



Global climate changes recorded in coastal wetland sediments: Empirical observations linked to theoretical predictions

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[1] Whether coastal areas are experiencing, and responding to, an accelerated rate of global sea-level rise (GSLR) is critically important for the ~2 billion people living near Earth's oceans. Accretion rates from a suite of physiographically diverse coastal wetlands surrounding Long Island, NY accelerated during the 20th century at $2.3 \pm 0.2 \times 10^{-2} \text{ mm yr}^{-2}$, which is comparable to reported rates of GSLR acceleration and global temperature changes. Wetlands varied in tidal range, salinity and geomorphic setting, and were located in embayments with limited human impacts in a region with limited and constant rates of subsidence. From geochronologies with temporal resolutions of 2–5 yr, we constructed new composite histories of sediment accretion and mineral deposition. Wetland dynamics are consistent with predictions from sedimentology and a numerical model of ecogeomorphic response, suggesting that these systems, and likely others worldwide, are responding to accelerated GSLR and related climatic changes. **Citation:** Kolker, A. S., M. L. Kirwan, S. L. Goodbred, and J. K. Cochran (2010), Global climate changes recorded in coastal wetland sediments: Empirical observations linked to theoretical predictions, *Geophys. Res. Lett.*, 37, L14706, doi:10.1029/2010GL043874.

1. Introduction

[2] Changes in global sea level are an excellent indicator of the integrated effects of global climate change because climate strongly influences fluxes of water between Earth's oceans and continents and the density of seawater [Levitus *et al.*, 2001]. Estimates of GSLR rates during the 20th century range from 1.1 mm yr^{-1} [Wadhams and Munk, 2004] to $1.5\text{--}2.0 \text{ mm yr}^{-1}$ [Miller and Douglas, 2004], and with higher rates $3.1 \pm 0.7 \text{ mm yr}^{-1}$ measured for the period 1993–2003 [Intergovernmental Panel on Climate Change (IPCC), 2007; Merrifield *et al.*, 2009]. Church and White [2006] used tide gauge records dating back to 1870 to demonstrate that GSLR rates accelerated during the past century at a rate of $1.3 \pm 0.6 \times 10^{-2} \text{ mm yr}^{-2}$ [Church and White, 2006]. Jevrejeva *et al.* [2008] reported an acceleration of a similar magnitude, but presented evidence from tide gauges

that this acceleration began c.1700. In New York, where this study is based, RSLR rates determined from 20th century tide gauges ranged 2.2 to 2.8 mm yr^{-1} [Gornitz *et al.*, 2001] (<http://tidesandcurrents.noaa.gov/>). The difference between these rates and the global average is generally attributed to glacial isostatic adjustments (GIA) and potentially dynamics [Gornitz *et al.*, 2001; Kolker and Hameed, 2007; Peltier, 2004], whereas the local variability in the rates is generally attributed to GIA alone [Gornitz *et al.*, 2001; Peltier, 2004].

[3] Sedimentological theory holds that sea-level rise, sediment deposition, and vertical accretion are linked in vegetated intertidal systems such as salt marshes, mangroves, and tidal freshwater forests [Allen, 2000; Reed, 2002]. Relative sea-level rise (RSLR) creates accommodation space for fine-grained sediments to settle, so that increases in the rate of RSLR theoretically lead to concomitant changes in rates of mineral sediment deposition [Redfield, 1972]. In cases where RSLR is modest and does not cause plant mortality, plant stems slow tidal currents thereby facilitating sediment deposition, while roots contribute to both mass and volume [Redfield, 1972]. In wetlands dominated by the marsh plant *S. alterniflora*, modest increases in the rate of RSLR appear to increase plant productivity, peat accumulation, the sediment trapping ability of wetland macrophytes, and ultimately vertical accretion [Morris *et al.*, 2002]. Indeed, accretion rates in many coastal wetlands have matched regional rates of RSLR from the late Holocene through the early Anthropocene (~4000–100 yr b.p.) [Allen, 2000; Redfield, 1972].

[4] Despite evidence that 20th century rates of GSLR were higher than 19th century rates [IPCC, 2007], and studies documenting wetland loss during the 20th century [Hartig *et al.*, 2002; Reed, 2002], conclusive evidence that accelerated GSLR is driving coastal processes has remained elusive. Several reasons account for this critical knowledge gap 1) Many large coastal systems are located in deltaic environments that have high rates of subsidence [Reed, 2002]. 2) Coastal zones are inherently variable, experiencing a range of sediment pathways, making it challenging to determine changes in trend from the background of natural processes. 3) Anthropogenic impacts to the coastal zone are widespread, further complicating patterns of subsidence, sediment transport, vertical accretion and plant productivity.

2. Methods

[5] To avoid these confounding effects, we compiled data from nine cores from central and eastern Long Island, NY, USA, (Figure 1) an area with slow and constant rates of subsidence that are driven primarily by GIA [Gornitz *et al.*, 2001; Peltier, 2004]. Cores came from four sites that differed in tidal range (by an order of magnitude), salinity (brackish to near full strength), geomorphology (incised

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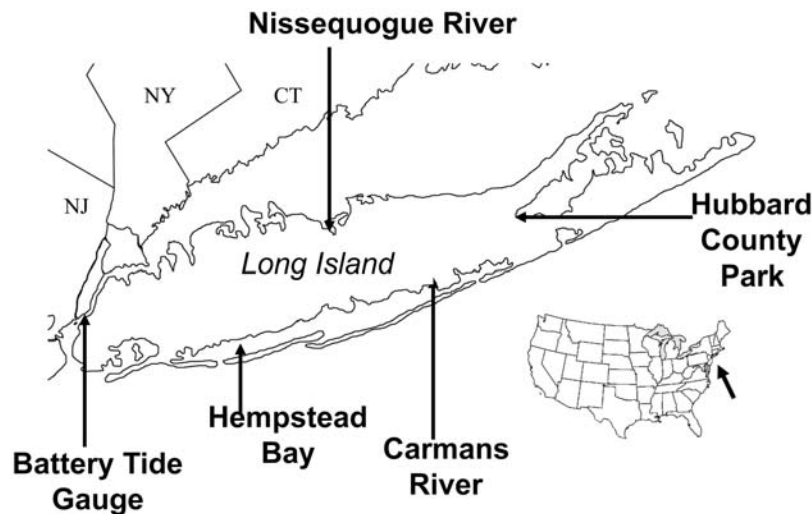


Figure 1. Location of sites from which cores were collected. The Nissequogue River wetlands sit in a glacially carved embayment with a tidal range of 2.5–3.0m. Hubbard County Park wetlands are coastal fringing sites where the tidal range is ~1.25 m. Carmans River marshes are located in a microtidal (0.25 m) river, and the Hempstead Bay marshes are located in a back-barrier setting with a tidal range of ~1.5 m. Cores were taken in interior settings with similar plant type (short-form *S. alterniflora*) to reduce local scale environmental variability, thereby making sites more comparable.

river valley, back-barrier coastal lagoon, microtidal river and coastal fringe) and exposure to storms (exposed coast, sheltered embayment, and medium fetch). Selecting several physiographically diverse sites provides a degree of confidence that linkages between accretion and GSLR are driven by climate, rather than local variability. While western Long Island is heavily impacted by anthropogenic processes, central and eastern Long Island have been relatively free from these impacts [Kolker *et al.*, 2009, and references therein]. Though no site can be classified as “pristine,” sites were selected without artificial fill, nearby sources of contaminants or large engineered structures, and the surrounding embayments were either legally protected or physiographically isolated from direct human interference [Kolker *et al.*, 2009]. Peat deposits in these wetlands are thin (1 ~ 4 m), and overlie hard substrates such as glacial outwash—significantly reducing the effects of local subsidence.

[6] Individual cores were dated with excess ^{210}Pb ($^{210}\text{Pb}_{\text{XS}}$ —the amount above that produced from ^{226}Ra decay in marsh sediments) using a constant rate-of-supply (CRS) model to determine fluctuations in accretion and mineral deposition based on 15–25 ages for each core [Kolker *et al.*, 2009; McCaffery and Thomson, 1980]. Previously, these individual cores were used to address questions related to how marshes adjust to short-term fluctuations in sea level [Kolker *et al.*, 2009]. Here, we construct composite chronologies of vertical accretion and mineral deposition to understand whether there were centennial-scale changes in sediment accumulation common to many Long Island coastal wetlands. To obtain these composite chronologies, we interpolated between dated sections to obtain an annual record of sediment accretion for each core. We averaged records from multiple cores at an individual site, and finally averaged the resulting chronologies from all 4 sites (see auxiliary material).¹ These composite chronologies helped

isolate long-term trends by averaging out short-term and small-scale spatial variability in a process analogous to the construction of composite sea-level histories by Church and White [2006] and Jevrejeva *et al.* [2008].

[7] The $^{210}\text{Pb}_{\text{XS}}$ inventories in these cores matched that expected by atmospheric flux alone [Cochran *et al.*, 1998; Kolker *et al.*, 2009], suggesting that there are minimal subtidal sources of $^{210}\text{Pb}_{\text{XS}}$, supporting the CRS modeling assumptions. A deposit that was suspected to be from the 1938 Hurricane dated to 1939, and a deposit suspected to be from Hurricane Gloria in 1985 dated to 1984. These were the largest storms in Long Island near the $^{210}\text{Pb}_{\text{XS}}$ dates reported, and their detection provides empirical evidence for the age model (see auxiliary material).

3. Results and Discussion

3.1. Chronologies of Sediment Accretion and Mineral Deposition

[8] The composite accretion rates range from 0.7 to 4.7 mm yr^{-1} and the composite mineral deposition rates range from 2.1 to $7.1 \times 10^{-2} \text{ g cm}^{-2} \text{ yr}^{-1}$. Accretion and mineral deposition rates are highly correlated ($R^2 = 0.90$, $p < 0.01$, $df = 12$ (Figure 2)), suggesting that accretion rates are linked to changes in mineral fluxes, rather than root growth. We calculate a long-term acceleration in accretion rate of $2.3 \pm 0.2 \times 10^{-2} \text{ mm yr}^{-2}$ and a long-term acceleration in mineral deposition rates of $3.52 \pm 0.22 \times 10^{-4} \text{ g cm}^{-2} \text{ yr}^{-2}$ (Figure 2). Despite decadal-scale variability, these values are similar to those obtained from trend lines linking exclusively maxima or minima suggesting that the accelerations calculated are not heavily influenced by outliers.

[9] The accretion rate acceleration is unlikely to be the result of variable subsidence rates or recent compaction. Rates of GIA in New York changed by $<0.05 \text{ mm yr}^{-1}$ during the past century [Peltier, 2004]. Spatial variability in GIA is low too, with rates varying by $<0.5 \text{ mm yr}^{-1}$ between New York and Massachusetts (~350 km) [Peltier, 2004].

¹Auxiliary materials are available in the HTML. doi:10.1029/2010GL043874.

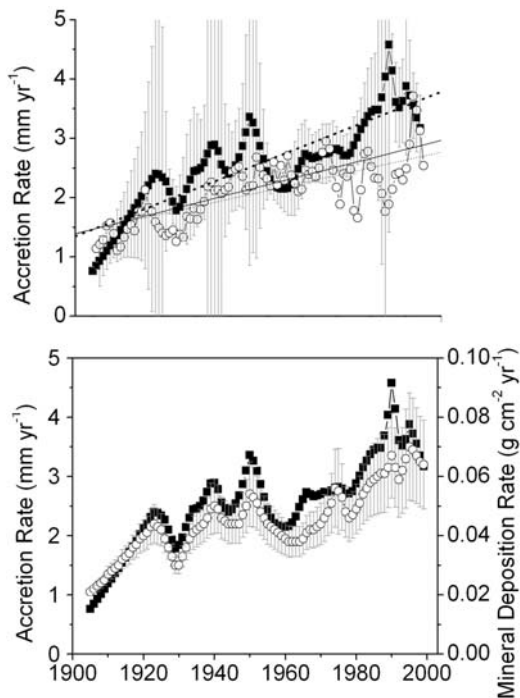


Figure 2. Sediment accretion and mineral deposition chronologies. (top) Long Island salt marsh composite accretion rate (black squares) with standard errors, and modeled New York accretion rate (open circles) over the 20th century. Also plotted, the best-fit linear trends in the Long Island composite accretion rate (0.023 mm yr^{-2} , dashed line) and modeled accretion rate (0.015 mm yr^{-2} , solid line), and the global trend in sea level (0.013 mm yr^{-2} from *Church and White, 2006*, dotted line). (bottom) Comparison of sediment accretion (black squares) and mineral deposition rates (open circles) in the composite chronology, with standard errors presented for the mineral deposition rates.

Since wetlands here consist of thin peat deposits ($1 \sim 4 \text{ m}$) that overlie hard substrates (e.g., sands, glacial moraines and outwash), the deep compaction that drives subsidence in many deltaic environments [*Reed, 2002*], is likely negligible here. Estimates of wetland compaction rate [*Tornqvist et al., 2008*] suggest that it is proportional to overburden, and that thin wetlands ($<4 \text{ m}$) like these will have compaction rates $<1 \text{ mm yr}^{-1}$.

[10] We specifically looked for local anthropogenic impacts (e.g., dredging effects, land use change, and local eutrophication) and believe that they are minimal in these study sites, in part because sites were specifically selected in environments that were either legally protected or physiographically isolated from direct anthropogenic disturbance [*Kolker et al., 2009*]. The accretion chronology is not consistent with the history of human activities on Long Island where large-scale suburbanization began in the post-World War II era, and continued through ~ 1980 [*Smits, 1974*]. Suburban development typically leads to land clearing and sediment liberation, which is followed by the construction of impervious surface and reduced sediment supplies [*Allen, 2000*]. If suburbanization drove changes in accretion or mineral deposition rates in these systems, one would expect to find increased rates from the 1940s to the 1970s. Instead, the opposite pattern is observed, suggesting that land-use

change is not a dominant signal in these environmental records.

[11] Other studies from this region suggest that changes in sediment availability did not increase in the late 20th century, and are thus unlikely to account for the changes in sediment accretion rates reported here. Mineral fluxes decreased to nearby Hudson River marshes after 1875, as farmlands were reforested [*Pederson et al., 2005*], and a similar transition likely occurred in the marshes along Long Island's north and eastern shores that are surrounded by young forests. A separate study in Long Island Sound used a box-modeling approach incorporating suspended sediment concentrations, settling rates, temperature, salinity, and water velocities and diffusion rates during 1988 and 1989 [*Kim and Bokuniewicz, 1991*] to calculate average sediment accumulation rates to the sounds benthos as 0.92 mm yr^{-1} [*Kim and Bokuniewicz, 1991*]. These rates are very close to rates determined from ^{210}Pb and ^{14}C in sediment cores in the sound ($0.7 \pm 0.1 \text{ mm yr}^{-1}$), suggesting little centennial-scale change in regional sediment availability [*Kim and Bokuniewicz, 1991*, and references therein].

[12] The effects of regional meteorological and geological processes are evident in individual sediment cores [*Kolker et al., 2009*]. Long Island marshes respond to both long-term sea-level changes that are driven by eustasy and isostasy, and short-term, dynamically driven sea-level changes, with the relative importance of each forcing depending on the local geomorphology [*Kolker and Hameed, 2007; Kolker et al., 2009*]. These new composite chronologies (Figure 2) help reduce the effects of this local variability and provide a regional assessment of long-term trends.

3.2. Numerical Model of Wetland Response to Sea-Level Rise

[13] In an effort to determine whether sea-level variability alone could explain the pattern of marsh accretion measured at Long Island, we utilized a numerical model that relates bed surface accretion to the depth of mean high water at the New York tide gauge and the dynamic rate of vegetation growth [*Kirwan and Murray, 2007*] (see auxiliary material). The model is based on the sedimentological principle that RSLR increases accommodation space which accelerates sediment deposition rates [*Allen, 2000*] and the ecological observation that modest rates of RSLR lead to increased plant productivity and enhanced sediment accretion [*Morris et al., 2002*]. Modeled accretion accelerates from 1 mm yr^{-1} to about 3 mm yr^{-1} , at a rate of $1.5 \times 10^{-2} \text{ mm yr}^{-2}$ over the 20th century (Figure 2). Modeled rates are well correlated with measured accretion rates ($r = 0.51$, $p < 0.01$, $df = 33$), and are similar in magnitude to the measured rate of sediment accretion ($0.8 \sim 5.0 \text{ mm yr}^{-1}$ for both modeled and measured rates) and the corresponding rate of accretion acceleration ($\sim 0.02 \text{ mm yr}^{-2}$ for both modeled and measured rates). Experiments where vegetation effects were removed are better correlated with the measured accretion rates ($r = 0.72$, $p < 0.01$, $df = 63$), however the overall magnitude is lower ($0.9 \sim 1.4 \text{ mm yr}^{-1}$ without plants vs. $0.8 \sim 4.7 \text{ mm yr}^{-1}$ with plants). Since the model is forced only by changes in sea level, it helps provide an assessment of how accretion rates might change when other drivers of wetland accretion, such as storms and changes in sediment delivery, are absent.

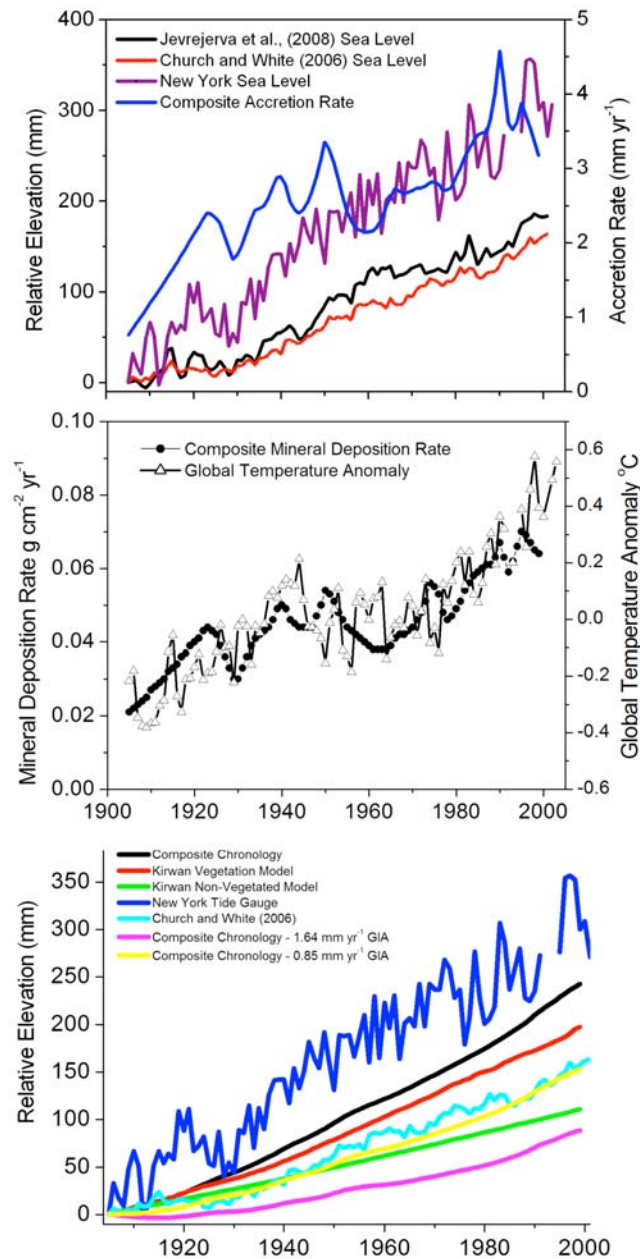


Figure 3. Comparison of temporal trends marsh accretion and mineral deposition rates with trends in sea level and global temperature. (top) Composite wetland accretion chronology compared with global and regional sea level indices. (middle) Comparison of mineral deposition rates and the global temperature anomaly [Smith and Reynolds, 2005]. (bottom) Relative change in elevation from the composite accretion rate data, in its raw form, when corrected for two models of global isostatic adjustments (GIA), and the ecogeomorphic model (vegetated and non-vegetated). Also plotted are the New York Tide Gauge (<http://www.pol.ac.uk/psmsl/>), and the global sea level reconstruction of Church and White [2006]. For comparative purposes, all data sets have been adjusted so that 1905 = 0 mm.

3.3. Relationship to Global Climate Change

[14] In an attempt to further examine the response of these wetlands to GSLR, we compared our accretion rate chronology with two global sea level datasets, both derived from tide gauges, that show a similar magnitude of sea level rise acceleration, but differ in their timing. The observed acceleration in accretion rate in these Long Island marshes is $2.3 \pm 2.0 \times 10^{-2} \text{ mm yr}^{-2}$, while the rate of GSLR acceleration determined by Church and White [2006] for the period 1870–2004 is $1.3 \pm 0.6 \times 10^{-2} \text{ mm yr}^{-2}$, and the acceleration determined by Jevrejeva *et al.* [2008] for the period 1700–2009 is $\sim 1.0 \times 10^{-2} \text{ mm yr}^{-2}$. These rates are broadly comparable despite being determined using methods with different levels of temporal resolution (Figure 2). (The geochronologies have a 2–5 yr resolution [Kolker *et al.*, 2009], while the tide gauge record is based on nearly continuous observations). This assertion is substantiated by the mineral deposition record, which also shows an acceleration that is strongly correlated ($R^2 = 0.90$) with the acceleration in accretion rates. Taken together, these datasets suggest that wetland accretion and mineral deposition are linked to an increase in accommodation space driven by GSLR. This view is consistent with long-held views that wetland accretion is linked to RSLR [Allen, 2000; Redfield, 1972], and provides independent support for altimeter and tide gauge observations that GSLR is accelerating [Church and White, 2006; Jevrejeva *et al.*, 2008; Merrifield *et al.*, 2009]. The slightly higher rates observed in the wetland accretion record suggest that non-linear factors may affect a wetland's response to accelerated SLR – a topic which deserves further research. The structure of the variability in accretion rate and wetland elevation change is also similar to the structure of the variability in the New York tide gauge and global sea level (Figure 3). This is important because linkages between the position of annual mean sea level and accretion rate are a good indicator of a wetland's response to long-term changes in sea level [Kolker *et al.*, 2009].

[15] The composite temporal patterns of accretion and mineral deposition rates in these wetlands are also similar to variations in global temperature (Figure 3, $r = 0.80$ $df = 71$). This relationship indicates that accretion rates increased at a rate of $3.0 \text{ mm yr}^{-1} \text{ per } ^\circ\text{C}$ of global temperature, which is strikingly similar to findings that 20th century GSLR increased at a rate of $3.4 \text{ mm yr}^{-1} \text{ per } ^\circ\text{C}$ of global temperature [Rahmstorf, 2007], and suggests a close linkage between climate change, the rate of GSLR, and the rate of the response of these wetlands. We propose two non-mutually exclusive reasons for this linkage. First, temperature influences the rate of GSLR, and the amount of time that wetlands are flooded, which leads to changes in mineral deposition and vertical accretion [Redfield, 1972]. Second, global temperature changes may also be increasing the length of the growing season, resulting in increased plant growth and enhanced sediment trapping by plant stems [Kirwan *et al.*, 2009].

[16] While climate change appears to be the dominant signal in these cores, it cannot explain every pattern. Our composite chronology of wetland accretion is limited to Long Island wetlands and is influenced by local processes [Kolker *et al.*, 2009]. Periods of divergence, e.g., 1905–1925, 1990–2000, may reflect divergences between local and regional sediment availability, impacts of nutrient loadings

on marsh processes, local anthropogenic changes, or periods when sea-level rise exceeded the ability of wetlands to accrete vertically. Nevertheless, we observe a long-term acceleration in accretion and mineral deposition rates that is remarkably similar to estimates of GSLR and temperature change. These findings indicate that a signal of climate change is discernable over a background of natural variability, and we expect the general response of wetland accretion to sea level acceleration to be more widespread. The response of these systems to future sea-level changes depends on the rate of climate change, the availability of sediment to support accretion, and the nature of other human impacts to the coastline.

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