheldt estuary, Belgium, *Mar. Geol., 193(1-2)*, 151-169, doi:Pii S0025-3227(02)00642-4.

Temmerman, S., G. Govers, P. Meire, and S. Wartel (2004a), Simulating the long-term development of levee-basin topography on tidal marshes, *Geomorphology, 63(1-2)*, 39-55, doi:10.1016/j.geomorph.2004.03.004.

Temmerman, S., G. Govers, S. Wartel, and P. Meire (2003b), Spatial and temporal factors controlling short-term sedimentation in a salt and freshwater tidal marsh, Scheldt estuary, Belgium, SW Netherlands, *Earth Surf. Proc. Land., 28(7)*, 739-755, doi:10.1002/esp.49.

Temmerman, S., G. Govers, S. Wartel, and P. Meire (2004b), Modelling estuarine variations in tidal marsh sedimentation: Response to changing sea level and suspended sediment concentrations, *Mar. Geol., 212(1-4)*, 1-19, doi:10.1016/j.margeo.2004.10.021.

TMAP - The Trilateral Monitoring and Assessment Program (2006), Salt marshes, on *http://www.waddensea-secretariat.org/TMAP/Data-Unit/Data.html,* accessed 20 November 2008, edited by Nationalparkverwaltung Schleswig-Holsteinisches Wattenmeer, Tönning, Germany.

Töppe, A., and A. Führböter (1994), Recent anomalies in mean and high tidal water levels at the German North Sea Coastline, *J. Coastal Res., 10(1)*, 206-209.

Törnqvist, T. E., C. Paola, G. Parker, K. Liu, D. Mohrig, J. M. Holbrook, and R. R. Twilley (2007), Comment on "Wetland sedimentation from hurricanes Katrina and Rita", *Science, 316(*5822), 201, doi:10.1126/science.1136780.

van Wijnen, H. J., and J. P. Bakker (2001), Long-term surface elevation change in salt marshes: A prediction of marsh response to future sea-level rise, *Estuar. Coast. Shelf S., 52(3)*, 381-390, doi:10.1006/ecss.2000.0744.

Vermeer, M., and S. Rahmstorf (2009), Global sea level linked to global temperature, *P. Natl. Acad. Sci. USA, 106(51)*, 21527-21532, doi:10.1073/pnas.0907765106.

von Storch, H., and R. Weisse (2008), Regional storm climate and related marine hazards in the Northeast Atlantic, in *Climate Extremes and Society*, edited by H. F. Diaz, and R. J. Murnane, pp. 54-73, Cambridge University Press, Cambridge.

Wahl, T., J. Jensen, and T. Frank (2010), On analysing sea level rise in the German Bight since 1844, *Nat. Hazard Earth Sys., 10(2)*, 171-179, doi:10.5194/nhess-10-171-2010.

Wahl, T., Jensen, J., Frank, T. and Haigh, I., 2011. Improved estimates of mean sea level changes in the German Bight over the last 166 years. *Ocean Dynam., 61(5)*: 701-715, doi:10.1007/s10236-011-0383-x.

Wang, A., X. Ye, and J. Chen (2010), Observations and analyses of floc size and floc settling velocity in coastal salt marsh of Luoyuan Bay, Fujian Province, China, *Acta Oceanol. Sin., 29(3)*, 116-126, doi:10.1007/s13131-010-0043-x.

Webster, P. J., G. J. Holland, J. A. Curry, and H. R. Chang (2005), Changes in tropical cyclone number, duration, and intensity in a warming environment, *Science, 309(5742)*, 1844-1846, doi:10.1126/science.1116448.

Weisse, R., and A. Plüβ (2006), Storm-related sea level variations along the North Sea coast as simulated by a high-resolution model 1958–2002, *Ocean Dynam., 56(1)*, 16-25, doi:10.1007/s10236-005-0037-y.

Woth, K., R. Weisse, and H. von Storch (2006), Climate change and North Sea storm surge extremes: An ensemble study of storm surge extremes expected in a changed climate projected by four different regional climate models, *Ocean Dynam., 56(1)*, 3-15, doi:10.1007/s10236-005-0024-3.

WSA - Wasser- und Schifffahrtsamt Tönning (2007), Wasserstandsinformationen: Hörnum/Sylt, on *http://www.wsv.de/wsa-toe/service/wasserstandinfo/index.html*, accessed 27 August 2010, edited by WSV – Wasser- und Schifffahrtsverwaltung des Bundes, Bonn, Germany.

Figure captions

Figure 1: The study area is located in the southeastern North Sea (cell 1), in the southern part of the island of Sylt (cell 2). The cores were taken on a transect in three dominant vegetation zones, indicated by points (cell 3). Source: *Schuerch et al.* [2012], Copyright: Springer.

Fig. 2: Histogram of peak residual water levels (left) and storm durations (right) during the baseline period.

Fig. 3: Performance of the model compared to measured historic marsh elevations during the calibration run (1953-1983) and the validation run (1983-2007)

Fig. 4: Marsh accretion rates for different increasing storm frequencies and storm intensities simulated for the baseline period 1999-2009.

Figure 5: Effect of various storm patterns (int_only, int_dom, freq_dom, freq_only; as defined in table 2) on the critical SLR rate in the case of constant rate of SLR.

Figure 6: Final marsh elevations relative to the critical height for vegetation growth after a 90-year simulation period for all accelerating SLR scenarios (as described in table 3) that potentially endanger the survival of the investigated salt marsh and for all storm scenarios (as defined in table 2).

Figure 7: Boxplots of marsh elevations, resulting from ten model runs from 2010 to 2100 for each storm scenario (as defined in table 2) with the exponential SLR scenario A1FI (medium).

Figure 8: Comparison of the critical SLR rate for the baseline scenario with the threshold SLR rates reported by *Kirwan et al.* [2010] and *D'Alpaos et al.* [2011]: The dashed gray lines indicate the threshold SLR rate as a function of SSC and tidal range presented by *Kirwan et al.* [2010]. The dotted gray line indicates the threshold SLR rate as a function of SSC and tidal range presented by *D'Alpaos et al.* [2010] for a tidal range of 2 m. The threshold SLR rate derived for the investigated study site (dot) is utilized to extrapolate the threshold SLR for SSC from zero to 100 mg/L. The current situation of the marsh is indicated as a square (HOE).

Tables

Table 1: Input parameters for the model

	Parameter	**Description**	**Value**	**Source**
Marsh characteristics	dS_{org}	Organic sedimentation rate[a]	0.0002 m yr^{-1}	Derived from data presented by *Schuerch et al.* [2012]
	dP	Compaction rate[b]	0 m yr^{-1}	
	IE	Initial marsh elevation	1.34 m (above MSL)	
	ρ	Dry bulk density	600 kg m^{-3}	
	h_{crit}	Critical height for vegetation growth	0.7 m (above MSL)	
Parameters for mean tidal curve	h_{MHW}	Mean high water level	1.0704 m (above MSL)	Derived from tide gauge data at “Hoernum Hafen” from 1999-2009 using equation 5
	a	Constant	3.7506 (dimensionless)	
	b	Constant	-19447.1 m s	
	X_0	Constant	-1301 s	
	c	Constant	-2.6802 m	
Water level function	SL	Storm water level	1 m	User-defined for the present application
	-	Range for calm weather period	-0.2 m to 0.2 m (MSL)	
	α	Level of significance for	0.05	

[a] Includes all the organic material accreting on the marsh surface (i.e. belowground and aboveground biomass as well as suspended organic particles settling onto the marsh surface).

[b] Natural compaction of the marsh sediments, creating subsidence of the marsh surface.

Table 2: Absolute increase of the 96-percentile and relative increase of the storm frequency and storm intensity for the final simulation period from 2090 to 2100 and for all 13 storm scenarios. All changes are given relative to the baseline period (1999-2009).

Name of scenario	**Increase of 96-percentile (m)**	**Max. increase of storm frequency (%)**	**Max. increase of storm intensity (%)**
Baseline			
zero increase	0	0	0
Low increase in storminess			
freq_only[a]	0.04	71.90	0
int_only[b]	0.04	0	11.75
freq_dom[c]	0.04	35.95	5.87
int_dom[d]	0.04	17.98	8.81
Moderate increase in storminess			
freq_only	0.08	143.81	0
int_only	0.08	0	23.50
freq_dom	0.08	71.90	11.75
int_dom	0.08	35.95	17.62
High increase in storminess			
freq_only	0.12	215.71	0
int_only	0.12	0	35.25
freq_dom	0.12	107.86	17.62
int_dom	0.12	53.93	26.43

[a] Storm scenario in which an increase of 96-percentile water level is triggered by an increase of the storm frequency only.

[b] Storm scenario in which an increase of 96-percentile water level is triggered by an increase of the storm intensity only.

[c] Storm scenario in which an increase of 96-percentile water level is mainly triggered by an increase of the storm frequency.

[d] Storm scenario in which an increase of 96-percentile water level is mainly triggered by an increase of the storm intensity.

Table 3: SRES scenarios[a] with the respective constant acceleration and the averaged SLR rate between 2010 and 2100.

Scenario	**Scenario abbreviation**	**Acceleration (mm yr^{-2})**	**Mean rate (mm yr^{-1})**
B1 (low)	B1_lo	0.085	8.22
B2 (low)	B2_lo	0.105	9.11
A1T (low)	A1T_lo	0.121	10
A1B (low)	A1B_lo	0.146	10
A2 (low)	A2_lo	0.160	10.11
B1 (medium)	B1_me	0.117	10.67
B2 (medium)	B2_me	0.141	11.78
A1FI (low)	A1F_lo	0.220	11.78
A1T (medium)	A1T_me	0.170	12.89
A1B (medium)	A1B_me	0.200	12.89
A2 (medium)	A2_me	0.212	12.89
B1 (high)	B1_hi	0.167	13.44
B2 (high)	B2_hi	0.203	15
A1FI (medium)	A1F_me	0.286	15
A2 (high)	A2_hi	0.280	16.11
A1B (high)	A1B_hi	0.270	16.22
A1T (high)	A1T_hi	0.241	16.44
A1FI (high)	A1F_hi	0.377	18.78

[a] See *Vermeer and Rahmstorf* [2009].