Tidal marshes as disequilibrium landscapes? Lags between morphology and Holocene sea level change

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[1] Historical acceleration in the rate of global sea level rise and recent observations of marsh degradation highlight the importance of understanding how marshes respond to sea level change. Here, we use an existing numerical model to demonstrate that marsh morphology, and its effect on biological productivity and vertical accretion, could lag century-scale sea level rise rate oscillations by several decades. This suggests that marshes, and perhaps other intertidal environments, have not been in equilibrium with Holocene sea level. Additional results suggest that marshes have not yet fully responded to historical sea level acceleration. Consequently, marshes today may be out of equilibrium with modern rates of sea level rise, and further adjustment in the form of platform deepening and channel erosion could be expected. Under an accelerating sea level rise rate, the morphology and productivity of marshland will reflect environmental conditions of the past, and studies of marshes today will underestimate their response to sea level rise. **Citation:** Kirwan, M. L., and A. B. Murray (2008), Tidal marshes as disequilibrium landscapes? Lags between morphology and Holocene sea level change, *Geophys. Res. Lett.*, *35*, L24401, doi:10.1029/2008GL036050.

1. Introduction

[2] Tidal marshes are generally thought to be near, rather than far away from, equilibrium with respect to rates of sea level rise [*Friedrichs and Perry*, 2001]. Long term measurements of vertical accretion commonly mimic concurrent rates of SLR, and thick sequences of uninterrupted high marsh peat are common [e.g., *Redfield*, 1965; *Friedrichs and Perry*, 2001]. Numerical models suggest that a moderate increase in the rate of SLR, producing an increase in inundation duration and frequency, will deliver more sediment to the marsh platform [e.g., *French*, 1993; *Allen*, 1995] and stimulate biomass growth [*Morris et al.*, 2002], causing accretion rates to increase. Accretion rates then increase in parallel with inundation until they mimic the rate of SLR, and a new equilibrium morphology is established [e.g., *Morris et al.*, 2002; *Kirwan and Murray*, 2007].

[3] The narrow range of marsh positions within the intertidal zone, and their ability to track changes in sea level, make tidal marsh deposits useful in determining the timing and magnitude of Holocene sea level change. Basal peat ages and marsh accretion rates have been used to identify the pattern of post-glacial transgression [*Redfield*, 1967], climate-induced episodes of slow and fast SLR in the late Holocene [*Shaw and Ceman*, 1999], and as evidence that average rates of SLR changed little between about 1000 and 1850AD [*Donnelly et al.*, 2004]. While this approach assumes that marshes are roughly in equilibrium with sea level, other techniques for reconstructing Holocene sea level consider a lag between changes in sea level and marsh elevation. Sea level curves derived from foraminifera assemblages, for example, sometimes add rates of marsh accretion to biostratigraphic indicators of water depth to address any "disequilibrium between marsh growth and relative sea level rise" [*Varekamp et al.*, 1992, p. 294]. Nevertheless, the time it takes for a marsh to adjust to sea level change remains an unresolved issue.

[4] Understanding how marshes adjust to changes in the rate of SLR seems especially relevant given the large and rapid sea level acceleration that has taken place over the last 200 years. Tide gauges and stratigraphic indicators suggest that rates of SLR accelerated to current rapid rates between 1800 and 1900 [e.g., *Donnelly et al.*, 2004; *Gehrels et al.*, 2008; *Jevrejeva et al.*, 2008]. Perhaps in response, marsh platforms today appear to be losing elevation relative to sea level [*Morris et al.*, 2005], channel networks appear to be expanding [e.g., *Hartig et al.*, 2002], and vegetation associated with relatively high elevations is being replaced by types of vegetation associated with relatively low elevations [e.g., *Donnelly and Bertness*, 2001]. These changes are of broad concern, since tidal wetlands are considered to be among the world's most economically valuable ecosystems [*Costanza et al.*, 1989].

2. Methods

[5] We model the long-term behavior of tidal marsh platforms using a previously described numerical model designed to explore basic interactions between sedimentary and biological processes [*Kirwan and Murray*, 2007]. Our basic approach is to model local elevation change determined by the growth rate of vegetation and the elevation of the platform relative to high-tide level. In the model, vegetation productivity increases with water depth until some optimum depth, beyond which productivity decreases [*Morris et al.*, 2002]. Deposition rates increase with water depth, and as a function of biomass productivity, reflecting the ability of plants to trap inorganic sediment and contribute organic matter to vertical accretion (for more information, please see auxiliary material)[1].

[6] We conduct model experiments on a 9 km^2 marsh platform and channel network system, discretized into 25 m^2

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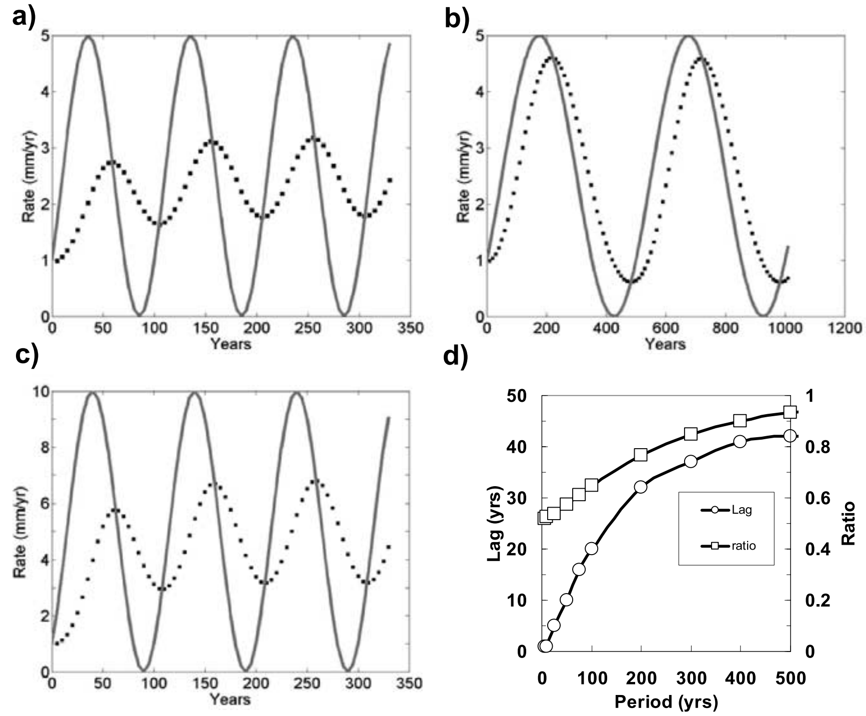

Figure 1. Platform accretion rate (black squares) response to periodic SLR rates (grey line): (a) 100 yr period, 2.5 mm yr^{-1} amplitude, (b) 500 yr period, 2.5 mm yr^{-1} amplitude, and (c) 100 yr period, 5.0 mm yr^{-1} amplitude. Water depth and biomass productivity (not shown) oscillate in similar pattern. (d) Summary of the time lag and ratio between maximum SLR rate and maximum accretion rate (accretion/slr) for a variety of periods. All experiments are conducted with a 4 m tidal range and 0.02 g/l suspended sediment concentration.

cells. Each experiment begins with an equilibrium morphology created under a constant, 1 mm/yr rate of SLR. In the first set of experiments, we subject the morphology to sinusoidal oscillations of SLR rate with periods of 1 to 500 years, and amplitudes of 2.5 mm/yr and 5 mm/yr. In a second set of experiments, we subject the morphology to a high-precision Late Holocene sea level history determined at Clinton, Connecticut [*van de Plassche et al.*, 1998]. This sea level history was determined by microfossil foraminiferal assemblages, which adjust to fluctuations in tidal inundation more quickly than lithologic indicators [e.g., *Horton et al.*, 2000]. In some of these experiments, we represent minor episodic vegetation disturbance, which commonly occurs on natural marshes for a variety of reasons (including wrack deposition and animal grazing), by removing vegetation from random cells on the marsh platform for 1–5 years, at which time it recovers to the biomass determined by the cell's new elevation [*Kirwan et al.*, 2008, and references therein]. Finally, we conduct an experiment where the rate of SLR increases from 1 to 3 mm/yr, representing possible sea level acceleration in the 19th century [e.g., *Donnelly et al.*, 2004].

[7] In these experiments we consider a limited number of processes, and treat them in highly simplified ways in order to allow investigation into long term processes acting over large spatial scales [*Kirwan and Murray*, 2007]. Most importantly, we do not explicitly model below-ground processes involved in peat accretion, which limits the model's usefulness in some high elevation marshes where organic matter accumulation dominates mineral sediment deposition (typical of New England marshes used in sea level reconstructions). Despite these simplifications, our model and those with similar approaches have generally produced topography and basic behaviors similar to those observed in marshes from a variety of geographic locations [*D'Alpaos et al.*, 2007; *Kirwan and Murray*, 2008; *Kirwan et al.*, 2008]. Nevertheless, the results of highly simplified models should be considered as an initial exploration of general behavior rather than a detailed simulation of a specific location [*Kirwan and Murray*, 2007].

3. Results and Discussion

[8] Immediately following a moderate increase in the rate of SLR, the rate of SLR exceeds vertical accretion, and water depths above the platform increase. Biomass productivity and accretion rates increase with water depth until accretion rates equal the rate of SLR.

[9] In the absence of plants, the response of a surface adjusting towards a new equilibrium state might be expected to follow an exponential function that is independent of the magnitude of change, and leads to a well defined time scale of adjustment [e.g., *Mudd and Furbish*, 2007]. However, we show that in the case of a marsh responding to a step change in the rate of sea level rise, ecogeomorphic feedbacks cause the marsh platform to adjust faster than predicted by an exponential relationship (see auxiliary material). If the new rate of SLR remains constant, then the marsh platform reaches dynamic equilibrium and water

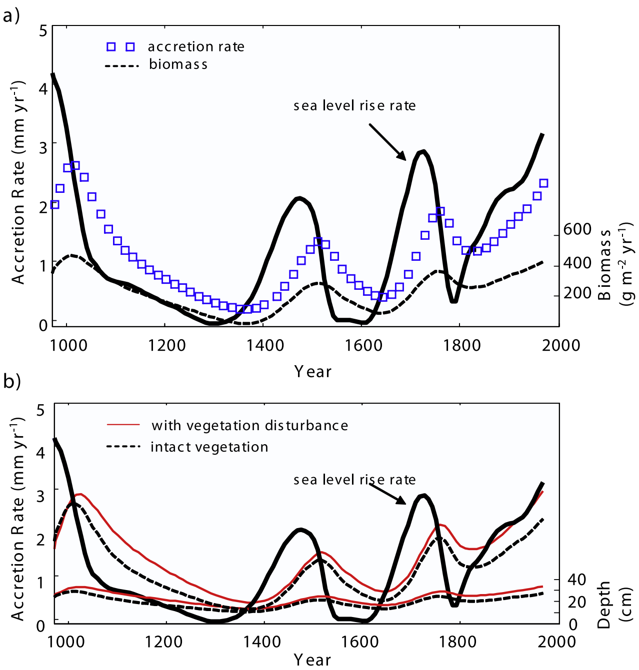

Figure 2. Response of accretion, biomass productivity, and water depth to Holocene SLR rates since 970 AD. Sea level curve, denoted by heavy solid line, from *van de Plassche et al.* [1998]. (a) Instantaneous, platform-averaged vertical accretion (blue squares) and biomass productivity (dashed line). (b) The response of platform-averaged water depth (lower lines) and accretion rate on vegetated surfaces (upper lines). The dashed black line represents the model experiment with intact vegetation; the continuous red line represents a model experiment with episodic vegetation disturbance. With episodic disturbance, accretion rates on vegetated surfaces are nearly identical to SLR rates since 1850 (2.4 vs. 2.5 mm/yr), despite overall platform deepening.

depth and biomass productivity remain constant [*Kirwan and Murray*, 2007]. However, in the case of an oscillatory SLR, the platform adjusts towards a continuously changing forcing condition, and a steady state equilibrium never occurs (Figure 1).

3.1. Sea Level Oscillations

[10] Water depth, biomass productivity, and accretion rates increase for the duration of sea level acceleration (Figure 1). Not until SLR rates begin to decline may accretion rates approach the rate of SLR. A maximum water depth (and accretion rate) occurs when the rate of SLR equals the rate of accretion. Beyond this point, accretion rates exceed SLR rates, and water depths decrease.

[11] The time lag between corresponding rates of SLR and accretion is related primarily to the period of SLR rate oscillation. With a constant amplitude of 2.5 mm/yr, increasing the period of oscillation from 100 years to 500 years changes the lag time from about 20 yrs (20% of period) to about 40 yrs (8% of period) (Figures 1a and 1b). For a given period, increasing the amplitude of oscillation has little effect on lag time. A SLR rate oscillation with a 100 year period has an approximately 20 year accretion lag with amplitudes of both 2.5 mm/yr and 5 mm/yr (Figures 1a and 1c). The greater change in water depth required to balance higher SLR rates is approximately offset by a more rapid rate of water depth change. Accretion rates fluctuate around the mean rate of SLR in all experiments, indicating a dynamic equilibrium, but the maximum rate of accretion is much lower for sea level rate oscillations with a 100 year period (~3 mm/yr) than with a 500 year period (~4.5 mm/yr). For long period sea level oscillations (>300 years), accretion rates resemble SLR rates and the lag between them asymptotically approaches about 50 years (Figure 1d). This suggests that marsh stratigraphy will tend to record long-term fluctuations in sea level, but may be unable to fully record short-term sea level change.

3.2. Late Holocene Sea Level

[12] During the late Holocene, relative SLR rates oscillated between about 0 mm/yr and 5 mm/yr [e.g., *van de Plassche et al.*, 1998; *Shaw and Ceman*, 1999]. In Clinton, Connecticut for example, slow SLR was punctuated by 4 episodes of rapid SLR since AD 450 [*van de Plassche et al.*, 1998]. Although this sea level record has been criticized for not addressing sediment compaction and potentially being influenced by storm erosion, similar sea level oscillations have been observed elsewhere in the region [*Nydick et al.*, 1995; *Gehrels et al.*, 2002]. Our model experiments suggest that if such oscillations existed in the late Holocene, then adjustments to the marsh platform lagged behind by several decades (Figure 2a). On a platform with undisturbed vegetation, maximum accretion rates, maximum biomass productivity, and maximum water depth lag behind maximum rates of SLR by about 50 years. Therefore, platform deepening continues even after SLR rates decline (as well as the opposite), resulting in a landscape continuously in disequilibrium. Because the marsh platform does not fully adjust before SLR rates begin to decline, the range of accretion rates does not fully capture the range of SLR rates. In the experiment without vegetation disturbance, SLR rates vary between about 0 and 3 mm/yr, while instantaneous accretion rates vary only between 0 and 1.5 mm/yr (Figure 2a). These experiments suggest that accretion rates averaged over sufficiently long time periods (at least one full SLR rate oscillation) will resemble SLR rates, but that accretion rates averaged over shorter time periods will be substantially different than SLR rates, and will be unable to capture the full variability of sea level change. Additional model experiments suggest that general marsh behavior, and lags between sea level and accretion, is not strongly sensitive to specific parameter values (see auxiliary material).

[13] Ironically, a slow adjustment to sea level change could help explain observations of uninterrupted sequences of high marsh peat that inspire hypotheses of marshes maintaining equilibrium with rates of SLR [e.g., *Redfield*, 1965]. If SLR rates varied during the late Holocene, and marshes adjusted quickly, then one might expect changes in stratigraphy (i.e. alternating low and high marsh facies). Instead, our model results suggest that because the marsh surface adjusts slowly and incompletely, platform water depths change by only 10–20 cm, which might be insufficient to generate noticeably different sedimentary characteristics.

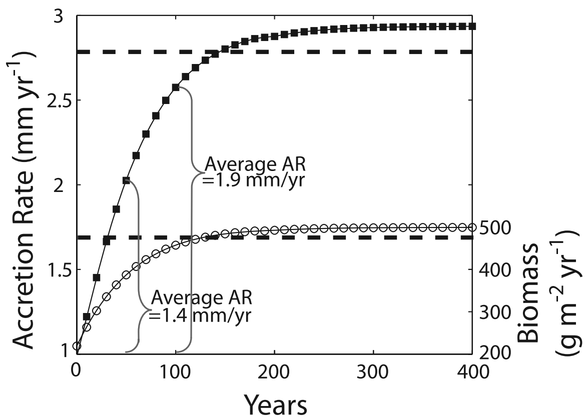

Figure 3. Response of platform accretion (squares) and biomass productivity (circles) to an abrupt increase in SLR rate from 1 mm/yr to 3 mm/yr [e.g., *Donnelly et al.*, 2004]. Dashed lines denote 95% of new equilibrium rates. Black squares denote platform-averaged instantaneous accretion rates; two long-term average accretion rates (AR), over 50 and 100 years, have been identified to illustrate that detection of an accelerating sea level from measurements of accretion may only be possible after several decades.

3.3. Recent Sea Level Acceleration

[14] High precision sea level histories inferred from foraminiferal stratigraphy in Northern Atlantic marshes (as well as global analyses of tide gauges) typically show acceleration beginning ~A.D. 1800 (Figure 2) [*Nydick et al.*, 1995; *van de Plassche et al.*, 1998; *Gehrels*, 1999; *Gehrels et al.*, 2002, 2006; *Jevrejeva et al.*, 2008]. However, at nearby Barn Island, Connecticut, *Donnelly et al.* [2004] measured rates of basal peat transgression that were constant (~1 mm/yr) from about 1300 to 1850–1900. Because tidal gauges measure a ~3 mm/yr rate of SLR since 1856, *Donnelly et al.* [2004] suggested regional sea level acceleration from 1–3 mm/yr did not begin until the late 19th century.

[15] Regardless of the timing of acceleration, our model experiments predict that marsh platforms should have deepened recently (elevations becoming lower in the tidal frame), and that accretion rates lag behind sea level acceleration by several decades (Figures 2a and 3). In the case of an abrupt change in SLR rate from 1 to 3 mm/yr [e.g., *Donnelly et al.*, 2004], 145 years elapse before modeled accretion rates reach within 95% of 3 mm/yr and approach a new equilibrium (Figure 3). Historical measurements of accretion typically express accretion rates as long-term averages rather than instantaneous rates of accretion. In the case of C-14, sampling intervals usually span more than 50 years. If averaging over 50 yr intervals, it takes between 50 and 100 years in our experiments for long-term average accretion rates to increase from 1 to 1.5 mm/yr, even though instantaneous accretion rates quickly exceed 2 mm/yr (Figure 3).

[16] These experiments suggest that if sea level acceleration began in the early 19th century, changes in marsh accretion rates might not easily be detectable until well after AD 1900. If true, estimates of sea level acceleration beginning in the early 19th century could apply to Barn Island, even though rates of marsh transgression did not accelerate prior to 1850–1900 [*Donnelly et al.*, 2004]. The timing is significant; such a result would favor the interpretation that recent sea level acceleration has a natural component [e.g., *Nydick et al.*, 1995; *Gehrels*, 1999], rather than responding solely to warming associated with late 19th century industrialization [*Donnelly et al.*, 2004]. However, we caution that our simplistic model is not designed to simulate a specific marsh, particularly not a marsh dominated by peat accumulation.

[17] While our model experiments predict that marshes should have deepened recently, and are consistent with observations of vegetation change [*Donnelly and Bertness*, 2001], most field measurements of long-term accretion mimic rates of SLR, both in New England [e.g., *Roman et al.*, 1997] and globally [e.g., *Friedrichs and Perry*, 2001]. The most common technique to measure long-term accretion (^{210}Pb) typically measures average accretion since ~1850–1900. For comparison, our model experiment forced by the Clinton, Connecticut sea level curve, predicts an average accretion rate of 1.7 mm/yr in response to a SLR rate of 2.3 mm/yr since 1850.

[18] We offer several hypotheses for the apparent discrepancy between field measurements that indicate marsh stability and our model experiments that suggest platform deepening. First, an increase in sediment availability could have offset sea-level induced deepening. Sediment delivery rates to marshes and other coastal environments increased 4–10 X following land clearance associated with European settlement on the Atlantic coast [*Pasternack et al.*, 2001; *Colman et al.*, 2002]. Secondly, long-term accretion rates do not account for subsidence. In many areas, including New England, direct measurements of elevation change show marsh platform deepening even though accretion rates equal or exceed SLR rates [e.g., *Cahoon et al.*, 1995]. Finally, measurements of long-term elevation change on vegetated surfaces will tend to exceed SLR rates on a platform with episodically disturbed vegetation [*Kirwan et al.*, 2008]. In this case, unvegetated patches become deep relative to sea level, but accrete rapidly when vegetation recolonizes them [*Kirwan et al.*, 2008]. When vegetation disturbance is incorporated into our late-Holocene model experiments, accretion rates on vegetated surfaces become closer to SLR rates, even though the mean platform deepened since 1800 (Figure 2b). Therefore, measurements of elevation change or vertical accretion on vegetated surfaces may give a marsh the appearance of being in tighter equilibrium with SLR than reality, and mask any deepening that has occurred since 1800.

[19] In contrast to a tight equilibrium, we hypothesize that marshes respond relatively slowly to changes in the rate of sea level. If our simplistic approach is reasonably reliable, our results suggest that marshes today have not responded fully to historical sea level acceleration, and that if SLR rates were to stabilize, further deepening [e.g., *Morris et al.*, 2005] and possible channel expansion [*D'Alpaos et al.*, 2007; *Kirwan et al.*, 2008] would be expected. If SLR rates continue to accelerate, then the morphology and productivity of marshland would always reflect environmental conditions of the past, rather than current conditions. In either scenario, studies of marshes today would underestimate their response to sea level rise.

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