How waves shape salt marshes

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ABSTRACT
We present high-resolution field measurements of five sites along the United States Atlantic Coast, and cellular automata simulations, to investigate the erosion of marsh boundaries by wave action. According to our analysis, when salt marshes are exposed to high wave energy conditions their boundaries erode uniformly. The resulting erosion events follow a Gaussian distribution, yielding a relatively smooth shoreline. On the contrary, when waves are weak and the local marsh resistance is strong, jagged marsh boundaries form. In this case, erosion episodes have a long-tailed frequency magnitude distribution with numerous low-magnitude events, but also high-magnitude episodes. The logarithmic frequency magnitude distribution suggests the emergence of a critical state for marsh boundaries, which would make the prediction of failure events impossible. Internal physical processes allowing salt marshes to reach this critical state are geotechnical and biological, and related to the non-homogeneity of salt marshes whose material discontinuities act as stress raisers.

INTRODUCTION
Large salt marsh losses have been documented in the United States, Asia, and Europe (e.g., Kirwan et al., 2010; Fagherazzi et al., 2013). If salt marshes continue declining, we risk losing their valuable ecosystem services. Among other benefits, salt marshes mitigate the impact of hurricanes and tsunamis, provide habitats for a variety of aquatic animal species, and mediate the exchange of sediments and contaminants between the marine and terrestrial environments (e.g., Zedler and Kercher, 2005).

Salt marshes are very resilient with respect to vertical dynamics because feedbacks among inundation, organic matter accretion, plant growth, and sediment deposition allow the marsh to keep pace with sea-level rise (e.g., Kirwan et al., 2010). However, recent results indicate that salt marshes are inherently weak with respect to horizontal erosion and that waves can trigger irreversible salt marsh deterioration even in the absence of sea-level rise (Fagherazzi et al., 2013). As a result, salt marshes do not display lateral equilibrium, but are always contracting or expanding at rates of meters per year (e.g., Fagherazzi, 2013).

Edge erosion has been also described as a repetitive stage, within an autocyclic mode, of marsh growth (e.g., Chauhan 2009; Van der Wal et al., 2008).

An understanding of the mechanisms controlling salt marsh erosion is thus of crucial importance for the correct management and preservation of coastal environments. Although salt marsh dynamics have been widely investigated, many processes are still poorly understood. Some studies adopt process-based or empirical models to estimate the location and size of erosion events (e.g., Fagherazzi et al., 2012; Ganju et al., 2013). An alternative conceptual model for marsh erosion can be based on simple stochastic models that could help extract universal features of the processes. Simple models, having few rules governing the interaction among individual components, can simulate complex systems, displaying structures with variability (e.g., Droessel et al., 1994; Goldenfeld and Kadanoff, 1999; Murray, 2007; Fagherazzi, 2008). Here we present a cellular automata model and high-resolution field measurements of marsh boundaries to explain erosional trends under different wind-wave exposures.

According to our results, salt marshes that are very exposed to wind-wave power are retreating uniformly. However, low wave power conditions correspond to long-tailed distribution of erosion events, which create rougher marsh fronts.

STUDY SITES
We focus on five sites, located in Plum Island Sound, Massachusetts, and Virginia Coast Reserve, Virginia (USA; Fig. DR1 in the GSA Data Repository1). The Plum Island Sound estuary is a coastal plain estuary characterized by prominent scarps at their seaward edges, typically 1.5 m or more above adjacent tidal flats.

METHODS
The stochastic model consists of a two-dimensional (2-D) square lattice (Fig. 1) whose elements, i, have randomly distributed resistance, $r_r$, between 0 and 1. Each cell has erosion rate $E_i$: $E_i = \alpha P^\beta \exp \left( -\frac{E_i}{P} \right)$.

Figure 1. Sketch of the cellular automata model. A: Possible domain configuration after removal of two domain elements. Each cell has erosion rate $E_i$; gray cells represent erodible elements and have erosion probability $P$. B: Possible domain configuration after removal of another cell ($E_i$). C: Another cell is removed from the domain ($E_i$). The crossed cell remains isolated from the rest of the boundary, and is thus automatically removed.

1GSA Data Repository item 2014314, Figure DR1 (study areas) and Figure DR2 (marsh boundary profiles), is available online at www.geosociety.org/pubs/ft2014.htm, or on request from editing@geosociety.org.
where $P$ is the wave power (kW/m) and $\alpha$ and $\beta$ are nondimensional constants equal to 0.35 and 1.1, respectively (Schwimmer, 2001). The first part of Equation 1 is in agreement with classical theoretical and empirical investigations on salt marsh boundary erosion. According to these, the retreat rate is proportional to wave power and follows a power-law relationship, having an exponent close to 1 (e.g., Schwimmer, 2001; Marani et al., 2011). The model does not take into account wind-wave directionality and temporal heterogeneity of wind-wave conditions. The second part of Equation 1 is meant to take into account the variety of biological and geomorphologic processes affecting each portion of the marsh. Among others, seepage erosion, crab burrowing, vegetation, and sediment cohesion make it difficult to predict which portion of the marsh will collapse first. Equation 1 is such that the local variability of marsh resistance is particularly relevant when the wave power is low (e.g., in this case the presence of vegetation could actively prevent the failure of a certain marsh portion). However, when wind-wave power is very high (e.g., during storms), local marsh characteristics play a secondary role and different marsh elements are eroded at a similar rate, because their resistance is small compared to the main external driver. In this case, the exponent in Equation 1 goes to 1 and every cell has the same erosion rate. Soil tensile and shear strength, as well as vegetation root tensile strength (kPa) could be considered first indicators for marsh resistance (e.g., Francalanci et al., 2013; Bendoni et al., 2014). At each time step, only the neighbors of previously eroded cells are susceptible to erosion (herein, neighbors means having one side in common; Fig. 1). Each neighbor is eroded with a probability

$$p_i = \frac{E_i}{\sum E_i},$$

where the sum refers to all cells that can potentially be eroded for a given time step. A cell is also automatically eroded if it remains isolated from the rest of the domain (Fig. 1C; crossed cell). In fact, isolated cells would represent isolated marsh stacks that are disintegrated fast as they are attacked by waves from several directions (Schwimmer, 2001). Similar models have already been adopted, in a different context, for the chemical etching of disordered solids (Štěpánek, 2008; Kolwankar et al., 2003). However, our model uses a different formulation for the erosion rate $E_i$, and the sum at the denominator of the erosion probability $p_i$ only runs over the boundary elements, rather than over the entire domain. Moreover, we automatically remove isolated cells. To our knowledge, there are no other applications of this kind of model to the marsh environment.

Marsh contours have been tracked using a real time kinematic global positioning system and an electronic total station. Data were collected with an average resolution of 1 m. When marsh contours were characterized by significant variations in boundary geometry, measurements were taken as much as 20 cm apart. Marsh boundaries have been monitored every September from A.D. 2008 to 2013 for the three sites in Plum Island Sound. For the two sites in the Virginia Coast Reserve, measurements were taken in March 2008 and August 2010. We define as magnitude of an erosion event, for a given year and for a certain point along the marsh boundary, the shortest distance of that point from the marsh boundary of the subsequent year.

**MODEL RESULTS**

Figure 2 shows results for two simulations run for small and high wave power. In case of high wave power, marsh erosion proceeds uniformly along the marsh shoreline and generates a profile that is rough at the scale of the single cell, but smooth at a larger scale. This is because each cell has similar resistance if compared to the main external driver. Low wave power conditions, however, correspond to the development of a jagged boundary. Indentations are produced by different erosion rates of individual cells that affect the global system behavior.

From a statistical viewpoint, the system behaves differently for the two extreme conditions of very low and very high wave power. The frequency magnitude distribution of erosion events in a time interval $\Delta t$ approaches a Gaussian distribution in the case of high wave power (Fig. 3A). In the model, the magnitude of an erosion event is the number of eroded cells. In the case of low wave power, the frequency distribution is characterized by a long-tailed power-law distribution (Fig. 3B). For the low wave power case, a long time is required to erode very resistant cells. However, once the most resistant cells are eliminated, several weak sites remain exposed and can be rapidly removed, with consequent generation of large-scale failures. Similar results were shown by Kolwankar et al. (2003), who demonstrated that when the etching power of the solution approaches zero, their model is identical to classical invasion percolation, with reaction rate limited by the invasion percolation threshold (e.g., Wilkinson and Willemse, 1983; Roux and Guyon, 1989).

Despite the occurrence of large-scale events, in the case of low wave power exposure, the remaining domain cells are very resistant due to the selected removal of the weakest sites. This differential removal is allowed by resistance variability among different cells. For a given low wave power condition, if cell resistance ($r_i$) values maintain the same mean but their range of variability ($\Delta r_i$) is reduced [e.g., $r_i \in (0.3; 0.7)$ instead of $r_i \in (0; 1)$], the domain starts eroding

**Figure 2. Results of the stochastic model: marsh boundary under low and high wave power conditions.**

![Figure 2](image)

**Figure 3. Frequency magnitude distributions of erosion events; $n$ is number of eroded cells, $N(n)$ is number of times $n$ cells are eroded within a time interval. Points are model results. A: High wave power conditions. Lines are the interpolation of model results using a logarithmic frequency magnitude distribution. B: Low wave power conditions. Lines are the interpolation of model results using a Gaussian frequency magnitude distribution.**

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uniformly, as for the high wave power condition. This uniform erosion rate leads to an accelerated erosion (Fig. 4) and is thus unfavorable for the maintenance of the domain elements.

For the two sites along the Virginia Coast Reserve, Chimney Pole is the most exposed and its erosion events follow a Gaussian distribution. The frequency magnitude distribution of erosion events at Hog Island is intermediate between the Gaussian and the logarithmic distribution.

Thus, at both Plum Island and the Virginia Coast Reserve, the lower the site exposure to wave action, the longer the power-law tail of the erosion events distribution. The frequency magnitude distribution of erosion events is also clearly recognizable from marsh boundary profiles (Fig. DR2).

FIELD DATA ANALYSIS

In Plum Island Sound, average erosion rates for the period of record (September 2008 through September 2013) are 0.2 m/yr at Refuge North, 0.35 m/yr at Stackyard Road, and 0.45 m/yr at Refuge South. For the two sites in the Virginia Coast Reserve, average erosion rates (March 2008 through August 2010) are 0.75 m/yr at Hog Island and 1 m/yr at Chimney Pole. The frequency magnitude distribution of biennial erosion events for each point along marsh shorelines is presented in Figure 5. The most sheltered sites in Plum Island Sound (Refuge North and Stackyard Road) have a logarithmic frequency magnitude distribution. Moreover, the lower the exposure to waves, the longer the tail of the power law (Fig. 5; the magnitude of the slope coefficient for Refuge North is lower than the one for Stackyard Road). For the Refuge South site, the power-law distribution starts to approach the Gaussian distribution and an intermediate condition arises, characterized by a shorter tail and maximum number of erosion events no longer corresponding to minimum magnitudes.

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**Figure 4.** Time (τ) required to erode half of the domain particles as a function of Δr and for a wave power P (see text) equal to 0.1; Δr is the amplitude of the range within which the cell resistance, r, can vary. The time required to erode half of the domain cells for a certain Δr range has been normalized by the time τ corresponding to a Δr equal to 1 [i.e., r ∈ (0; 1)].

**Figure 5.** Frequency-magnitude distributions of erosion events for three sites in Plum Island Sound and two sites in the Virginia Coast Reserve; n is the erosion event (m) occurring N(n) times. RN—Refuge North, SR—Stackyard Road, RS—Refuge South, HI—Hog Island, CP—Chimney Pole.

**Discussion and Conclusions**

Our simple model appears to capture important marsh boundary features and gives some new insight into salt marsh erosional processes. High-resolution field measurements at five locations along the United State Atlantic Coast confirm the numerical results. Our investigations have been related to high or low wave power exposure, as well as to weaker or more resistantmarsh platforms (given a fixed wind-wave exposure). Very exposed sites are characterized by a uniform rate of marsh retreat along the shoreline, with erosion events following a Gaussian frequency magnitude distribution. Less exposed sites show a long-tailed frequency magnitude distribution with numerous small events and few (but not negligible) bigger events, which are unpredictable and can happen despite reduced wave action. The fact that sites at Plum Island have longer tailed distributions than the study sites in Virginia can be related to the increased likelihood of marsh slumping in macrotidal environments with respect to microtidal marshes; in the former case, higher marsh scarp promote undercutting and tensional break development.

We maintain that, in the case of low wave exposure, the system could reach self-organized criticality (SOC). Self-organization refers to the ability of certain nonequilibrium systems to develop structures and patterns in the absence of any fine tuning from external agents. Criticality refers to the fact that all the members of the system influence each other and that local instabilities generate broader scale order disturbances (e.g., Bak et al., 1987; Bak, 1996).

The power-law relationship is a necessary condition for SOC and it is frequently used to test whether SOC is present. According to Bak et al. (1987, 1989), if frequency data fit a power-law distribution over a range of event magnitudes, the system is likely self-organized and could be at a critical state. However, the power-law relationship is a necessary but not sufficient condition for SOC, as it could also happen in a range of non-SOC systems. Other necessary conditions (but not sufficient, as sufficient conditions are unknown) for the development of SOC are (1) the existence of a quasi-steady critical state at which the system self-organizes; (2) an internal mechanism by which the system can reach this critical state; (3) the response of the system to perturbations varies in magnitude independently of perturbation size; (4) the presence of mechanisms for the system energy dissipation; and (5) the presence of many degrees of freedom within which internal processes can operate.

Conditions 4 and 5 are easily verified, as salt marshes are inherently dissipative systems characterized by a continuous loss in both potential and kinetic wave energy, consequent sediment removal, and further energy dissipation. Condition 3 is confirmed by the logarithmic distribution of erosion events that spans multiple length scales. For conditions 1 and 2, we propose that the critical state for marsh boundaries is the one promoting the removal of weak sites and consequent exposure of more resistant and uniform marsh portions. The critical state would thus be the one maximizing salt marsh resistance to wave action. In our simplified model, this condition corresponds to the contour approaching the percolation cluster made of the slowest-eroding sites and surrounded by easily erodible
ones. Field data confirm this assumption, considering that the slope of the logarithmic distribution of the less exposed sites (Refuge North) is close to 1.53 and thus in agreement with classical invasion percolation problems. Internal processes allowing the system to reach its critical state are geotechnical and biological mechanisms connected to system discontinuities. Discontinuities enhance wave stresses and lead to crack development. In the presence of cracks, the system approaches the minimum energy state independently from external agents (e.g., Roylance, 2001). Failures of marsh portions become possible and independent from any fine external tuning. Tension crack development is also promoted by drying and shrinkage of the soil, or by cyclic oscillations of mean and effective stresses (Franzalanci et al., 2013; Bendoni et al., 2014). Particular attention is required when trying to explain the behavior of a system through SOC (e.g., Frigg, 2003), and further efforts are required to definitely recognize it.

In our simplified model, discontinuities correspond to contact area between clusters having relatively high or low erosional rates. In a natural system, discontinuities could correspond to contact surfaces between marsh blocks weakened by groundwater seepage. Stress concentration along these discontinuities favors the failure of weak marsh clusters of different sizes. For example, marsh slumping, triggered by cracks and seepage, can lead to large-scale changes, which in turn promote long-tailed distribution. Once the weakest sites are removed, more resistant marsh portions are uncovered, which are difficult to erode. Thus, variability in marsh properties allows marsh boundaries to be resistant to wind-wave action by means of selected removal of weak elements.

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