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ORIGINAL

Effects of the North Atlantic Oscillation and wind waves on salt marsh dynamics in the Danish Wadden Sea: a quantitative model as proof of concept

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Abstract Long-term eustatic sea-level variation has been recognized as a primary factor affecting the hydrological and geomorphic dynamics of salt marshes. However, recent studies suggest that wind waves influenced by atmospheric oscillations also may play an important role in many coastal areas. Although this notion has been conceptually introduced for the Wadden Sea, no modeling attempts have been made yet. As a proof of concept, this study developed a simulation model using the commercially available STELLA® software, based on long-term data on water level and sedimentation collected at a back-barrier marsh on the Skallingen peninsula in Denmark. In the model, the frequency (number year^{-1}) of wind-driven extreme high water level (HWL) events (>130 cm Danish Ordnance Zero) was simulated in terms of the North Atlantic Oscillation (NAO) index. Then, surface accretion (cm year^{-1}) and submergence duration (h year^{-1}) were simulated for the period 1933–2007. The model showed good performances: simulated rates of surface accretion and simulated durations of submergence decreased from 1950 to 1980, the point at which the NAO shifted from its negative to its positive phase, and increased thereafter. Despite continuous increases in surface elevation, increases in simulated submergence duration were apparently due to wind-driven HWL events, which generally increased in frequency after 1980. These findings for the Danish Wadden Sea add to the growing body of evidence that the role of atmospheric oscillations—e.g., the NAO—as drivers of wind-generated water level variations merits more attention in assessing the impact of climate change on coastal marshes.

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Introduction

Scientists have often considered long-term eustatic sea-level variation as a primary factor controlling hydrological and geomorphic processes within salt marshes (see seminal works by, for example, Redfield 1972; Reed 1990, 1995, 2002; and more recent research by Temmerman et al. 2003 for the North Sea; Kirwan and Murray 2008 for the east Pacific; Fagherazzi et al. 2012 for general numerical modeling perspective). Many studies have implicitly or explicitly assumed that a gradual rise in sea level controls the regime of seawater inundation and sediment accretion on marsh platforms. This emphasis on the long-term hydrological processes affecting coastal marshes is understandable, given worldwide concerns about global climate change and melting polar ice (Hegerl and Bindoff 2005).

However, short-term water level variations nested within these longer-term trends also may play an important role in salt marsh dynamics (e.g., Stumpf 1983; Beeftink 1987; Cramer and Hytteborn 1987; Reed 1989; Cahoon 2006; Kim et al. 2011). Variations in atmospheric conditions such as the

North Atlantic Oscillation (NAO) and the El Niño–Southern Oscillation (ENSO) drive meteorologically forced storminess on various ocean surfaces (for ENSO, see Günther et al. 1998; Bromirski et al. 2003; for NAO, see Kolker and Hameed 2007; Vilibić and Šepić 2010). For example, the NAO has been in a predominantly positive phase since the 1980s (Osborn 2004). When the NAO is in its positive phase, westerly gales increase in frequency and strength and cross the eastern Atlantic Ocean on a more northerly track, resulting in an increase in short-term wind tides in the North Sea (Serreze et al. 1997; Deser et al. 2000; Hurrell and Deser 2009).

The hydrological and geomorphic effects of wind tides vary depending on marsh physiography. Wind-driven storm surges commonly cause erosion and loss of terrestrial habitat in exposed beaches and dunes (for general textbook, see Psuty and Ofiara 2002; recent regional examples include Castelle et al. 2008 for the Gold Coast of Queensland, Australia; Fearnley et al. 2009 and Garrison et al. 2012 for the Gulf of Mexico). But sheltered back-barrier marshes experience an increase in the duration and depth of submergence due to sustained onshore wind-driven rises in water levels (e.g., Bartholdy et al. 2004 for a Danish Wadden Sea sector), which occur regardless of lunar tidal forces. Changes in the submergence regime, in turn, are long known to affect rates of surface accretion (see seminal papers by Orson et al. 1985; Stevenson et al. 1986; for a more recent overview, see Fagherazzi et al. 2012).

For the Wadden Sea (southern North Sea), this logic was conceptually introduced by Kim et al. (2011) who investigated long-term vegetation and sedimentary dynamics in a back-barrier marsh of the Skallingen peninsula in Denmark. They found that the Skallingen marsh has experienced water level variations induced by wind events, the frequency and severity of which have augmented noticeably over the past several decades. The implications of wind and storm surges at Skallingen have already been discussed in depth by Aagaard et al. (2007), who focused predominantly on the formation of sand dunes. In a larger regional framework across the North Sea, similar studies involving wind events include Winter et al. (2006), Chang et al. (2007), Kolditz et al. (2012), Schuerch et al. (2012), and Switzer et al. (2012, and other works in that special issue).

In this current study, and as proof of the concept of Kim et al. (2011), a quantitative model was developed to explore the potential influence of wind tides driven by temporary ocean storminess on salt marsh dynamics. Model development is based on long-term data on water level and sedimentation collected at the Skallingen salt marsh. In the model, the frequency (number year^{-1}) of wind-driven high water level (HWL) events (>130 cm Danish Ordnance Zero, DNN) was simulated in terms of the NAO index. Then, surface accretion (cm year^{-1}) and submergence duration (h year^{-1}) were simulated from 1933 to 2007. The results served to evaluate the ability of the model to simulate historic patterns of marsh surface accretion and marsh submergence at the study site, and to help elucidate the processes generating these patterns.

Study site

The study site is a sheltered back-barrier salt marsh on the Skallingen peninsula in southwestern Denmark (Fig. 1). The peninsula exhibits a complex geomorphic zonation, with depositional sequences from the ocean (west) to the back-barrier lagoon (east) representing beach, dune, salt marsh, and tidal flat. The salt marsh sediments commonly comprise 15 % fine sand, 46 % silt, and 39 % clay (Bartholdy 1997). Marsh development began around the beginning of the 20th century on already existing sand flats (Nielsen 1935). The marsh experiences semidiurnal tides with a mean tidal range of 1.6 m, and vegetation formation begins at about 80 cm DNN (Bartholdy et al. 2004). The mean water level was approx. 13.5 cm DNN in the second half of the 20th century, and became slightly over 20 cm DNN after 2000. The average heights of the spring and neap high water levels are about 105 and 72 cm DNN, respectively. Water levels exceeding 80 cm DNN are considered HWL events, that is, events that can cause marsh flooding. The highest astronomical tide (HAT) in the study marsh is estimated as 130 cm DNN (A.T. Bartholdy et al. 2010). HWL events above the HAT are predominantly wind-driven.

Whereas the west-facing beach and foredunes of Skallingen are influenced directly by westerly storms that cause migration or transformation of swash bars and washover fans (Aagaard et al. 1995; Houser and Greenwood 2007), the back-barrier marsh experiences storm effects indirectly via temporary "setups" of the sea surface, during which the marsh can become submerged for up to 24 h (Bartholdy and Aagaard 2001). Bartholdy et al. (2004) found that the duration and magnitude of submergence, as well as the rate of measured sedimentation increased during periods of frequent setups. They also demonstrated that a significant (R^2=0.63, p<0.01) amount of the variation in annual sedimentation rates from 1970 to 1999 could be explained by changes in the NAO index, due to the increased frequency and duration of wind-driven setups as the NAO shifted into a predominantly positive phase in the early 1980s.

Methods

Conceptual and empirical basis of model

A conceptualization of the effect of wind-driven water level variations on salt marsh dynamics is given in Fig. 2. Variations

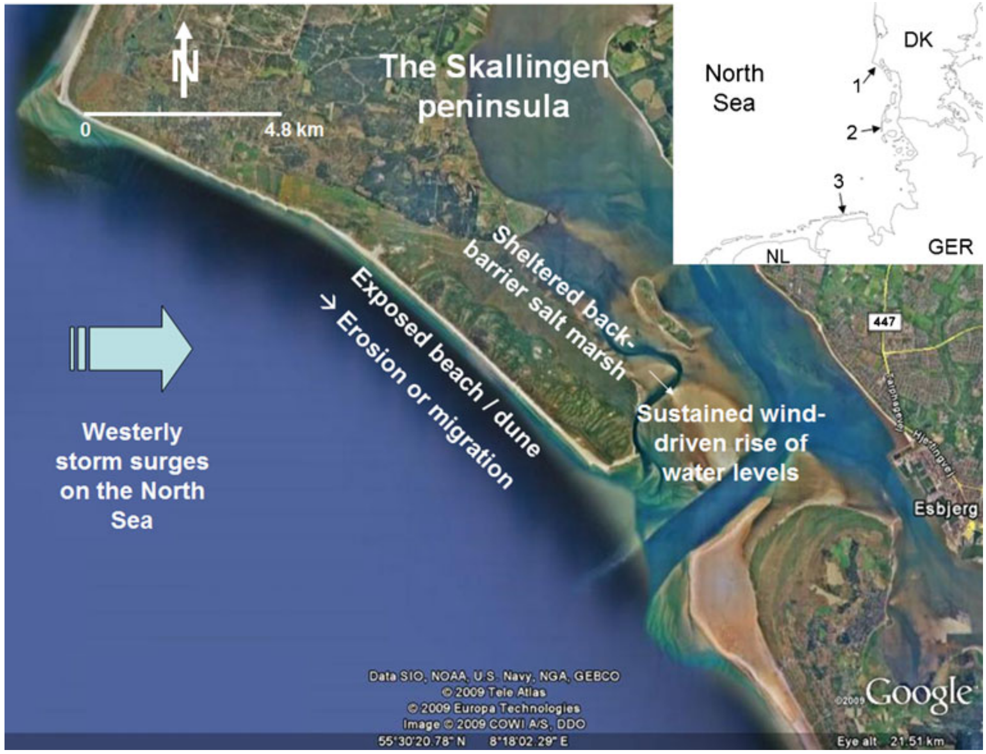

Fig. 1 Study site in a back-barrier salt marsh on the Skallingen peninsula (Denmark): during westerly storm surges and associated wind waves from the North Sea, the exposed sand beach and dune of Skallingen experience erosion and migration of swash bars, whereas the sheltered back-barrier marsh undergoes sustained wind-driven rise of water levels. *Inset* Locations of the present work and some related studies in the Wadden Sea: *1* Skallingen, *2* Sylt (Schuerch et al. 2012), *3* Langeoog (Kolditz et al. 2012)

in atmospheric conditions influence the frequency of wind-driven extreme HWL events, thereby affecting the dynamics of marsh submergence and marsh surface accretion. The positive phase of the NAO is characterized by more pronounced Icelandic low-pressure and Azores high-pressure systems. The ensuing enhancement of storminess in the North Sea entails more frequent extreme HWL events, which is initially accompanied by increases in the frequency and duration of submergence and thereby promotes sedimentation and expansion of the marsh surface. This conceptual framework incorporates a negative feedback mechanism accounting for the fact that the rate of sedimentation can obviously not increase indefinitely: it is basically assumed that, as the surface elevation increases over time, the frequency and duration of HWL events will decrease, as a consequence of which sedimentation rates will also decrease.

The empirical basis of the model consists of (1) the long-term trend in the NAO index (Fig. 3), (2) data from the study site on mean water levels, the frequency of HWL events, and

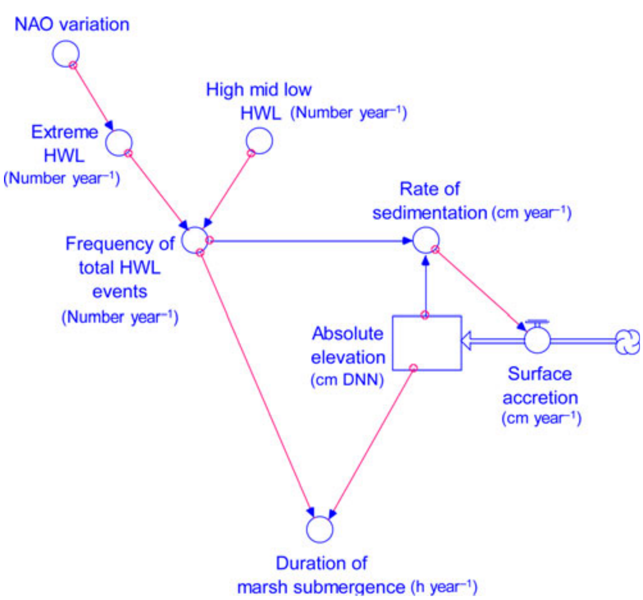

Fig. 2 Conceptualization of the effect of wind-driven water level variations on salt marsh dynamics

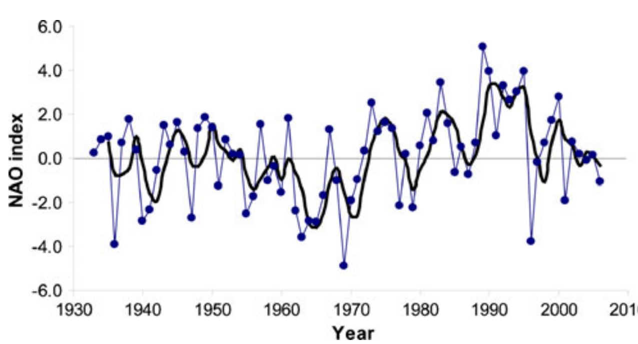

Fig. 3 Annual changes in the North Atlantic Oscillation (NAO) index (*dots*) and 3-year running mean for the period 1933–2007 (for data source, see main text)

marsh surface elevations (Fig. 4), (3) the relationship between the frequency of extreme wind-driven HWL events at the study site and the NAO index (Fig. 5), and (4) the estimated durations of different HWL categories at various surface elevations within the study site (Table 1). The long-term NAO data were acquired from the National Center for Atmospheric Research (http://climatedataguide.ucar.edu/, last accessed 7 January 2013). Mean water level data are available from records of the Danish Meteorological Institute until 1978, and from the harbor authorities of the city of Esbjerg since then. The hourly water level data are relative to DNN. Marsh surface elevations were obtained from Bartholdy et al. (2004) and Bartholdy (2008).

The HWL events were categorized as "low" (80–90 cm DNN), "mid" (90–110 cm DNN), "high" (110–130 cm DNN), and "extreme" (>130 cm DNN; Table 1), based on the general criteria of Coldewey and Erchinger (1992) and the analyses of Bartholdy et al. (2004). The "extreme" category corresponds to wind-driven HWLs that exceed the HAT. The duration of a HWL event in each category was also estimated drawing upon the dataset of Bartholdy and Aagaard (2001), recognizing that different HWL categories would entail flooding of variable duration at a given location.

Quantitative model structure

The model was formulated as a compartment model based on difference equations (Δt=1 year) programmed in STELLA® 7.0.1 (High Performance Systems, Inc., Hanover, NH). For an overview of the model conceptual diagram and code, the reader is referred to the electronic supplementary material available online for this article. The following three subsections describe the empirical relationships among the NAO, the frequency of wind-driven HWL events, rates of marsh surface accretion, and duration of marsh submergence of which the model is comprised.

NAO and frequency of wind-driven HWL events

The NAO data comprise annual values of the index observed from 1933 to 2007 (Fig. 3). The frequency (number year^{-1}) of extreme (wind-driven) HWL events was modeled using the correlation between the frequency of extreme HWL events at the study site (>130 cm DNN, i.e., >HAT) and the NAO index (Fig. 5). Since HWL events ≤HAT at the study site represent the combined effect of ocean storminess and long-term mean sea-level variation, any correlation between these HWL events and the NAO index might have been obscured. Therefore, the observed frequencies (number year^{-1}) of low, mid, and high events and the simulated frequency of extreme HWL events were combined, and these total HWL signatures were used as driving variable to estimate surface accretion. Mean annual frequencies by decade are summarized in

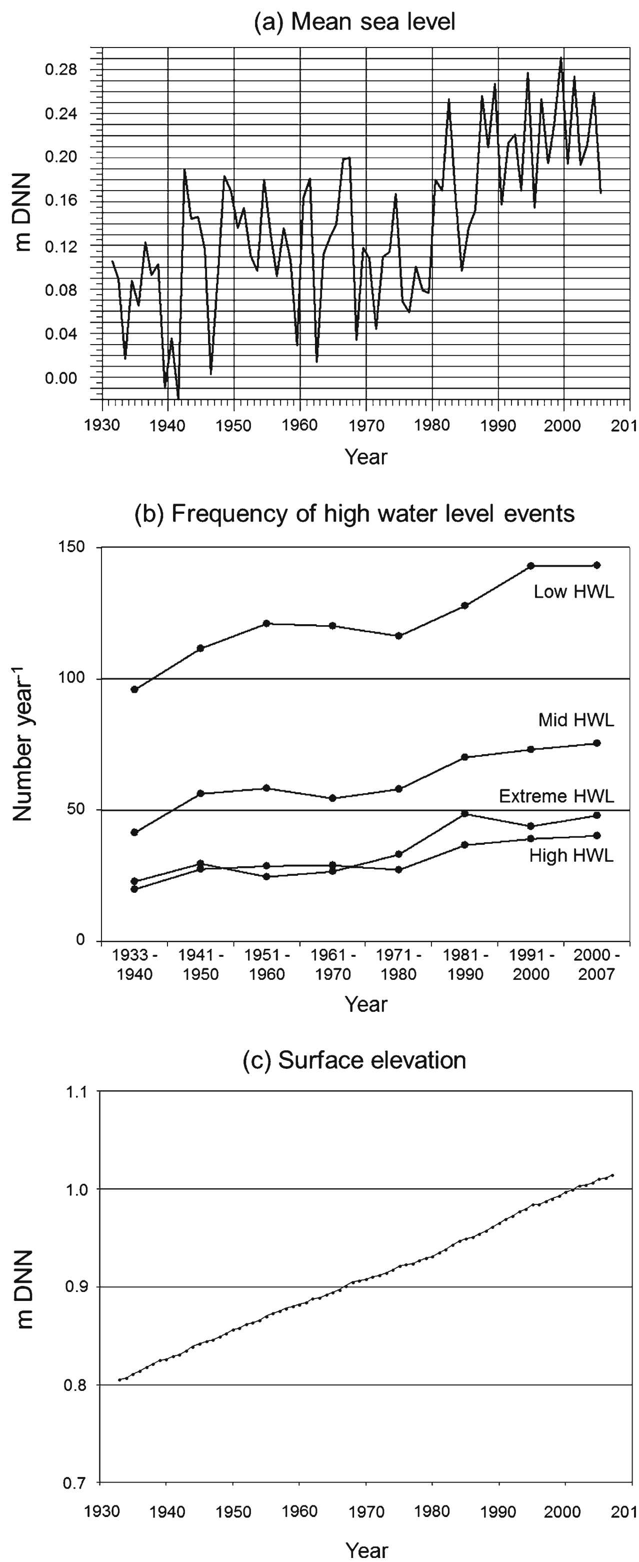

Fig. 4 **a** Mean water levels (m Danish Ordnance Zero, DNN), **b** frequencies (number year^{-1}) of high water level (HWL) events classified as "low" (80–90 cm DNN), "mid" (90–110 cm DNN), "high" (110–130 cm DNN), and "extreme" (>130 cm DNN), and **c** marsh surface elevations (m DNN) modeled at a mean position at the Skallingen salt marsh (Denmark; see Bartholdy et al. 2004; **a**–**c** extracted from Kim et al. 2011; water levels measured by a tidal gauge in Esbjerg (Fig. 1), and corrected for the Skallingen marsh based on Bartholdy et al. 2004)

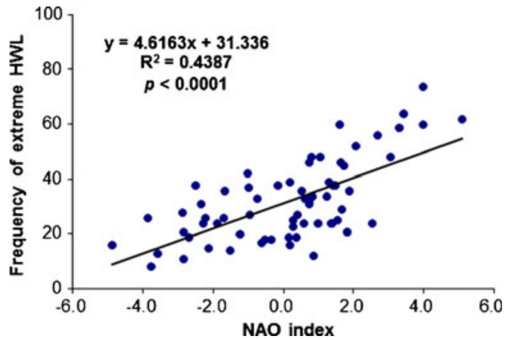

Fig. 5 Correlation between the frequency (number year^{-1}) of extreme (wind-driven) high water level (HWL) events (>130 cm Danish Ordnance Zero, i.e., exceeding the highest astronomical tide) at the Skallingen salt marsh (Denmark) and the North Atlantic Oscillation (NAO) index (for information on water levels, see Fig. 4 caption)

Fig. 4b; HWL events have been a common occurrence each year of the investigated time series, with even extreme HWL events occurring tens of times in some years.

Marsh surface accretion

The rate of marsh surface accretion (A, cm year^{-1}) was modeled by slightly modifying the coefficients of the original equation developed by Bartholdy et al. (2004). They related the average rate of surface accretion (A_{ave}, cm year^{-1}) from 1931 to 1998 to marsh surface elevation (E, cm DNN) at an "intermediate" location within the Skallingen marsh. Later, A.T. Bartholdy et al. (2010) and J. Bartholdy et al. (2010) improved the equation by incorporating an autocompaction effect. Based on this improvement, this current research developed a new equation:

$$A_{ave} = 2 \times 10^{-5} \times E^2 - 0.0076 \times E + 0.777 \quad (1)$$

This is based on a positive correlation between the characteristic concentration of suspended sediments in the flooding water and the frequency of HWL events (A.T. Bartholdy et al. 2010; J. Bartholdy et al. 2010). To account for annual departures from A_{ave} due to annual variations in the frequency of HWL events, A_{ave} was multiplied by the ratio (R_y) of the number of HWL events in a given year (HWL_y) to the average number of HWL events in the period 1931–1998 (HWL_{ave}=237):

$$R_y = HWL_y / HWL_{ave} \quad (2)$$

Table 1 Durations (h) of typical categories of high water level (HWL) events at various marsh surface elevations (cm DNN, Danish Ordnance Zero) at the Skallingen salt marsh (Denmark), based on Bartholdy et al. (2004), and estimated at the high end of the range of each HWL category: "low" (estimated at 90 cm DNN), "mid" (110 cm DNN), "high" (130 cm DNN), and "extreme" (150 cm DNN)

HWL category	Marsh surface elevation				
	77	83	86	89	93
Low	1.3	1.0	0.8	0.4	0.0
Mid	3.7	3.4	3.2	3.0	2.7
High	6.0	5.6	5.4	5.3	5.0
Extreme	7.6	7.3	7.2	7.0	6.8

Duration of marsh submergence

Based on water level records from the central part of Skallingen before, during, and after the storm surge in December 1999 (Bartholdy and Aagaard 2001), a second-degree polynomial regression was generated in the present work to describe the over-marsh part of tides inundating the back-barrier area:

$$h_t = a \times t^2 + b \times t + HWL_m \quad (3)$$

where a and b are constants, HWL_m is mean high water level (m DNN), and h_t is the water level (m DNN) relative to high tide at time t in seconds.

The empirical constants a and b were calibrated as functions of HWL_m:

$$a = -3.5 \times 10^{-9} - \left[4 \times 10^{-9} / (HWL_m - 0.1)^7\right] \quad (4)$$

$$b = -5.595 \times 10^{-6}\, HWL_m + 1.497 \times 10^{-5} \quad (5)$$

These algorithms served to estimate the duration of inundation (h) at various marsh levels for each category of HWL events (Table 1). Multiplying these durations by the corresponding frequency of HWL occurrence enabled calculation of the duration of annual flooding for each HWL category.

Results

Below, results of a simulation representing marsh dynamics at the study site from 1933 to 2007 are presented. The surface elevation was initialized at 80 cm DNN, considered to represent the onset of marsh formation at the study site in the early 1930s (Aagaard et al. 1995; Bartholdy et al. 2004).

Frequency of HWL events

The simulated mean annual frequency of HWL events (243.7 year^{-1}) was similar to the mean calculated for the study site (237.3 year^{-1}) between 1933 and 2007. Simulated annual frequencies increased gradually from 1933 to 1950,

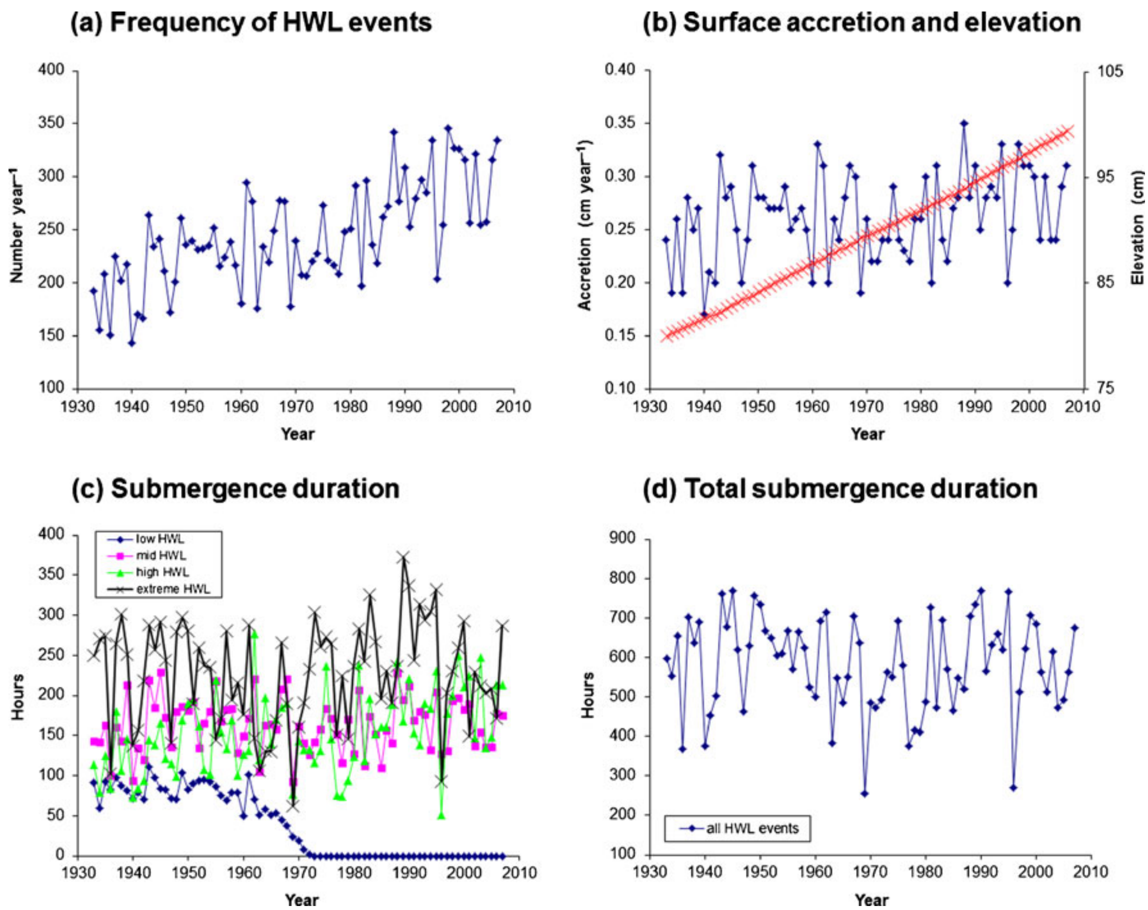

Fig. 6 Simulated **a** frequency (number year^{-1}) of high water level (HWL) events, **b** rate of marsh surface accretion (cm year^{-1} Danish Ordnance Zero DNN, *dots*) and marsh surface elevation (cm DNN, *red line*), **c** duration (h) of submergence for each HWL category, and **d** duration (h) of submergence for all HWL categories combined

were relatively stable from 1950 to 1980, and increased again from 1980 to 2007 (Fig. 6a).

Marsh surface accretion and marsh surface elevation

The simulated mean surface accretion rate (0.26 cm year^{-1}) was within the range (0.2–0.4 cm year^{-1}) reported for the study site by Bartholdy et al. (2004) for the period 1931–1999. Simulated marsh surface elevations differed from those observed by Bartholdy et al. (2004) and Bartholdy (2008) by no more than 1.6–2.0 cm (Table 2, period 1949–2007), which lies within the vertical error (2.0 cm) associated with a recent detailed topographic survey of the study site (Kim et al. 2010). Simulated accretion was positive each year, resulting in continuously increasing marsh surface elevations (Fig. 6b). Annual accretion rates decreased slightly between 1950 and 1980, due to increasing surface elevations and the subsequent decrease in the duration of marsh submergence (see below). Despite continuously increasing surface elevations, annual accretion rates began increasing gradually after 1980 due to the increasing frequencies of HWL events (Fig. 6a).

Marsh submergence

Simulated annual durations of submergence decreased noticeably between 1950 and 1980, and increased thereafter (Fig. 6d), primarily as a result of enhanced submergence caused by extreme HWL events (Fig. 6c). Submergence due to mid and high HWL events did not change noticeably after 1980, but submergence due to low HWL events decreased to zero by 1973 as a result of increases in marsh surface elevation over 90 cm DNN. Overall, the total submergence duration and the rate of surface accretion were significantly

Table 2 Comparison of simulated marsh surface elevations (cm Danish Ordnance Zero, DNN) with those observed at the Skallingen salt marsh (Denmark) during the indicated years (latter data extracted from Bartholdy et al. 2004 and Bartholdy 2008)

	1949	1999	2007
Observed	85.8	99.1	101
Simulated	83.8	97.1	99.4
Difference	2	2	1.6

positively correlated (R^2=0.6561, p<0.0001). In particular, the accretion rate showed varying correlations with the durations of low (R^2=–0.0025), mid (R^2=0.6561), high (R^2=0.6084), and extreme (R^2=0.2401) HWL events.

Discussion

The increases in simulated frequencies of HWL events and submergence durations since 1980 coincide with the entrance of the NAO into its positive phase, and also with observed increases in the frequency of temporary wind-driven water level rise in the North Sea (Alexander et al. 2005; Vilibić and Šepić 2010) and at the study site (Bartholdy et al. 2004; Kim et al. 2011). The slight dampening in the simulated rate of increase in annual frequencies of HWL events after the turn of the century (Fig. 6a) is similar to the trend reported by Matulla et al. (2008) for long-term European (including North Sea) storminess.

The present results suggest that short-term wind-driven water level variations related to atmospheric oscillations may significantly influence hydrological and geomorphic processes within salt marshes. As evident in Fig. 6c and d, the increased duration of marsh submergence since 1980 was primarily driven by the higher frequency and duration of *extreme* HWL events. As discussed above (see Study site), such extreme events hardly occur without wind-driven water level fluctuations, which have become more frequent and intense since 1980 when the NAO entered its positive phase. These discussions help understand why the mean water level started to increase from 1980 onward (see Fig. 4a).

It would have been ideal if water level variations driven by tidal versus wind forces had been separated in the model. The back-barrier of Skallingen is affected by both astronomical and wind tides. For example, some HWL events below HAT (i.e., 80–130 cm DNN) might have been driven by wind as well as tidal forces. However, the main argument of this paper—that wind-driven water level variations should be explicitly included in modeling dynamics of coastal environments—does not depend upon an unequivocal differentiation between these two forces. At Skallingen, wind tides are far more important drivers of salt marsh sedimentation because, under calm wind conditions, the normal astronomical tidal regime does not generate significant suspended sediment concentrations within the marsh (Bartholdy 1997, 2012; see also Kirwan et al. 2010; Marani et al. 2010; D'Alpaos et al. 2011). In particular, D'Alpaos et al. (2011) showed that marsh elevation was unable to record short-term fluctuations in mean water level. This result indirectly helps confirm the significant effects of the predominantly positive NAO phase since 1980 on marsh surface accretion. In sum, wind, and thus waves, is needed to resuspend the fine-grained intertidal sediments in the study area. The present model was parameterized such that simulated extreme HWL events occurred over HAT only. Such extreme events are predominantly driven by wind, regardless of tidal regime.

This logic of causal links between wind waves and sediment resuspension has been recently supported elsewhere. For example, Mariotti and Fagherazzi (2010) presented a one-dimensional model that simulates the evolution of the scarp between salt marshes and tidal flats. They reported that landform dynamics and sediment redistribution were significantly influenced by the resuspension of sediments driven by wind waves. Later, Tambroni and Seminara (2012), also in a one-dimensional context, studied the problem of salt marsh responses to sea-level rise. From the model it was found that, in cases where wind effects were accounted for, the marsh border prograded seaward and managed to survive longer in various scenarios of sea-level rise. Most recently, Schuerch et al. (2013) demonstrated that changing storm intensity and frequency influenced the ability of a salt marsh to keep pace with sea-level rise.

A wealth of information exists concerning the dynamics of coastal wetlands responding to climate change and wind storms (e.g., Michener et al. 1997; Hopkinson et al. 2008; Fearnley et al. 2009). However, few of these previous studies have explicitly modeled salt marsh dynamics focusing on the potential role of *atmospheric oscillations*. Zedler (2010) reported that sea storms induced by variations in the Pacific Decadal Oscillation and ENSO between 1978 and 1998 affected the dynamics of sedimentation and vegetation in a southern California salt marsh by causing catastrophic flooding. However, the existence of such a causal chain has not been documented in other regions of the Pacific.

The current work is the first modeling attempt to fill this knowledge gap in the Wadden Sea. Through the model, the NAO index proved to be an important driving variable for, in particular, extreme HWL events beyond the highest astronomical tide. Also, the model showed good performances in that the trends of simulated surface accretion and submergence duration were very similar to what has been observed at the Skalligen marsh since the early 1930s. Overall, these results for the Danish Wadden Sea add to the ever-increasing body of evidence that the role of atmospheric oscillations—e.g., the NAO—as drivers of wind-generated water level variations merits more attention in assessing the impact of climate change on coastal marshes.

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