Wetlands Ecol Manage (2011) 19:373–388
DOI 10.1007/s11273-011-9222-6

ORIGINAL PAPER

Inter-annual variability in Delaware Bay brackish marsh vegetation, USA

Michael S. Kearney · J. C. Alexis Riter

Received: 27 February 2011 / Accepted: 7 June 2011 / Published online: 22 June 2011

Abstract Reports of sudden marsh browning, or even dieback, suggest that the many heretofore "healthy" coastal marshes have reached some tipping point with respect to sea level rise, necessitating better and more widespread monitoring. In this paper, we examine spatial and temporal variations in marsh vegetation cover, substrate wetness, and sediment exposure for mesohaline to oligohaline marshes in Delaware Bay over a 15-year period (1993–2008) using three spectral indices (the Normalized Difference Vegetation Index, the Normalized Difference Water Index, and the Normalized Difference Soil Index) based on Landsat Thematic Mapper and Enhanced Thematic Mapper + imagery. In general, degrading marsh areas show low percentages of vegetation cover compared to bare marsh substrate, and substrate wetness tends to be high. But this characterization is not consistent from one year to the next, and in marshes that are in incipient stages of degradation, apparent vegetation health can improve substantially for a few years. Detailed transect data collected from July to September in an area of Bombay Hook National Wildlife Refuge, where little marsh loss was evident, document considerable variability in vegetation dynamics. The marshes along the transect kept pace with the major transgressive pulse of the 1990s, but as the rate of sea level rise decreased after 2000, vegetation vigor fell, especially in 2004, the year after Hurricane Isabel. The years of maximum vegetation cover, 2003 and 2005, coincided with short-term, sea level high stands and/or very wet and cooler summers. We theorize that after keeping up with the dramatic rise in sea level during the 1990s, marsh surface elevations in these microtidal systems are now too high to allow adequate flushing of sulfides and low dissolved oxygen waters except for high precipitation events or short-term sea level rises. If this situation were to continue, it could affect the "health" of marshes that otherwise were accommodating high rates of sea level rise well.

Keywords Marsh vegetation · Delaware Bay · Remote sensing · Sea level rise · Hurricane impacts

M. S. Kearney (✉) · J. C. Alexis Riter
Department of Geography, University of Maryland,
College Park, MD 20742, USA
e-mail: mkearney01@yahoo.com

J. C. Alexis Riter
e-mail: ariter99@yahoo.com

Introduction

The impact of accelerated sea level rise on coastal marshes is a major concern for assessing coastal responses to global climate change. Over the past 30 years, research on how marshes (and other coastal wetlands) adjust to changes in rising sea levels has demonstrated that marsh survival is jeopardized when marsh surface elevations fail to keep pace with relative sea level rise; such marshes are invariably characterized by slower rates of *net* vertical accretion (i.e., vertical accretion adjusted for factors like sediment compaction) compared to mean trends for regional sea level rise deduced from tide gauges (Stevenson et al. 1986; Reed 1995). The factors at play on both sides of this relationship vary in time and space. The determinants of vertical accretion are in particular subject to considerable in situ variations (often within a few meters; Kearney et al. 1994), reflecting changes in canopy structure and the inherent inconstancy of suspended sediment fluxes from transient phenomena like storms. For brackish marshes that characterize much of the U. S. Atlantic and Gulf Coasts, the potential for spatial (let alone temporal) variability in rates of vertical accretion becomes even greater, especially for lower salinity mesohaline to oligohaline marshes where species diversity and biomass reach a maximum in most estuaries (Sharpe and Baldwin 2009). In such circumstances, the likelihood of capturing a realistic, coast-wide marsh response to sea level rise from a few field sites seems at best remote.

Accounting for short-term spatial and temporal variability in coastal marshes that may reflect factors other than sea level variation is crucial to obtain a lower "signal-to-noise" characterization of marsh response to sea level rise. A clear example is the phenomenon of "sudden dieback" in otherwise ostensibly healthy marshes, with reports encompassing the appearance of bare patches to widespread marsh "browning" (Alber et al. 2008; Christopher Bason, Center for the Inland Bays, personal communication 2005). Various reasons are offered for the phenomenon, from low dissolved oxygen to inadequate flushing of sulfides (Mendelssohn and McKee 1988; Mendelssohn and Morris 2000). But whatever the cause or causes—and especially if low vertical accretion rates are implicated—sudden dieback or marsh browning remains mysterious if for no other reason than it seems to be reversible in some circumstances. In any event, understanding more fully the differences between transient changes in apparent marsh vigor versus the onset of an actual sustained decline could provide for better planning of where to target mitigation efforts. In this paper, we examine large scale inter-annual variability in vegetation of brackish marshes of the Delaware River estuary (Fig. 1) obtained with Landsat Thematic Mapper and Landsat Enhanced Thematic Mapper + data.

Methods

Study area

The area of Delaware Bay selected for study is in the mesohaline reaches of the estuary (Fig. 1). This area is characterized by extensive marshes of the Bombay Hook National Wildlife Refuge on the Delaware

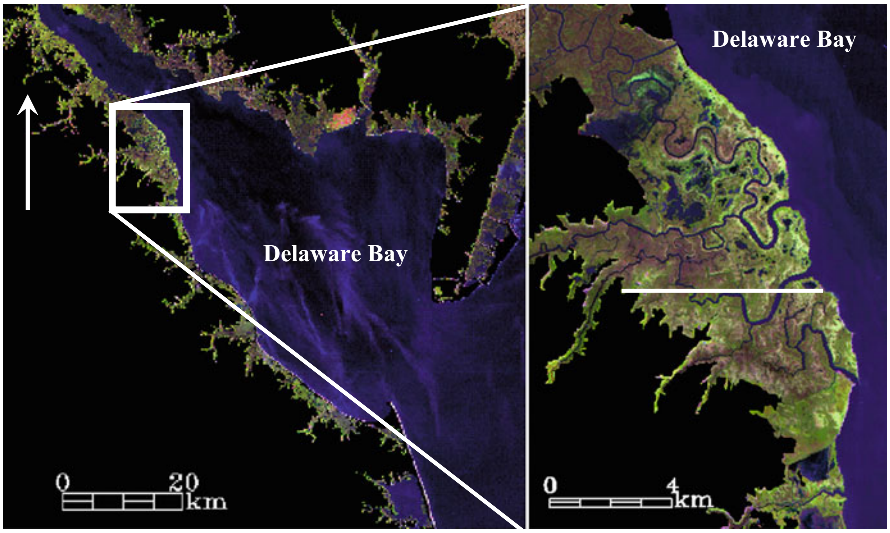

Fig. 1 Landsat Thematic Mapper color composite image (Landsat bands 3, 4, 5) of Delaware Bay, USA, for August 29, 1993, with the study area outlined by a white rectangle. An enlargement of Bombay Hook is on the *right*, with the Simons River transect indicated by a *white line*

shore, which consist of broad marsh physiographic types such as submerged upland, fringe and estuarine meander marshes as well as marsh islands (cf. Stevenson et al. 1986). Similar marsh types occur on the New Jersey shore. Levees along tributaries, guts between marsh islands, and more elevated areas of shorelines on both sides of the bay are typically distinguished by Atlantic Giant Cordgrass Marshes, dominated by *Spartina cynosuroides*. Brackish Tidal Low Marshes dominated by *Spartina alterniflora* comprise most shorelines (Westervelt et al. 2006). In lower salinity, oligohaline areas along tidal creeks and the in the vast interior areas of large submerged marshes, several marsh communities occur, the most common being Central Atlantic Brackish Marsh with characteristic species such as *Schoenplectus robustus, Spartina patens, S. alterniflora,* and *Amaranthus cannabinus* (Westervelt et al. 2006). *Typha angustifolia*, *Phragmites australis*, and *Hibiscus moscheutos* dominate in well-drained, upland marsh margins.

Two major reasons guided the selection of this area of Delaware Bay for the study. First, there is a pronounced seasonal difference in allochthonous sediment inputs between marshes on the Delaware shore as opposed to those on the New Jersey shore. Depending on the frequency of nor'easters during winter in any particular year, waves generated by strong northeast winds from these storms tend to produce substantial input of subtidal sediment from nearshore areas into marshes on the Delaware shore from overwash (Stumpf 1983). In contrast, the same northeast winds blow water and sediment out of marshes on the New Jersey shore. This seasonal disparity in sediment influx, no doubt manifested in lower vertical accretion rates in the New Jersey marshes, yields substantial differences in the level of marsh degradation between both shores (Kearney et al. 2002). The two Delaware Bay shores thus provide a useful basis for contrasting inter-annual variability in vegetation vigor between marshes presumably differing in their ability to maintain surface elevation with sea level rise.

The second reason for choosing this part of the Delaware Bay was to avoid the extensive areas of marsh restoration in the most seaward part of the New Jersey shore in Cape May and southern Cumberland counties. Though no large marshes on either shore of the Delaware Bay are entirely free from human intervention (e.g., marsh burning and spraying of herbicides for *Phragmites* control), the scale and type of restoration efforts in these counties could introduce a source of variability that might blur any more typical inter-annual phenomena.

Sensor and data selection

The Landsat TM and ETM + sensors provide an optimal combination of spatial and temporal resolution and the spectral wavelength detectors required for this study (Table 1). Other no- or low-cost satellite data available for this study either had to be pre-ordered for data collection, had low spatial resolution, or lacked the 1.567–1.784 μm infrared band/channel required (Table 1). Some commercial satellite data have advantages in terms of higher special resolution; but again, generally lack a long temporal archive.

We chose seven Landsat data sets to investigate changes between 2003 and 2008, a period which witnessed several hurricanes or tropical storms (including Isabel in September 2003) and two fluctuations in relative sea level, a regressive phase in 2003–2004 and a slight transgressive phase between 2005 and 2007. For comparison, we also analyzed images from 1993 and 1999, which approximate the beginning and the end of the major transgressive episode of the 1990s (cf. Kearney et al. 2002). The criteria for selection of images were based on: (i) atmospheric clarity (few or no clouds or haze); (ii) tidal stage approaching mean lower low water (MLLW) since reflectance can be significantly diminished by high water levels; and (iii) the peak stage in vegetation growth for Landsat Path 14 Row 33 scenes of Delaware Bay. Since no single image between 1993 and 2008 met ideal atmospheric, tidal and growth-stage characteristics, the nine Landsat scenes selected (Table 2) were those judged to be at least acceptable in terms of tidal and atmospheric requirements, recognizing that optimal ground or atmospheric conditions seldom are available.

Peak vegetation growth stage typically occurs in mid-July through mid-August depending on weather conditions. Inspection of true-color images of the Landsat scenes available on the United States Geological Survey Global Visualization Viewer (USGS GLOVIS) web site confirmed that vegetation health varies significantly over the course of the summer

Table 1 Comparison of Landsat Thematic Mapper, Landsat Enhanced Thematic Mapper +, Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), NOAA Advanced Very High Resolution Radiometer (AVHRR), and Moderate Resolution Imaging Spectrometer (MODIS) sensor system characteristics (Jensen 2000; Chander et al. 2009)

Spectral resolution (μm)	L5 TM	L7 ETM +	ASTER	AVHRR	MODIS
Band 1	0.452–0.518	0.452–0.514	0.52–0.60	***0.580–0.68***	***0.620–0.670***
Band 2	0.528–0.609	0.519–0.601	***0.63–0.69***	**0.725–1.10**	**0.841–0.876**
Band 3	***0.626–0.693***	***0.631–0.692***	**0.76–0.86**	3.55–3.93	0.459–0.479
Band 4	**0.776–0.904**	**0.772–0.898**	**1.600–1.700**	10.30–11.30	0.545–0.565
Band 5	**1.567–1.784**	**1.547–1.748**	2.145–2.185	11.50–12.50	1.230–1.250
Band 6	10.45–12.42	10.31–12.36	2.185–2.225		**1.628–1.652**
Band 7	2.097–2.349	2.065–2.346	2.235–2.285		2.105–2.155
Band 8		0.52–0.90	2.295–2.365		0.405–0.420
Satellite	Landsat 5	Landsat 7	Terra	NOAA 6–14[a]	Terra and Aqua
Launch date	March 1984	April 1999	December 1999	June 1979–December 1994	December 1999 May 2002
Altitude (km)	705	705	705	851	705
Inclination (°)	98.20	98.20	98.30	98.922	98.00
Number of bands/ channels	7	8	14	5	36
Spatial resolution (m unless otherwise noted)	30	30 15 for band 8	15 for bands 1–3, 30 for bands 4–9, 60 for bands 10–14	1.1 km	250 for bands 1–2, 500 for bands 3–7, 1 km for bands 8–36
Swath width at nadir (km)	185	185	60	2,700	2,330
Repeat cycle (in days)	16	16	16, but collected only upon demand	<1	1–2

Spectral resolutions only provided for first seven ASTER bands and MODIS channels. The ASTER, AVHRR and MODIS band and channel wavelengths equivalent to Landsat bands 3, 4, and 5 are in bold font and are italicized, underlined and in bold font only respectively

[a] There are 14 NOAA satellites, each of which carries an AVHRR sensor

Table 2 Dates and overpass times of Landsat TM and ETM + Path 14 Row 33 scenes used in this study

Date	Landsat overpass time GMT	Landsat satellite	Water height in meters and (ft) above MLLW
1993 August 29	15:02:38	TM	+0.46 (1.5)
1999 July 5	15:33:01	ETM +	+0.70 (2.3)
2003 August 25	15:17:13	TM	+0.30 (1.0)
2004 August 11	15:23:10	TM	+0.21 (0.7)
2005 August 14	15:28:18	TM	+0.30 (1.0)
2006 August 17	15:33:43	TM	+0.37 (1.2)
2008 July 21	15:26:42	TM	+1.28 (4.2)
2008 August 22	15:25:47	TM	+1.22 (4.0)
2008 September 7	15:25:20	TM	+0.70 (2.3)

Tidal stage at the Lewes, Delaware tide gauge station at time of Landsat TM or ETM + overpass is from http://tidesandcurrents.noaa.gov/data_menu.shtml?stn=8557380%20Lewes,%20DE&type=Historic%20Tide%20Data

(late June through early September). We decided to use August scenes whenever possible to insure that summer maximum growth was captured in years where marsh “green-up” was delayed by a cooler than average spring and early summer. No images from 2007 were included in the study because summer images for this year proved unsuitable for analysis due to heavy cloud or haze cover.

Accommodating the influence of tidal fluctuations

Five of the nine images (Path 14 Row 33) are 0.21–0.5 m (1.0–2.3 ft) above MLLW at the Lewes, Delaware, tide gauge station (National Oceanic and Atmospheric Administration [NOAA] National Ocean Service tide station ID# 8557380) at the time of the Landsat satellite overpass (http://tidesandcurrents.noaa.gov/) (Table 2). The mean tidal range is approximately 1.5 m (5 ft) at Lewes, Delaware, and increases to the north.

We analyzed four Delaware Bay data sets from a transect along the Simons River in Bombay Hook National Wildlife (Fig. 1) from July through August 2006 to September 2008 to determine the effect of tidal stage on the marsh surface condition (Fig. 2). The tidal range encompassed by these four images is near 1 m (+0.91 m). Although we expected this comparatively significant difference in tidal stage to be reflected in a parallel significant increase in the percentage water at higher tidal stages, the difference in percent water along a transect adjacent to the Simon River in Bombay Hook was typically less than 6%, and large areas of the marshes had only a 1 or 2% difference in the percentage of water, well within the range of error. The greatest deviations in water level occurred at the shoreline, which can be interpreted as the effects of waves from onshore winds.

Spectral unmixing model

A spectral unmixing model developed for assessing change in marsh surface condition (Kearney et al. 2002; Rogers and Kearney 2004) was used to decompose pixels from Landsat composite images into spectral end members for vegetation, water, and soil after deriving radiance from co-registered scenes using standard techniques, and then applying the FLAASH module for atmospheric correction and calculation of surface reflectance (Jensen 2000; Chander et al. 2009; Berk et al. 2002). The three end members are defined in the linear mixture model as:

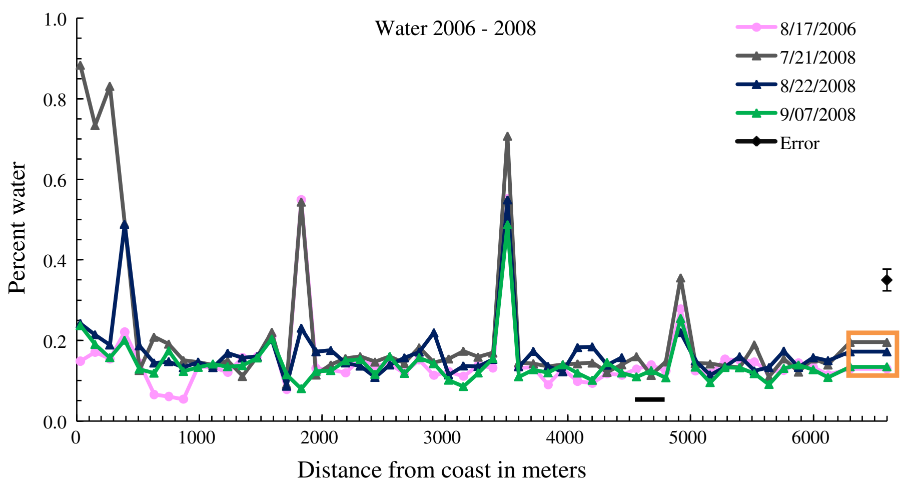

Fig. 2 Comparison of the percentage water for August 17, 2006, July 21, 2008, August 22, 2008, and September 7, 2008 detected in pixels on a traverse from 30 m from the Delaware Bay to the edge of the Bombay Hook National Wildlife Refuge. A break in the August 22, 2008 line on this and other graphs is due to cloud cover over the pixels located 4560, 4680, and 4800 m from the coast. The missing data are indicated by a *black line* at the base of the graphs. Although the tidal stages for the July 21, 2008 and August 22, 2008 data are 1.7–1.8 times higher than that for September 7, 2008, the differences in the water percentages for these data are well within the errors for the method (see error bar in lower right corner). The largest peaks occur where the traverse crosses or approaches a body of water, typically the Simons River (e.g., 1830 m from Delaware Bay). The estimated error, equivalent to the maximum error calculated for the nine dates based on the standard deviation of 34 airfield pixels at the Dover Air Force Base, is shown at the *far right* of the graph in *black* (Table 4)

$$R_1 = \rho_{v1} f_v + \rho_{w1} f_w + \rho_{s1} f_s \quad (1a)$$

$$R_2 = \rho_{v2} f_v + \rho_{w2} f_w + \rho_{s2} f_s \quad (1b)$$

$$R_3 = \rho_{v3} f_v + \rho_{w3} f_w + \rho_{s3} f_s \quad (1c)$$

where the ρ's represent the reflectance of a given substrate for a particular band; v, w, and s represent vegetation, water, and soil respectively; the f's represent the proportion of the pixel covered by vegetation, water, or soil; and the R's represent the total reflectance in each band of all the individual substrate reflectances (Rogers and Kearney 2004). Two other assumptions are that f_v, f_w, and f_s are greater than or equal to 0 and that

$$f_w + f_v + f_s = 1. \quad (2)$$

Marsh sediments encompass a wide range of reflectance values (Borel and Gerstl 1994); therefore, we calculated three spectral indices, the Normalized Difference Vegetation, Water and Soil Indices, by normalizing the difference between Landsat bands to define a data space where variations in vegetation, water and soil end member spectra are reduced (Rouse et al. 1974; McFeeters 1996; Rogers and Kearney 2004):

$$\mathrm{NDVI} = (\rho_{\mathrm{band\,4NIR}} - \rho_{\mathrm{band\,3Red}})/(\rho_{\mathrm{band\,4NIR}} + \rho_{\mathrm{band\,3Red}}) \quad (3a)$$

$$\mathrm{NDWI} = (\rho_{\mathrm{band\,3Red}} - \rho_{\mathrm{band\,5IR}})/(\rho_{\mathrm{band\,3Red}} + \rho_{\mathrm{band\,5IR}}) \quad (3b)$$

$$\mathrm{NDSI} = (\rho_{\mathrm{band\,5IR}} - \rho_{\mathrm{band\,4NIR}})/(\rho_{\mathrm{band\,5IR}} + \rho_{\mathrm{band\,4NIR}}). \quad (3c)$$

The use of normalized difference indices eliminates some of the noise contained in the data sets; however, it was necessary to constrain the sum of the fraction of the three components to 1 to obtain results. This should not have been necessary for data sets that met the rigorous mathematical standards of linear unmixing.

The composite NDX data set was produced by stacking the NDVI, NDWI and NDSI data for each of the scenes selected. We used image-derived, end member spectra, which yield better results than theoretical (ideal) spectra. However, the ability to obtain "pure" spectra from satellite data for an end member is limited typically by the presence of small areas of other end member components. The three end members were then used to spectrally unmix the NDX data sets to determine the % vegetation, % water and % soil in each pixel.

To validate the accuracy of the spectral mixture model, algorithms reproducing the pattern of rivers, streams, and creeks on the September 7, 2008 imagery were compared to aerial photography collected for the study area on September 3–4, 2008 by the Delaware Department of Natural Resources and Environmental Control (DNREC). Testing of algorithms yields a water-and-soil algorithm [($\mathrm{Al_{WS}}$) = (percent water + 0.10) + (percent soil × 0.45)] that best replicated the September 3 and 4, 2008 DNREC photographs; however, it also produced much greater amounts of degradation for most Landsat data sets then the water-only algorithm ($\mathrm{Alg_{W2.25}}$) = (percent water × 2.25). This may be in part reflect that the tidal stage (+0.70 m above MLLW) for the September 7, 2008 data set was significantly higher than the average tidal stage (+0.44 m). The other data sets, collected at lower tidal stages, may have been characterized by more exposed soil adjacent to tidal creeks, resulting in some marshes being classified as more degraded.

Results

Changes in overall surface condition 1993–2008

Changes in the percentage of vegetation per pixel and relative marsh degradation (based on percentage of soil and water per pixel and water per pixel) for mid-August from 1993–2008 are shown in Fig. 3. In general, there appears to be no consistent year-to-year trend in any of the indices. Several areas on both shores regularly (if not for each year selected) tended to be classified as either degraded or non-degraded (i.e., the area northwest of the transect in Bombay Hook), and vegetation percentages are generally lower on the New Jersey shore. Percent vegetation was highest on both shores in this area of Delaware Bay in 2003 and 2005, with almost an equally high percentage reflectance observed in 1993, the earliest scene examined. In contrast, percent vegetation notably declined in 2004 and 2006. On the marsh surface condition maps based on the water-and-soil and water-only algorithms (Fig. 3), areas of likely degradation mostly coincide with those where

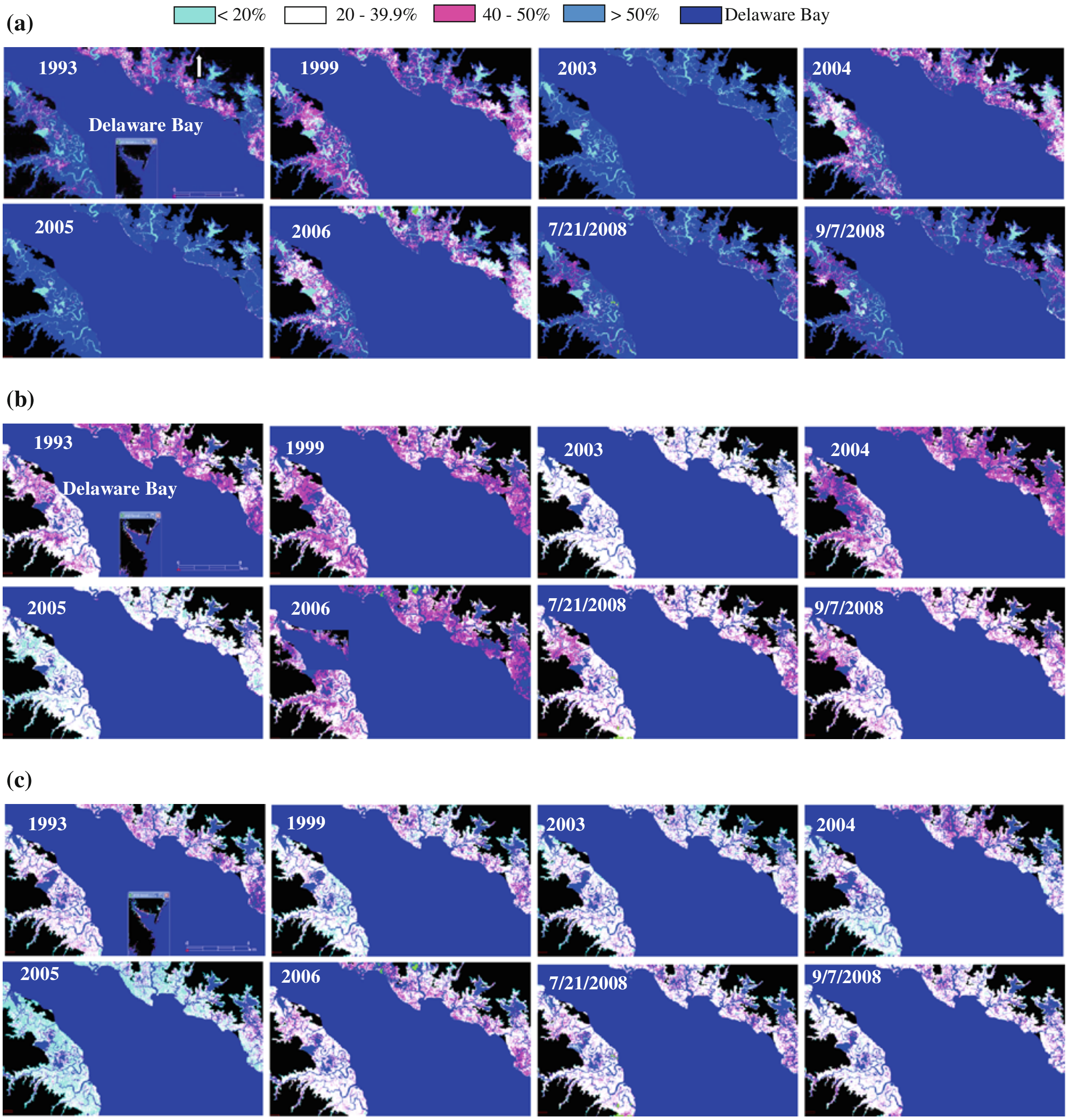

Fig. 3 Spatial variation in the degree of marsh degradation as estimated from spectral unmixing for: **a** the percentage of vegetation, **b** the water-and-soil algorithm, and **c** the water-only algorithm for August 29, 1993, July 5, 1999, August 25, 2003, August 11, 2004, August 14, 2005, August 17, 2006, July 21, 2008, and September 7, 2008. The results for August 22, 2008 are not shown but are similar, showing slightly more degradation than the results for the September 7, 2008 data set

vegetation percentages are low. Undoubtedly, this reversal in the percentage of vegetation versus other components (water and soil) to some degree can be attributed to problems of closure when dealing with percentages that sum to a hundred percent. However, it is reasonable to assume that as percent vegetation falls off at least some of this change indicates a decline in biomass, with a concomitant drop in general leaf area and greater reflectance of the marsh surface or water.

Spatial changes

Bombay Hook National Wildlife Refuge was used to determine spatial changes in the three indices since marsh burning was discontinued after 1999 in the refuge, and areas treated for *Phragmites* control are well mapped and can be avoided. A transect, adjacent to Simons River, was selected across an area of Bombay Hook that spanned the widest range of marsh types and sedimentary environments, ranging from shorelines dominated by *S. alterniflora* to uplands with *T. angustifolia* and *P. australis*.

Figure 4 a, b, and c shows change in percent vegetation for all years examined, as well as for the periods between 1993–2005 and 2006–2008. August, 1993, was chosen as the earliest year for the analysis, as this image for this date was not only cloud-free, but also the clearest with respect to the effects of aerosols (mainly high water vapor) in the early Landsat Thematic Mapper archive. The decreases in percent vegetation at 1830 m in the transect, where it crosses a major tidal creek, serves as a reference point. The vigor of shoreline vegetation appears to have declined consistently, which probably indicates shore erosion, a common local phenomenon from waves from northeast winter storms (cf. Stumpf 1983). This decrease paralleled changes in a series of small interior ponds between 500 and 800 m, which between 1993 and 2003 (Fig. 4a) appear to have become larger as suggested by measurements of their perimeters in bands 3, 4, 5 composites. After 2004, the ponds appear to have been initially diminished size, especially between 2004 and 2006 (Fig. 4a, b), and then have been more or less stable.

The high inter-annual variability should not be surprising, given the dynamics of coastal marshes. However, comparing transects for 1993 and 1999 (Fig. 4a) suggests that there has been a relative long term decline in the vegetation vigor in this part of Bombay Hook marsh system. This supports earlier conclusions (Kearney et al. 2002) based on 1984–1993 Landsat data that indicated overall marsh substrate condition in Bombay Hook was degrading, particularly in the area immediately north of the transect which was (and is) characterized by large and enlarging interior ponds and declining plant biomass. Sea level rise was proposed as triggering this widespread deterioration in marsh health and structure (Kearney et al. 2002). The 1990s witnessed one of the highest periods of relative sea level rise for almost half-a-century, approaching an average annual rate of greater than a centimeter per year (Kearney et al. 2002). However, whether this exceptional secular jump in the relative sea level trend left a permanent imprint on the transect marshes is complicated by two factors: (i) the occurrence of Hurricane Isabel in 2003, and (ii) a flattening of the sea level trend since 2000 that may have allowed other stressors to come into play.

Hurricane Isabel

2004 was characterized by the second lowest year value for percent vegetation, and bracketed by the years of the highest apparent vigor of all those examined, with 2005 exhibiting a dramatic turnaround in vegetation condition (Fig. 4a). Hurricane Isabel made landfall on the mid-Atlantic Coast on September 18, 2003 and moved landward through Virginia, West Virginia, and western Pennsylvania. Though a fairly “dry” storm in terms of its total precipitation yield and one which weakened to a tropical storm soon after landfall (Matarrese et al. 2005), its wind field was still strong enough to produce maximum sustained winds at Dover Air Force Base (the closest meteorological station to the study area) of almost 100 km/h on September 18 with sustained winds the following day of 66 km/h (http://www.tutiempo.net). The storm produced high waves, a significant storm surge, and extensive coastal flooding which compounded the extensive flooding that resulted from Tropical Storm Henri in Delaware Bay less than a week earlier (see http://www.fema.gov/news/event.fema?id=2446/). By comparison, 2005 saw the highest percent vegetation across the transect landward of 2000 m from the shoreline. Hence, it is possible that the dramatic drop in percent vegetation in 2004 is a manifestation of marsh damage from Hurricane Isabel and Tropical Storm Henri. A mostly bare marsh surface portrayed by the soil index (Fig. 5) appears to corroborate this, and the literature of tropical storm impacts highlights often extensive surface sedimentation by storm surges and waves (Turner et al. 2006; McKee and Cherry 2009), with concomitant adverse effects on perennials like *Spartina* at the rhizome level (though it may not be permanent; McKee and Cherry 2009). Landsat TM and ETM + composite images for November and

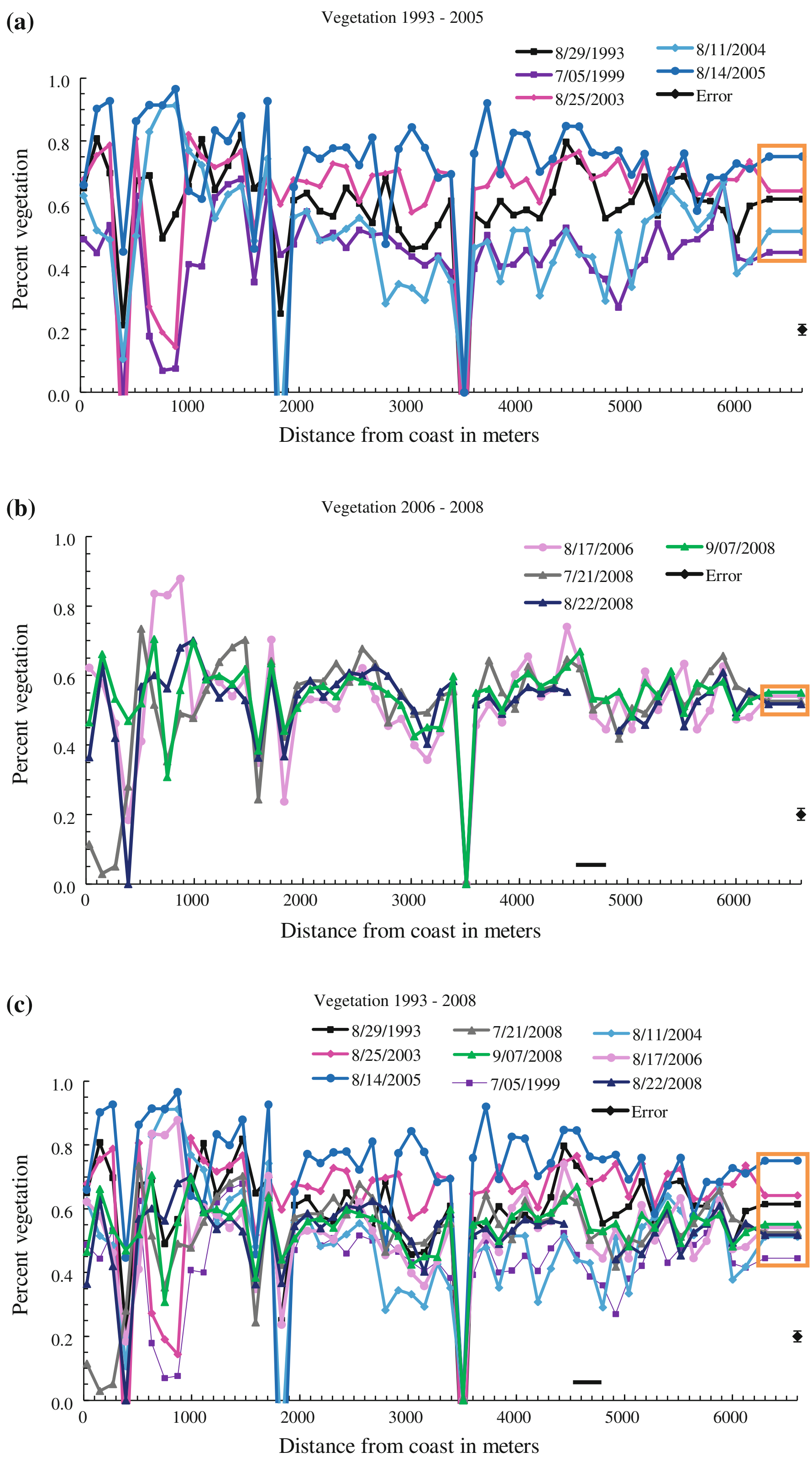

Fig. 4 Changes in percent vegetation per pixel for: **a** 1993–2004, **b** 2005–2008, and **c** 1993–2008 along the Bombay Hook transect line calculated for spectral unmixing results of composite NDXI stacked images of NDVI (vegetation), NDWI (water), and NDSI (soil) of each of the nine Landsat data sets. *Boxes* on the *right* indicate the calculated average for each date. The calculated averages exclude pixels representing Simons River. The estimated error, equivalent to the maximum error calculated for the nine dates, is shown at the *far right* of the graph in *black* (Table 4)

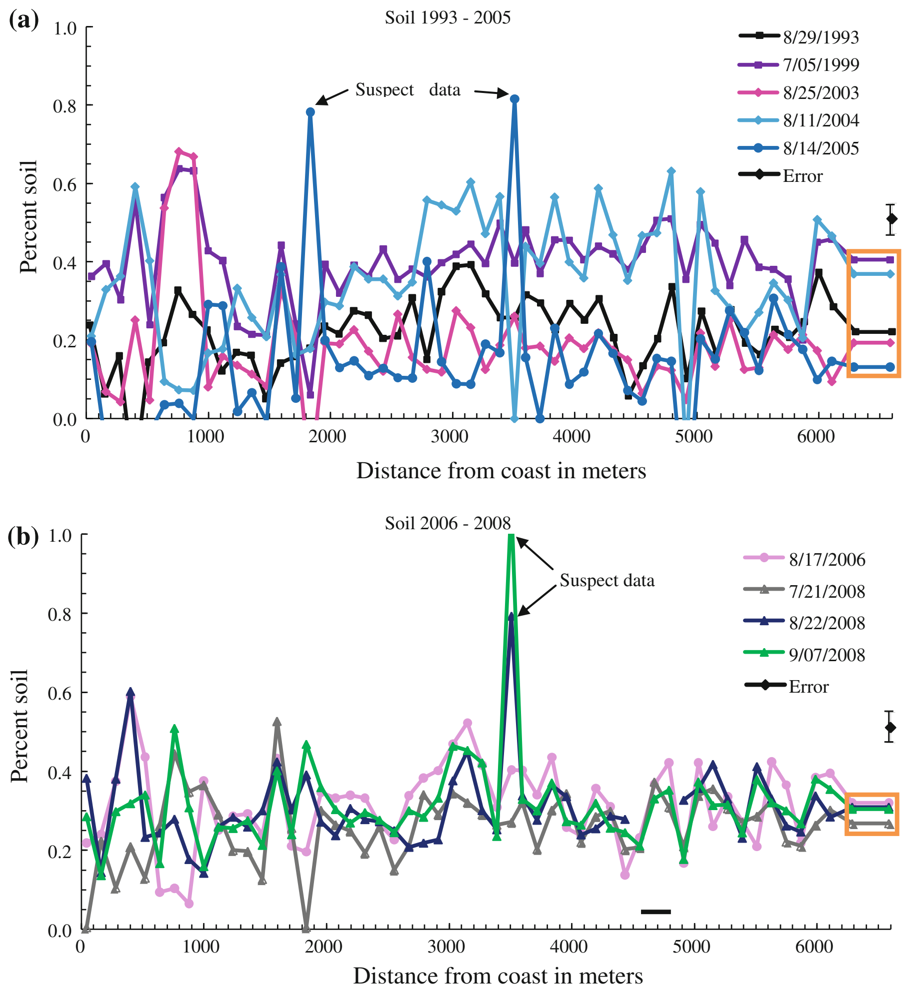

Fig. 5 Changes in soil percentage coverage for the Bombay Hook transect: **a** for 1993–2005 and **b** 2006–2008. The % soil data for the August 14, 2005, August 22, 2008, and September 7, 2008 are suspect as the percent water + percent soil sum to 151, 163, 134%, and 157% respectively for pixels that are located in the Simons River. The estimated error, equivalent to the maximum error calculated for the nine dates, is shown at the *far right* of the graph in *black* (Table 4)

December 2003 (Bombay Hook was cloud covered in October images) showed considerable pond enlargement and erosion compared to images from 2001 to 2003. Both factors exacerbated by prolonged flooding with salt water would not only kill existing plants, but the lingering, above normal salinities in sediment pore water combined with high sediment influx might discourage germination of annuals the following season (cf. Peterson and Baldwin 2004). Either or both of these reasons might underlie the general decrease in percent vegetation values toward the upland boundary shown in the 2004 transect.

Post Isabel changes: effects of sea level and climate variations

Sea levels rose dramatically in Delaware Bay in the 1990s (over a 1 cm/year; Fig. 6a), but since 1999 have slowed and despite a one-year jump in rate in 2005 have remained comparatively flat. Nevertheless, the yearly trend masks considerable intra-annual fluctuations and, in general, the period of 2000–2008 has been notable for the depth of many sharp downturns (Fig. 6b), particularly in 2007, when monthly sea levels dropped briefly to an elevation

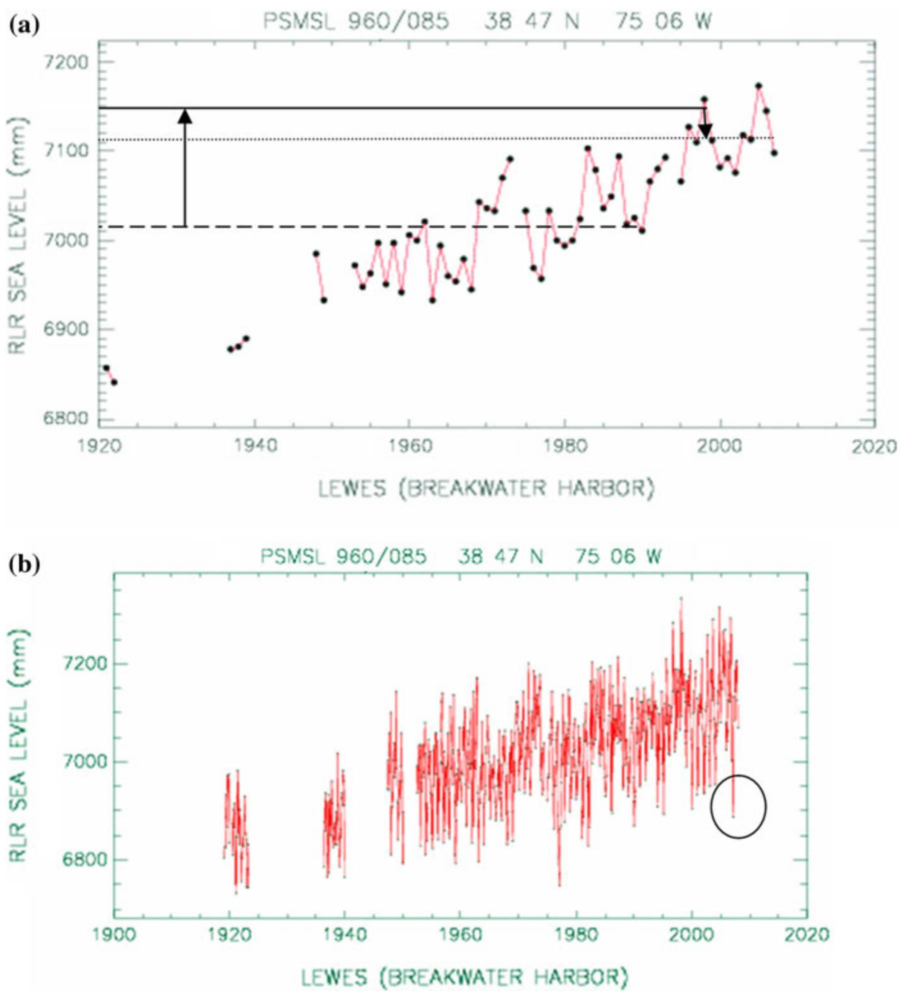

Fig. 6 Graphs of sea level changes from **c**. 1920–2007 for Lewes, Delaware, for both yearly (**a**) and monthly (**b**) periods. Figure 5a also shows the average annual sea level for this area of Delaware Bay for 1988–1990 (*dashed line*), 1999–2000 (*solid line*), and 2001–2007 (*dotted line*). The difference between the *dashed* and *solid lines* is presumably commensurate with the vertical accretion change in marshes of the Bombay Hook transect that occurred during the rapid upswing in sea level during most the 1990s. The difference between the *solid* and *dotted line* shows how high above mean sea level the marsh surface has been on average since 2001. The *circle* in Fig. 5b highlights the exceedingly low monthly still stand in 2007

above the regional datum more characteristic of the late 1980s to early 1990s. This is a very unlikely scenario for "marsh drowning" and, in fact, the percent water figures (Fig. 7) show no significant change for this period, varying between 15 and 20%, except for several years along the shoreline, which probably reflect high tidal stages and shore erosion.

Despite a temporary decline of sea level rise as a stressor since 2000, the values for percent vegetation for most of the present decade are not markedly higher than those for 1993. Curiously, the percent soil cover and percent water since 2000 (Figs. 5, 7) have also varied around the 1993 averages, portraying a marsh by and large in the same relative condition a decade later. The years 2003 and 2005, however, stand in striking contrast, and provide the key to why the marsh vegetation has not otherwise flourished without the continual press of rapid sea level rise upon its ability to sustain surface elevation.

This alternative explanation involves the residual effects that a short period of acceleration in the rate of sea level rise may have on marshes that ostensibly kept pace once the trangressive pulse ends. Though there are no direct data on vertical accretion rates for the transect area, these transect marshes must have accreted at rates at least equal to the tempo of regional sea level change in the 1990s because reconnaissance of the area by aerial photography shows no physical evidence to the contrary, such as incipient interior ponds or bare patches. In keeping up with rising sea levels during this time, their surface elevations should have risen by about 13 cm, an exceptional figure in view of the comparatively slow vertical accretion rates for estuarine marshes in the

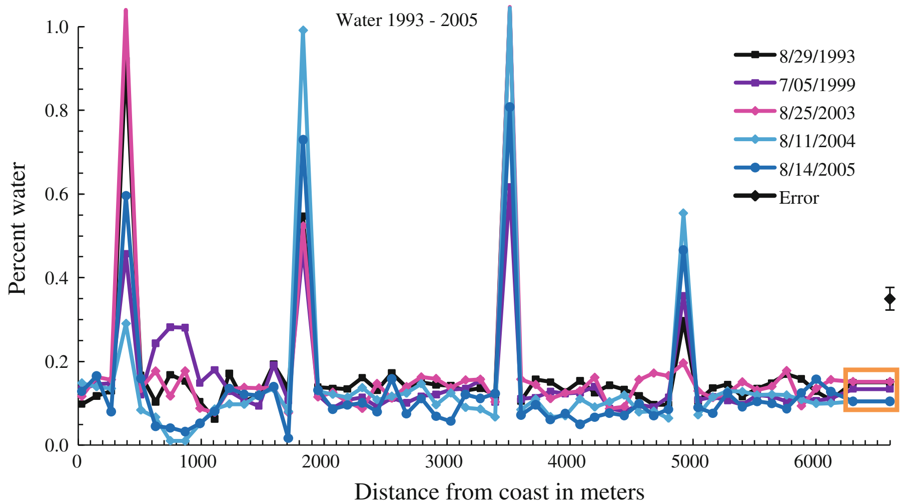

Fig. 7 Changes in percentage water per pixel for the Bombay Hook transect from 1993 to 2008 derived from the Normalized Difference Water Index (NDWI). As noted, the very high percentages for areas at c. 390, 1830, 3500, and 4920 m for most years are where the transect crossed near water bodies, generally the Simons River, the exception being the large interior pond at c. 390 m. In some years, variations in the water percentage response in the area of the pond indicate a probable change in pond size, with pond sizes in the scenes for 1993, 2006, and, in particular, 2003 being apparently smaller than other years. However, the influence of tidal variations cannot be discounted (see caption for Fig. 2)

U. S. middle Atlantic Coast (Stevenson et al. 1986). Since 2000, sea levels have dropped from 3 to 6 cm depending on which tide gauge record (Lewes, Delaware or Cape May, New Jersey) for Delaware Bay is considered. Moreover, there were many (~6) episodes when monthly mean sea levels plummeted to low stands not seen for almost a decade.

The physiological consequences that drought and hot summer temperatures hold for marsh vegetation highlighted in recent literature on marsh browning (DeLaune et al. 1994; McKee et al. 2004; http://www.brownmarsh.net/) point to at least a partial answer. Sudden waning in vigor of otherwise "healthy" marshes has been suggested to result from an excessive accumulation of sulfides coupled with low levels of dissolved oxygen. Ideal conditions for such a scenario are thought to be late summer when peak temperatures promote lower dissolved oxygen levels and rainfall is limited only to sporadic local convective storms, with the upshot that flushing of sulfides from substrates is diminished. Table 3 shows the average temperatures between 1999 and 2008 for the period May 1 to the date of the Landsat observations, and the total precipitation for the same period. Mean summer temperatures vary very little for most years, with the exception of 2003, when the average temperature was almost 2° C below the other years.

Coincidentally, the summer of 2003 also appears to have been comparatively wetter than the summers of other years studied. Compared to the other years examined, climatic conditions at this time should have been more conductive to greater levels of dissolved oxygen (lower ambient water temperatures) and, as well, low sulfide concentrations in the root zone from flushing by rainfall, despite the relatively low sea level. It is probably not coincidental that the high percent vegetation values for August 2003 (the second highest of the years studied) suggest that the marsh plant growth was much more hardy than average.

By comparison, during the summer of 2005, the year when marsh vegetation growth seemed to have particularly thrived, mean sea level had jumped to all time high, promoting even greater flooding and flushing of the marsh at high tides. Moreover, though average temperatures were close to the mean for all years and average maximum temperature was high (but not exceptional) total summer precipitation was only 120 mm lower than the peak of 2003. Greater tidal flushing of marsh substrates from higher sea levels coupled with enhanced freshwater dilution of

Table 3 Mean and maximum monthly temperatures and mean monthly precipitation between 1999 and 2008 for Dover Air Force Base, Delaware

Year	Total precipitation (mm) May 1 − DO	Mean temperature (°C) May 1 − DO	Maximum temperature (°C) May 1 − DO
1993	256.8	22.7	28.0
1999	No data	22.3	27.6
2003	556.3	20.5	25.4
2004	338.4	22.4	27.0
2005	432.6	22.1	26.6
2006	384.1	22.5	27.6
2008	291.8	22.5	28.6

Data from www.tutiempo.net. Data for precipitation and temperature are average for the first month of average full "leaf out" (May) through the date of the observation by the satellite (DO in the table heading)

Table 4 Average spectral unmixing results of percent vegetation (% veg), percent water (% water), and percent soil (% soil) of 34 concrete pixels at the Dover Air Force Base for the nine Landsat data sets

	% veg	Standard deviation veg	% water	Standard deviation water	% soil	Standard deviation soil
August 29, 1993 1993	0.0348	0.0065	0.366	0.014	0.590	0.018
July 5, 1999	0.0295	0.0060	0.360	0.015	0.602	0.015
August 25, 2003	0.0361	0.0145	0.357	0.014	0.599	0.023
August 11, 2004	0.0198	0.0161	0.359	0.025	0.613	0.037
August 14, 2005	0.0283	0.0170	0.352	0.027	0.611	0.039
August 17, 2006	0.0282	0.0149	0.371	0.018	0.592	0.025
July 21, 2008	0.0510	0.0166	0.357	0.023	0.583	0.037
August 22, 2008	0.0452	0.0102	0.361	0.013	0.584	0.018
Sept 7, 2008	0.0514	0.0113	0.368	0.017	0.571	0.027
Average	0.0360	0.0126	0.361	0.018	0.594	0.027
Maximum	0.0514	0.0170	0.371	0.027	0.613	0.039
Minimum	0.0198	0.0060	0.352	0.013	0.571	0.015

The standard deviation on the % vegetation, water, and soil is the best available estimate of the error on the spectral unmixing results due to the lack of in situ or ground-measured spectral reflectance values collected at the time of the Landsat satellite overpasses

pore water and aeration of the root zone from increased precipitation at this time could have overcome the deleterious effects of high sulfides and low dissolved oxygen on marsh growth in late summer.

Discussion

The degree of inter-annual variability in summer vegetation cover and apparent vigor reflected in vegetation percentages in mesohaline to oligahaline marshes on both shores of the mid-Delaware Bay is surprising, even considering the amount of documented preexisting degradation in many areas. Even within the otherwise healthy marshes examined in the Bombay Hook transect, inter-annual variation was considerable, and it is not always evident what drivers underpin such yearly differences. Only the devastation of the marshes wrought by Hurricane Isabel in September 2003 can be cited as a ready explanation for the very low percent vegetation values—and corresponding extensive areas of bare marsh substrate—the following August of 2004. The dramatic increase in vegetation in August 2005 probably also documents the legacy of Isabel, in this case recovery of the marsh with re-establishment of seed banks and regeneration of rhizomes, spurred by the still nutrient-rich substrates produced by the storm's flood waters. Moreover, as noted, the high sea level and rainfall amount at this time were conducive to limiting growth stressors such as high sulfide accumulation and the incidence of low dissolved oxygen in ambient waters.

Such results underscore the fact that the significant, inherent temporal and spatial variability in the vegetation of brackish coastal marshes necessitate close attention to ways of discerning which year-to-year differences indicate ongoing deterioration in marsh condition from those which might appear initially to be some tipping point in marsh vigor, but are simply transient phenomena. Ground-based observations are probably unsuitable, due to the limitations of accommodating a wide enough spatial coverage in any timely fashion. Moreover, satisfactory, ground-level assessment of the nominal health of small annuals, which comprise most of the local marsh understory, is difficult from a distance because they are overtopped and hidden by canopy dominants like *S. alterniflora*. Any over-the-canopy solution—whether by helicopter surveys or satellite imagery—is preferable, as long as the assessments are made at nadir and the coverage is synoptic in scale.

The results of this study also cast a new light on the impact of sea level rise on nominally stable marshes. It appears that the decade-long acceleration in relative sea level rise in the 1990s had a substantial (if indirect) impact on apparent vegetation cover and vigor, because as vertical accretion rates kept pace with this trend, marsh surfaces became too high in elevation for effective tidal flushing of high sulfide and low dissolved oxygen levels during summer when mean sea levels dropped the following decade. It is also possible that shallow rooting, encouraged by high nutrient levels from agricultural runoff flooding marsh surfaces at every spring tide (Valiela et al. 1976; Darby and Turner 2008; Turner 2010), contributed to the problem. When combined with hot and dry late summers, this scenario could result in incipient marsh "browning".

This last point is perhaps that most intriguing for its implications for long term survival of marshes that until recently have been keeping pace with sea level rise. If overall sea level trends remain flat for the foreseeable future, the potential for frequent episodes of temporary vegetation stress—or even the early onset of end-of-season senescence—may greatly increase. Under conditions of repeated stress during the growing season, it is feasible that marsh plants might not maintain the carbohydrate stores necessary to ensure plant survival if sea levels again rise at the rate that characterized the 1990s. Kirwan et al. (2008), in modeling marsh response to temporary vegetation disturbance, showed even seemingly transient impacts can result in pronounced changes in marsh surface stability and biomass despite increases in vertical accretion that exceed relative sea level rise once the disturbance fades. In this regard, the increasing amplitude of inter-annual variations in the sea level signal since the 1960s (cf. Kearney et al. 2002) could pose as much risk to marsh survival as an overall acceleration in the sea level trend. The Bombay Hook marshes appear to have been little affected by the high rate of relative sea level rise in the 1990s. Nevertheless, once rates of sea level rise slowed dramatically after 1999–2000, the effect of this short-term, but significant jump in mean tide level—exceeding the low-end scenarios for global sea level rise by 2100 AD (IPCC 2007)—resulted in distinct declines in marsh plant vigor.

Conclusions

Changes in marsh vegetation between 1993 and 2008 showed a high degree of inter-annual variability, although marshes on the Delaware shore of the estuary generally appeared to be more vigorous than those on the New Jersey shore, probably due to shore influx of sediment from winter storms ("nor'easters"). Despite a rate of sea level rise during 1990s exceeding a 1 cm/year, marsh degradation was limited on the Delaware shore, with sites in the New Jerseys showing more distinct declines in marsh area. The most significant changes in marsh vegetation during the fifteen year period studied occurred as result of Hurricane Isabel in 2003, with relative vegetation percentage cover and vigor in the following summer of 2004 being the lowest recorded. A sea level high stand in 2005, however, combined with a wet summer marked an abrupt turn-around in relative vegetation and vigor.

The influence of inter-annual variation in sea levels in a period of little net rise in sea level is shown by changes in vegetation in Bombay Hook during the summer of 2008. This year was characterized by one of the most dramatic low stands during the study periods and, in addition, hot and dry summer conditions. Vegetation vigor consequently declined. But once rainfall levels began to increase in September, relative vegetation vigor rebounded. Such changes suggest that temperature and precipitations fluctuations when sea levels are low may be associated with marsh "browning" or even sudden dieback.

Acknowledgments This work was funded by grants from the Delaware Department of Natural Resources and Environmental Control (DNREC), Wetland Monitoring and Assessment Program, the DuPont Delaware Bay Estuary Program, and Environmental Protection Agency Region III and the Pennsylvania Coastal Zone Program in conjunction with the Partnership for the Delaware Estuary. We thank in particular Amy Jacobs, Danielle Kreeger, and Chris Bason for help in securing funding support and their guidance concerning the results of the study.

References

Alber M, Swenson EM, Adamowicz SC, Mendelssohn IA (2008) Salt marsh dieback: an overview of recent events in the US. Estuar Coast Shelf Sci 80(1):1–11

Berk A, Adler-Golden SM, Ratkowski AJ, Felde AJ, Anderson GP, Hoke ML, Cooley T, Chetwynd JH, Gardner JA, Maththew MW, Bernstein LS, Acharya PK, Miller D, Lewis P (2002) Exploiting MODTRAN radiation transport for atmospheric correction: the FLAASH algorithm. Proc Fifth Int Conf Inform Fusion 2:798–803

Borel CC, Gerstl SAW (1994) Nonlinear spectral mixing models for vegetative and soil surfaces. Remote Sens Envir 47(3):403–416

Chander G, Markham BL, Helder DL (2009) Summary of current radiometric calibration coefficients for Landsat MSS, TM, ETM +, and EO-1 ALI sensors. Remote Sens Envir 113:893–903

Darby FA, Turner RE (2008) Effects of eutrophication on salt marsh root and rhizome biomass accumulation. Marsh Ecol Prog Ser 363:63–70

DeLaune RD, Nyman JA, Patrick JWH (1994) Peat collapse, ponding and wetland loss in a rapidly submerging coastal marsh. J Coast Res 10:1021–1030

IPCC (2007) Climate change 2007: synthesis report. In: Core Writing Team, Pachauri, RK, Reisinger A (eds) Contribution of working groups I, II and III to the fourth assessment report of the intergovernmental panel on climate change. IPCC, Geneva

Jensen JR (2000) Remote sensing of the environment: an earth resource perspective. Prentice Hall, Upper Saddle River

Kearney MS, Stevenson JC, Ward LG (1994) Spatial and temporal changes in marsh vertical accretion rates at Monie Bay: implications for sea-level rise. J Coast Res 10(4):1010–1020

Kearney MS, Rogers AS, Townshend JRG, Stevenson JC, Stevens J, Rizzo E, Sundberg K (2002) Landsat imagery shows decline of coastal marshes in Chesapeake and Delaware Bays. EOS, Trans Am Geophys Union 83(16):173, 177–178

Kirwan ML, Murray AB, Boyd WS (2008) Temporary vegetation disturbance as an explanation for permanent loss of tidal wetlands. Geophys Res Lett 35:L05403. doi:10.1029/2007GL032681

Matarrese R, Vermote E, Kearney MS (2005) Impact of Hurricane Isabel on the water properties of the Chesapeake Bay area. In: Sellner K (ed) Hurricane Isabel in perspective, conference proceedings, Chesapeake Bay research consortium, Edgewater, pp 127–134

McFeeters SK (1996) The use of the normalized difference water index (NDVI) in the delineation of open water features. Int J Remote Sens 17:1425–1432

McKee KL, Cherry JA (2009) Hurricane Katrina sediment slowed elevation in subsiding brackish marshes of the Mississippi River Delta. Wetlands 29(1):2–15

McKee KL, Mendelssohn IA, Materne MD (2004) Acute salt marsh dieback in the Mississippi River deltaic plain: a drought-induced phenomenon? Glob Ecol Biogeogr 13:65–79

Mendelssohn IA, McKee KL (1988) *Spartina alterniflora* dieback in Louisiana: time-course investigation of soil waterlogging effects. J Ecol 76:509–521

Mendelssohn IA, Morris JT (2000) Eco-physiological constraints on the primary productivity of *Spartina alterniflora*. In: Weinstein MP, Kreeger DA (eds) Concepts and controversies of tidal marsh ecology. Kluwer Academic, Dordrecht, pp 59–80

Peterson JE, Baldwin AH (2004) Variations in wetland seed banks across a tidal freshwater landscape. Am J Bot 91(8):1251–1259

Reed DJ (1995) The response of coastal marshes to sea-level rise: survival or submergence? Earth Surf Process Landf 20(1):39–48

Rogers AS, Kearney MS (2004) Reducing signature variability in unmixing coastal marsh TM scenes using spectral indices. Int J Remote Sens 25(12):2317–2335

Rouse JW, Haas RH, Schell JA, Deering DW (1974) Monitoring vegetation systems in the Great Plains with ERTS. In: Proceeding third earth resources technology satellite-1 symposium. Greenbelt, NASA SP-351, 3010-317

Sharpe PJ, Baldwin AH (2009) Patterns of wetland plant species richness across estuarine gradients of Chesapeake Bay. Wetlands 29(1):225–235

Stevenson JC, Ward LG, Kearney MS (1986) Vertical accretion rates in marshes with varying rates of sea-level rise. In: Wolfe DA (ed) Estuarine variability. Academic Press, London, pp 241–259

Stumpf RP (1983) The process of sedimentation on the surface of a salt marsh. Estuar Coast Shelf Sci 17(5):495–508

Turner RE (2010) Beneath the salt marsh canopy: loss of soil strength with increasing nutrient loads. Estuar Coasts. doi:10.1007/s12237-010-9341-4

Turner RE, Baustian JJ, Swenson EM, Spicer JS (2006) Wetland sedimentation from Hurricanes Katrina and Rita. Science 314(5798):449–452

Valiela IJ, Teal JM, Persson NY (1976) Production and dynamics of experimentally enriched salt marsh vegetation: belowground biomass. Limnol Oceanogr 21(2):245–252

Westervelt K, Largay E, Coxe R, McAvoy W, Perles S, Podniesinski G, Sneddon L, Strakosch Walz K (2006) A guide to the natural communities of the Delaware Estuary: version 1. NatureServe, Arlington