Studies in Avian Biology No. 32:214–228

HIGH TIDES AND RISING SEAS: POTENTIAL EFFECTS ON ESTUARINE WATERBIRDS

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Abstract. Coastal waterbirds are vulnerable to water-level changes especially under predictions of accelerating sea-level rise and increased storm frequency in the next century. Tidal and wind-driven fluctuations in water levels affecting marshes, their invertebrate communities, and their dependent waterbirds are manifested in daily, monthly, seasonal, annual, and supra-annual (e.g., decadal or 18.6-yr) periodicities. Superimposed on these cyclic patterns is a long-term (50–80 yr) increase in relative sea-level rise that varies from about 2–4 + mm/yr along the Atlantic coastline. At five study sites selected on marsh islands from Cape Cod, Massachusetts to coastal Virginia, we monitored marsh elevation changes and flooding, tide variations over time, and waterbird use. We found from long-term marsh core data that marsh elevations at three of five sites may not be sufficient to maintain pace with current sea-level rise. Results of the short-term (3–4 yr) measures using surface elevation tables suggest a more dramatic difference, with marsh elevation change at four of five sites falling below relative sea-level rise. In addition, we have found a significant increase (in three of four cases) in the rate of surface marsh flooding in New Jersey and Virginia over the past 70–80 yr during May–July when waterbirds are nesting on or near the marsh surface. Short-term, immediate effects of flooding will jeopardize annual fecundity of many species of concern to federal and state agencies, most notably American Black Duck (*Anas rubripes*), Nelson's Sharp-tailed Sparrow (*Ammodramus nelsoni*), Saltmarsh Sharp-tailed Sparrow (*A. caudacutus*), Seaside Sparrow (*A. maritima*), Coastal Plain Swamp Sparrow (*Melospiza georgiana nigrescens*), Black Rail (*Laterallus jamaicensis*), Forster's Tern (*Sterna forsteri*). Gull-billed Tern (*S. nilotica*), Black Skimmer (*Rynchops niger*), and American Oystercatcher (*Haemotopus palliatus*). Forster's Terns are probably most at risk given the large proportion of their breeding range in the mid-Atlantic and their saltmarsh specialization. At a scale of 1–2 decades, vegetation changes (saltmeadow cordgrass [*Spartina patens*] and salt grass [*Distichlis spicata*] converting to smooth cordgrass [*Spartina alterniflora*]), interior pond expansion and erosion of marshes will reduce nesting habitat for many of these species, but may enhance feeding habitat of migrant shorebirds and/or migrant or wintering waterfowl. At scales of 50–100 yr, reversion of marsh island complexes to open water may enhance populations of open-bay waterfowl, e.g., Bufflehead (*Bucephala albeola*) and Canvasback (*Aythya valisneria*), but reduce nesting habitats dramatically for the above named marsh-nesting species, may reduce estuarine productivity by loss of the detrital food web and nursery habitat for fish and invertebrates, and cause redistribution of waterfowl, shorebirds, and other species. Such scenarios are more likely to occur in the mid- and north Atlantic regions since these estuaries are lower in sediment delivery on average than those in the Southeast. A simple hypothetical example from New Jersey is presented where waterbirds are forced to shift from submerged natural marshes to nearby impoundments, resulting in roughly a 10-fold increase in density. Whether prey fauna are sufficiently abundant to support this level of increase remains an open question, but extreme densities in confined habitats would exacerbate competition, increase disease risk, and possibly increase predation.

Key Words: Atlantic coast, breeding habitat, marsh flooding, marsh surface, sea-level rise, tidal fluctuations, waterbirds.

MAREAS ALTAS Y MARES QUE ASCIENDEN: EFECTOS POTENCIALES EN AVES ACUÁTICAS DE ESTUARIO

Resumen. Las aves acuáticas de costa son vulnerables a los cambios en el nivel del agua, especialmente bajo las predicciones acerca del levantamiento acelerado del nivel del mar y el aumento en la frecuencia de tormentas durante el siguiente siglo. Las fluctuaciones causadas por marea y viento en los niveles del mar que afectan a las marismas, sus comunidades de invertebrados, y sus aves acuáticas dependientes son manifestadas en periodicidades diarias, mensuales, estacionales, anual y supra-anuales (ej. en décadas o 18.6 años). Super impuestos en estos patrones cíclicos hay un incremento de largo plazo (50–80 años) en el levantamiento del nivel del mar que varia de cerca de 2–4 + mm/años a lo largo de la línea costera del atlántico. En cinco sitios de estudio seleccionados en islas de marisma de Cabo de Bacalao, Massachussets hasta la costa de Virginia, monitoreamos los cambios en la elevación de la marisma e inundaciones, las variaciones de la marea en el tiempo, y utilización de aves acuáticas. De datos centrales de marisma de largo plazo encontramos que las elevaciones de marisma en tres de los cinco sitios quizás no son suficientes para mantener el ritmo con las actuales elevaciones en el nivel del mar. Resultados de las medidas de corto plazo (3–4 años) utilizando tablas de elevación de la superficie, sugieren una diferencia más dramática, con un cambio en la elevación de marisma de cuatro sitios cayendo por debajo de la elevación del nivel del mar. Además, hemos encontrado un incremento significativo (en tres de los cuatro casos) en la proporción de la superficie de marisma en inundación en Nueva Jersey y Virginia durante los últimos 70–80 años durante Mayo–Julio cuando las aves acuáticas están anidando en o cerca de la superficie de la marisma. A corto plazo, efectos inmediatos de inundación ponen en peligro la fecundidad anual de muchas especies del interés de agencias federales y estatales, más notablemente en el Pato Negro Americano (*Anas rubripes*), el Gorrión Cola Aguda Nelson (*Ammodramus nelsoni*), el Gorrion de Marisma Salado Cola Aguda (*A. caudacutus*), el Gorrion Costero (*A. maritima*), el Gorrion Pantanero (*Melospiza georgiana nigrescens*), la Polluela Negra (*Laterallus jamaicensis*), el Charran de Foster (*Sterna forsteri*). El Charran Picogrueso (*S. nilotica*), el Rayador Americano (*Rynchops niger*), y el Osterero Americano (*Haemotopus palliatus*). Los Charranes de Foster se encuentran probablemente más en riesgo, dada la gran proporción de su rango reproductivo en el Atlántico medio y su especialización a la marisma salada. A la escala de 1–2 décadas, los cambios en la vegetación (*Spartina patens* y *Distichlis spicata* convirtiéndose a *S. alterniflora*), la expansión interior de charcos y la erosión de marismas reducirán el hábitat de anidamiento para muchas de estas especies, pero quizás mejoren el hábitat de alimento de aves migrantes de playa y/o de gallinas de agua migrantes o de invierno. A escalas de 50–100 años la reversión de los complejos de islas de marisma para abrir el agua quizás mejoren las poblaciones de gallinas de agua de bahía abierta, ej. Pato Monja (*Bucephala albeola*) y Pato Coacoxtle (*Aythya valisneria*), pero reduzcan dramáticamente habitats de anidación para las especies de marisma de anidacion nombradas anteriormente, quizás se reduzca la productividad de la marisma por la pérdida de la cadena alimenticia detrital y el hábitat de criadero para los peces e invertebrados, y causa la redistribución de las gallinas de agua, aves de playa y otras especies. Tales escenarios son más susceptibles a suceder en las regiones medias y del norte del Atlántico, ya que estos estuarios son más bajos en la repartición de sedimento en proporción a aquellos en el sureste. Un simple ejemplo hipotético de Nueva Jersey es presentado donde las aves acuáticas son forzadas a cambiar de marismas naturales sumergidas a encharcamientos cercanos, resultando en aproximadamente un incremento en densidad de 10 pliegues. Si la fauna de presa es suficientemente abundante para soportar este nivel, sigue siendo una pregunta abierta, pero densidades extremas en habitats confinados exacerbaría la competencia, incrementaría el riesgo de enfermedades, y posiblemente incrementaría la depredación.

Concern is growing in many areas of the US and throughout the world that as sea levels continue to rise, coastal-marsh elevations may not be able to keep pace (Titus 1988, Emery and Aubrey 1991, Warrick et al. 1993, Brinson et al. 1995, Nicholls and Leatherman 1996, Nerem et al. 1998). This will have large implications not only to human infrastructure (Titus 1991, Titus et al.1991) but also to many rare and imperiled species of animals and plants (Reid and Trexler 1992). The obvious first victims of accelerated sea-level rise will be those plants and animals that are obligate saltmarsh residents or coastal-dependent migratory species such as waterbirds. Even though the total area of the coastal estuarine zone is a fraction of the upland areas of the US, the large number of migratory waterbirds (nearly 100 species in the US) and threatened-to-endangered species using the coastal fringe is disproportionately high (Reid and Trexler 1992, Daniels et al. 1993).

Global sea levels are predicted to rise from 10–90 cm during the next 100 yr, with a median model estimate of 48 cm (Intergovernmental Panel on Climate Change 2001). Of course, the degree to which marsh surface dynamics in a given estuary departs from global average predictions depends on complex interactions of marsh shallow subsidence (e.g., compaction, decomposition, and water storage and extraction; Cahoon et al. 1999), plate-tectonic movements (glacial or isostatic rebound; Emery and Aubrey 1991), landscape position relative to sediment source (Kearney et al. 1994, Roman et al. 1997), storm frequency (Giorgi et al. 2001), and biotic factors such as grazing or trampling by herbivores (Chabreck 1988; Mitchell et al., *this volume*).

Variation in the effects of large-scale phenomena such as sea-level rise occurs at all spatial scales. Within a coastal embayment, the position of the marsh may strongly influence its ability to maintain elevation. Lagoonal marshes, in the middle of a large bay, may have insufficient sources of sediments to maintain their elevations compared with marshes near barrier islands (storm-driven inorganic sand) or those close to the mainland (high organics) (Hayden et al. 1991, Roman et al. 1997). In addition to local variation at the sub-estuary and estuary levels, regional differences occur in marsh accretion and relative sea-level rise (RSLR), i.e., that due to both water-level changes as well as change in land-surface elevation. In part, this is caused by post-glacial crustal uplift in New England and northward, but down warping in the mid-Atlantic region (National Academy of Science 1987, Emery and Aubrey 1991).

In parts of New England and the Carolinas along the U.S. Atlantic Coast, average marsh-accretion rates seem to be much greater than RSLR; however, in parts of Georgia, the

Chesapeake Bay of Maryland, and Connecticut, RSLR is greater than average marsh accretion (National Academy of Science 1987, Warren and Niering 1993). Examining accretion rates, however, only reveals part of the dynamics. Subsidence can be significant in areas of the Chesapeake Bay (Nerem et al. 1998), in Virginia, and especially in Louisiana (Boesch et al. 1983). Recognizing the importance of measuring both components has led to the evolution of the surface elevation table (SET), a mechanical device that allows for monitoring of surface elevation changes over time from a permanent benchmark (Cahoon et al. 2002 and references therein).

Tide and sea-level variations also have frequency components associated with daily, monthly, yearly, and decadal and 18.6-yr periods (Kaye and Stuckey 1973, Pugh 1987, Stumpf and Haines 1998; Fig. 1). Regular fluctuations in the timing of high- and low-water events can have profound effects on the evolution and life histories of the myriad of organisms associated with saltmarshes (Bertness 1999). These predictable temporal variations must be factored into the ecological and evolutionary responses of organisms that are also facing steadily increasing sea levels that may also be associated with more frequent but unpredictable storm events (Intergovernmental Panel on Climate Change 2001).

One of the end results of rising sea levels and marsh submergence is declining quality or loss of wildlife habitat. Global warming with concomitant storm increases and sea-level rise has sparked major concern among ornithologists and coastal managers with disturbances or loss of both intertidal habitats of international importance as well as adjacent emergent marshes (Titus et al. 1991, Peters and Lovejoy 1992, Ens et al. 1995, Fenger et al. 2001). Special concerns have been voiced for loss of shorebird habitats (Myers and Lester 1992, Galbraith et al. 2002). Using a coarse-simulation model of changes in water levels and coastal elevations at five critical shorebird staging areas in the US, Galbraith et al. (2002) estimated intertidal habitat losses of 20–70%.

In addition to shorebirds, a number of other species and groups of waterbirds are potentially vulnerable to coastal storms and sea-level rise (Table 1). Along the Atlantic Coast over the past 50 yr, habitat quality and quantity have declined as human density and disturbances have increased. A number of waterbird species that use Atlantic marshes during some part of the year has been listed by federal and/or state agencies as being at risk or of special concern because of population declines in certain regions; these include American Black Ducks (*Anas rubripes*), Forster's Terns, (*Sterna forsteri*). Gull-billed Terns (*S. nilotica*), Common Terns (*S. hirundo*), Black Skimmers (*Rynchops niger*), American Oystercatchers (*Haematopus palliates*), Black Rails (*Laterallus jamaicensis*), and marsh-nesting passerines such as Seaside Sparrows (*Ammodramus maritimus*), Nelson's Sharp-tailed Sparrows (*A. nelsoni*), Saltmarsh Sharp-tailed Sparrows (*A. caudacutus*), and Coastal Plain Swamp Sparrows (*Melospiza georgiana nigrescens*) (see appendices in the Waterbird Conservation for the Americas Plan <http://www.waterbirdconservation.org> [6 July 2006]).

Because global climate-change and sea-level rise scenarios have major implications to coastal habitats, especially federally owned parks and national wildlife refuges, the U.S. Geological Survey has provided major funding within its research programs directed at these topics since 1998. Our study has focused on monitoring marsh changes, tide levels, and waterbird use of selected coastal sites that are known to be important for one or more guilds of waterbird and where coastal managers and scientists have voiced concerns over marsh changes.

The questions we pose are:

1. Is sea-level rise occurring at consistent rates at all mid- and north Atlantic locations? How do these rates compare with marsh elevation changes in lagoons over the short and long terms?

TABLE 1. NUMBER OF AVIAN SPECIES USING EMERGENT SALTMARSHES FOR NESTING, FEEDING, AND/OR RESTING IN THE MID-ATLANTIC COASTAL REGION.

Group	Breeding	Migration	Wintering
Waterfowl[a]	6	26	24
Shorebirds[b]	5	29	12
Seabirds[c]	12	13	4
Wading birds[d]	10	10	4
Marsh birds[d]	3	8	1

[a] Bellrose (1976), Palmer (1976).
[b] Bent (1962a, b).
[c] Bent (1963a).
[d] Bent (1963b).

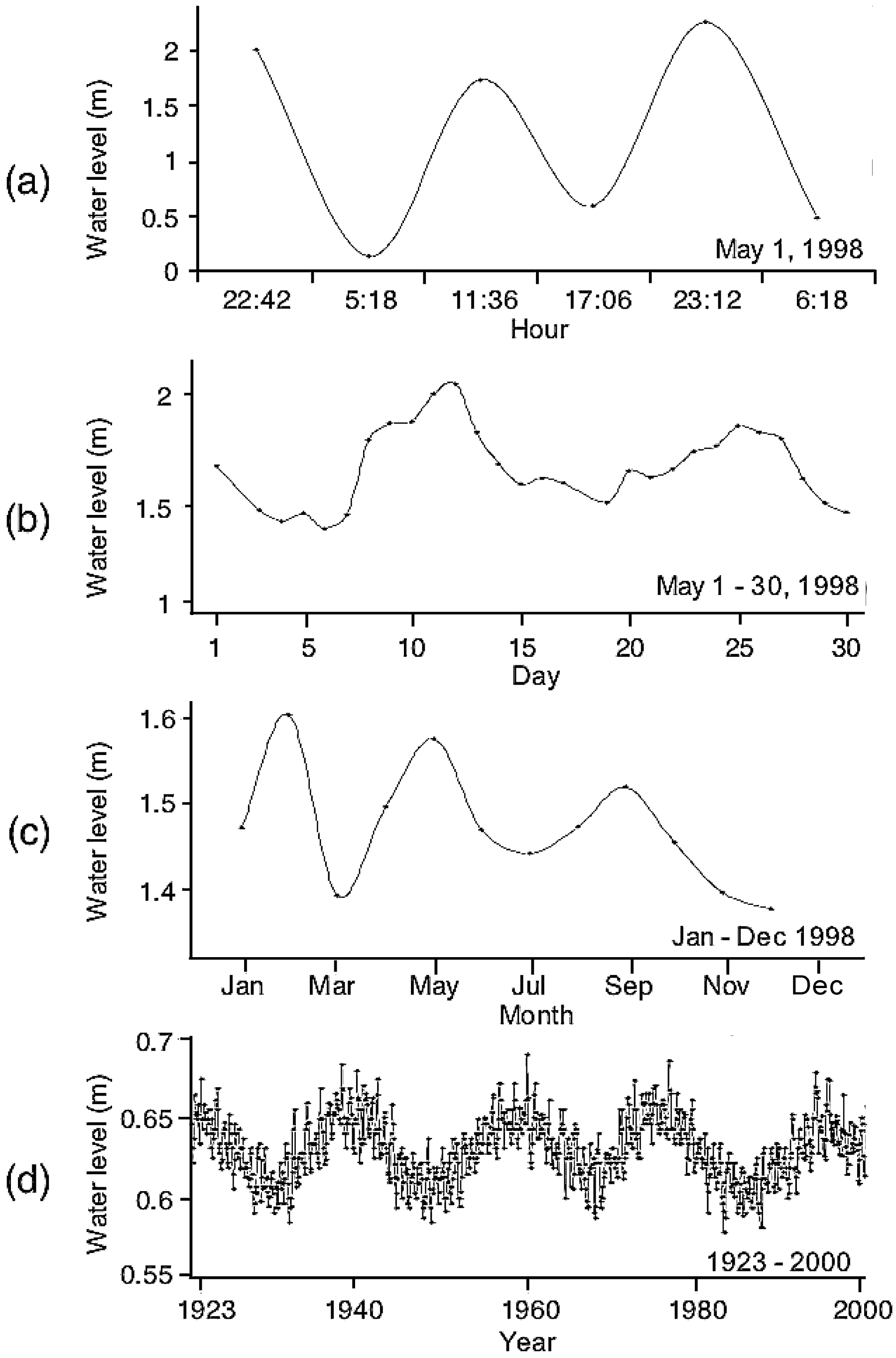

FIGURE 1. Comparison of simultaneous temporal cycles associated with tidal waters. Raw data obtained from National Oceanic and Atmospheric Administration's (NOAA) National Ocean Service (<http://www.co-ops.nos.noaa.gov/> [31 July 2006]). All data were obtained for the Atlantic City tide gauge with mean low low water as the datum. (a) Low and high tides based on 24 hours, 1 May 1998; (b) Daily high high tides for the month of May 1998 (full moon and new moons were 11 May and 25 May, respectively); (c) Monthly mean high tides for 1998; and (d) Monthly mean sea level minus monthly mean high tide calculated to show the approximate 18.6-yr cycle known as the metonic cycle or lunar nodal cycle (Kaye and Stuckey 1973).

2. What are flooding rate patterns in marshes and how might these affect nesting species?
3. Which waterbird species are affected most by marsh inundation over short, intermediate and long terms?
4. What are some implications of habitat shifts required of affected waterbird species?

METHODS

SITE SELECTION

Three regional study areas were established in saltmarshes along the Atlantic Coast of the US to determine the latitudinal variations in sea-level rise, marsh-elevation change, and bird use. The study areas in New Jersey and Virginia each consisted of two separate sites (Fig. 2), resulting in a total of five sites from Cape Cod to southern Virginia. Sites were chosen based on their importance to waterbirds and the presence of ongoing management (especially on federal lands such as Cape Cod National Seashore and E. B. Forsythe National Wildlife Refuge [NWR]) and research activities. The Virginia sites are within the Virginia Coast Reserve, an area of ongoing estuarine research supported by the University of Virginia's Long Term Ecological Research program (<http://www.vcrlter.virginia.edu/> [7 July 2006]). We selected lagonal marsh complexes, i.e., islands in the middle of embayments, because for most species of waterbirds these are the most important. Each site included randomly selected marsh elevation sampling plots (N = 15; located in the high marsh at least 15 m from the main marsh channel) as well as a waterbird survey plot containing tidal ponds, pannes, and/or mudflats to document waterbird usage. Predominant vegetation included short-form smooth cordgrass (*Spartina alterniflora*), glassworts (*Salicornia* spp.), and beach salt grass (*Distichlis spicata*) with one exception being a site at Mockhorn Island, Virginia, where the dominant vegetation type was tall-form smooth cordgrass The plots to be sampled for marsh surface elevation change were replicated at each site (two–six replicates) with at least 100 m separating the marsh surface plots.

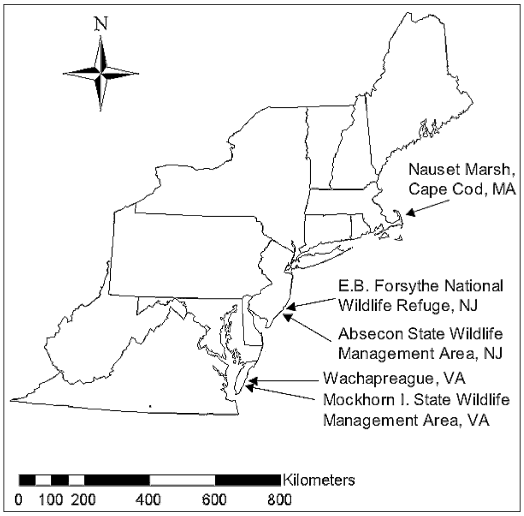

FIGURE 2. General locations of marsh study sites along the East Coast of the US: Nauset Marsh, Cape Cod National Seashore, Massachusetts; E. B. Forsythe National Wildlife Refuge, and Absecon State Wildlife Management Area, New Jersey; Wachapreague and Mockhorn Island State Wildlife Management Area, Virginia.

MARSH ELEVATION

Surface elevation table

Changes in marsh elevation were measured using a surface-elevation table (SET after Boumans and Day 1993, Cahoon et al. 2002), a portable device that attaches to a permanent stable benchmark pipe driven into the substrate until the point of refusal, roughly 5–6 m (Fig. 3). The device is designed to detect changes in marsh elevation at a high resolution (+/- 0.7–1.8 mm; Cahoon et al. 2002) by repeatedly measuring the same position on the marsh surface over time. We took measurements every 6 mo in the spring and fall and rates of elevation change were determined by linear regression analysis of the cumulative elevation change (i.e., time_t - time_0).

Accretion (feldspar)

The SET measures total marsh elevation change. To determine the influence of shallow subsidence or compaction, the accretion component must be separated from total elevation change. Sediment accretion was measured on the same time interval as the SET. Three feldspar marker horizons (N = 45) were positioned around each SET plot at the time of the initial SET reading (Cahoon and Turner 1989). A liquid nitrogen cryocorer was used to obtain a frozen sediment core in a manner that does not cause compaction of the sample (Cahoon et al. 1996). The amount of accretion was determined by measuring the amount of material (both organic and inorganic) above the white feldspar layer to the nearest 0.1 mm using calipers.

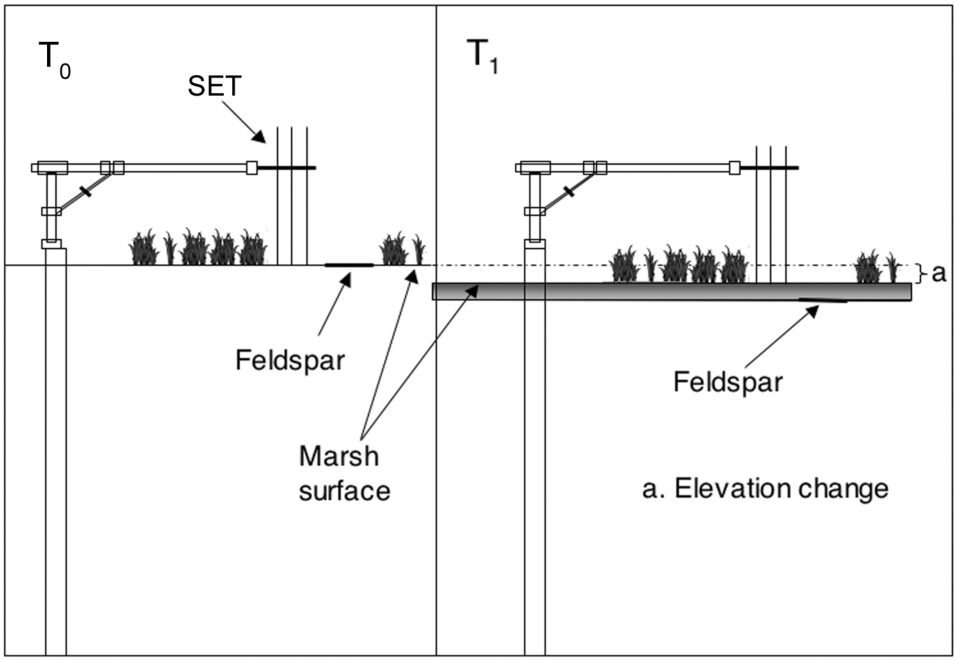

FIGURE 3. Relative placement of the SET platform and feldspar marker horizons (diagram not to scale). At time$_0$ the baseline elevation readings are taken and the feldspar marker horizons are placed on the marsh surface surrounding the SET. At time$_1$ (~6 mo later), marsh elevation is measured again along with vertical accretion. The example above depicts a scenario where vertical accretion was present (evidenced by the gray shaded area) but shallow subsidence was greater yielding a net loss of elevation. This is just one example and not necessarily representative of all results.

Long-term accretion (^{210}Pb)

The SET and cryogenic coring data present a short-term picture of marsh-elevation dynamics; however, radiometric dating using radioisotopes in the substrate allows one to establish historic accretion rates (ca. 100 yr; Kastler and Wiberg 1996). Two sediment cores were taken from the high marsh at each of our study sites in Virginia and New Jersey using a piston corer, approximately 1 m long and 10.25 cm in diameter (C. Holmes, USGS, unpubl. data). Long-term sedimentation rates for Nauset Marsh were obtained from previously published results (Roman et al. 1997). The cores were sampled at 1-cm intervals for the first 10 cm and at 2-cm intervals thereafter. Using the radioactive isotopes ^{210}Pb and ^{137}Cs, the age of the sample was determined by comparing the original isotopic concentrations to the percent remaining in the sample. A constant-flux:constant-sedimentation model was deemed most appropriate to analyze the sedimentation rates for the New Jersey and Virginia cores. This model assumes a constant flux of unsupported ^{210}Pb and a constant dry-mass sedimentation rate. (C. Holmes, USGS unpubl. data; Robbins et al. 2000).

Sea-level Trends and Marsh Flooding

Water-level data were obtained from the National Oceanic and Atmospheric Administration's (NOAA) National Ocean Service (<http://www.co-ops.nos.noaa.gov/> [7 July 2006]) to show geographic differences in rates of sea-level rise for each general location along the East Coast (Boston, Massachusetts; Montauk, New York; Atlantic City, New Jersey; and Chesapeake Bay Bridge Tunnel, Virginia). Data from the Boston and Atlantic City tide gauges span roughly the past 80 yr; however, the New York and Virginia data sets date back approximately 50 and 25 yr, respectively. Because the Wachapreague, Virginia, local tide-gauge station only dated from 1980, those water-level data were not used; instead we used the tidal data from Sandy Hook, New Jersey, because this is the standard long-term reference for coastal Virginia. Monthly mean data were used to calculate sea-level rise trends and linear regression analysis was used to determine the rate of sea-level rise for each location.

During the nesting season (May–July), extreme spring tides often destroy the nests of and cause mortality to marsh-nesting waterbirds such as Forster's and Common Terns (Storey 1987, Burger and Gochfeld 1991a). Based on previous observations, we estimated that a tide that reached at least 20 cm above the surface of the marsh would be sufficient to flood the majority of nests in most colonies. To determine the frequency of such tides, we installed data loggers at our study sites at E. B. Forsythe NWR, New Jersey, and at Wachapreague, Virginia, in spring and summer 2001 to monitor the height of the water above the marsh surface. We used both the Solinst Leveloggers®, which use pressure sensors to detect changes in water level, and powdered cork, which was placed inside clear acrylic tubes. When the water rose inside the tube, the cork adhered to the sides revealing the maximum height of the previous tides.

The data loggers provided readings of water level, date, and time (5-min intervals over 3–7 d) and the cork gauges corroborated the level of the tide event. Comparing these data to that from local NOAA tide gauges, we determined the NOAA tide-gauge reading at the time when the marsh reached our designated flooding point (20 cm above the marsh surface). Tide gauges in Atlantic City and Sandy Hook, New Jersey, were used to reference past flooding events for the New Jersey and Virginia sites, respectively. We hindcasted through the tidal record to determine the frequency of marsh flooding events (>20 cm over the marsh surface) during the breeding season (mid-May–mid-July) at E. B. Forsythe NWR, New Jersey, and Wachapreague, Virginia.

Two methods of hindcasting were used. The first approach assumes steady-state conditions of the marsh surface wherein historic tide heights were compared to current marsh sediment elevations. It is apparent, however, given the long-term accretion rates revealed from the ^{210}Pb data, that material was deposited on the marsh surface, suggesting an increase in marsh elevation over time. Neglecting to account for long-term accretion may in effect reduce the number of flooding events predicted in earlier years, resulting in bias toward an increasing flooding trend over time. In an attempt to correct for this potential bias, a second test was performed where the historic water-level data were compared to marsh elevations adjusted for vertical accretion over the duration of the tidal record.

Making the rather large assumption that accretion was constant over time, we determined an annual accretion rate by averaging the annual rates from each of the two cores taken at each site. This rate was multiplied by the number of years included in the tidal record to provide a total amount of accretion over the given time period. Because we did not know the actual present or historical elevation of the marsh surface relative to mean sea level, we had to adjust the water-level data in order to compensate for marsh elevation change. To do this, we increased the water levels for the initial year in the tidal record by the cumulative amount of accretion gained over the entire time series. In effect, this lowered the elevation of the marsh relative to sea level. The amount added to the water levels was reduced annually by the calculated rate of sediment accretion occurring from the beginning of the tidal record to the year in question.

Both of these methods of documenting the frequency of marsh-flooding events have flaws. Assuming a constant rate of accretion is probably somewhat unrealistic, given the stochasticity of storm events. However, we feel that this exercise represents both conservative and liberal estimates of historic flooding frequencies.

HYPOTHETICAL SEA-LEVEL-RISE SCENARIO: ATLANTIC COUNTY, NEW JERSEY

Relative sea-level rise could have a profound effect on waterbird habitat, especially the intertidal pannes and pools that are especially important to shorebirds using these areas for feeding during migration. We developed a hypothetical scenario for Atlantic County, New Jersey, to estimate the numbers of shorebirds displaced at high tide if a major portion of their natural feeding habitat was eliminated due to sea-level rise and to identify possible refugia capable of providing suitable feeding habitat.

We calculated an estimate of total saltmarsh area and shorebird feeding habitat for Atlantic County, New Jersey using a geographic information system (GIS) and National Wetland Inventory (NWI) maps obtained from the USDI Fish and Wildlife Service (<http://wetlands.fws.gov/nwi> [7 July 2006]). Of the 12 quadrangles used, all were originally classified using aerial photography from March 1977; however, nine of the 12 were recently updated and reclassified based on aerial photography from April 1995. All geoprocessing and analyses were done using ArcGIS 8.2 (Environmental Systems Research Institute 2002). Maps were imported into ArcGIS 8.2 and the areas located in Atlantic County, New Jersey, representing intertidal as well as ponds and pannes, as these are the primary shorebird feeding habitat, were selected.

NWI maps are often not detailed enough to show features such as interior pools or pannes. Because of that, many such features were digitized from digital orthophotos. Four marsh areas were selected based on randomly generated points. A 1,000-m buffer was established around each point and any marsh body that intersected the buffer was selected and all of the pannes and pools in that marsh were digitized. It should be noted that the digital orthophotos we used for digitizing habitat features only covered roughly 50% of the coastal Atlantic County marshes. As a result, when the random points were generated they were only generated for the area covered by the photos. Even so, we are confident that they marshes sampled in this analysis accurately represent the marshes throughout the county. Upon completing the digitizing, the areas of the pannes and pools were calculated for the four randomly selected marshes. Any polygon not having an area of at least 100 m^2 was eliminated to ensure consistency. The proportion of panne and/or pool area to marsh area for the four randomly selected subsets was used to help estimate the total area of pannes and pools in the entire county.

Assuming a large portion of shorebird feeding habitat such as the pannes and pools in Atlantic County, New Jersey, would no longer be available, we identified a likely suitable alternative. E. B. Forsythe NWR, which has a complex of three large impoundments that already provides feeding habitat for many migrant shorebirds and would presumably attract birds displaced from their natural feeding areas by sea-level rise.

An empirical example of the number of shorebirds using the marsh pannes and pools in the county for feeding was estimated based on surveys (N = 17) we conducted during the fall (August–October) of 2000 at our study site (28 ha) located on a marsh island in the county. Surveys were conducted from a 3-m platform and divided into four consecutive 30-min intervals that began 2 hr prior to the peak tide. Shorebird density was based on the combined area of the main feeding habitats (pannes and pools) and the peak survey for shorebird species (15August 2000; 93 birds). This figure was then extrapolated to yield an estimate of shorebirds using similar feeding habitat in the county based on the estimated area of suitable feeding habitat derived above from the GIS analysis.

Shorebird data for the impoundments (540 ha) at E. B. Forsythe NWR for fall 2000 were collected on a weekly basis by refuge volunteers (N = 10 surveys). As with the previous data set, density was calculated based on the known areas of the impoundments and the maximum number of shorebirds seen on a single survey during that season (31 August 2000; 9,445 birds). This density was then recalculated to account for the additional number of shorebirds that would be using the impoundments due to the loss of their natural habitat.

RESULTS

CHANGES IN RSLR AND MARSH SURFACES

Rising water levels are apparent from the long-term tide station records from Boston, Massachusetts, to the mouth of the Chesapeake Bay, Virginia, with estimates ranging from 2.6 mm/yr for Boston to 5.9 mm/yr for the Chesapeake Bay Bridge-Tunnel (Fig. 4).

When comparing the increases in RSLR to long-term (ca. 100 yr) accretion rates, it appears that marshes are maintaining pace with RSLR based on five of nine cores (Table 2). However,

TABLE 2. LONG-TERM TRENDS (CA. 100 YR) OF MARSH ELEVATION (ACCRETION) CHANGE BASED ON CORE ANALYSES COMPARED WITH RELATIVE SEA-LEVEL RISE (RSLR).

Location	Number of cored sites	Long-term accretion (^{210}Pb) (mm/yr)	Relative sea-level rise (RSLR) (mm/yr)
Nauset Marsh, Massachusetts[a]	1	4.2 ± 0.6	2.4[b]
Absecon, New Jersey	2	3.9 ± 0.0	4.1[a, c]
		3.7 ± 0.0	
E. B. Forsythe NWR, New Jersey	2	3.4 ± 0.1	4.1[a, c]
		4.1 ± 0.0	
Wachapreague, Virginia	2	3.1 ± 0.0	3.9[a, d]
		3.9 ± 0.0	
Mockhorn Island, Virginia	2	5.4 ± 0.0	3.9[a, d]
		16.0 ± 0.0	

[a] Data from Roman et al. (1997) RSLR figure based on NOAA tide gauge data from 1921–1993 (Boston, MA station number 8443970; core data only from the Fort Hill site).

[b] $P < 0.01$, regression analysis H_0: sea-level rise = 0.

[c] Calculated from 77 yr (1923–2000) of NOAA tide gauge data (Atlantic City, New Jersey, station number 8534720).

[d] Calculated from 67 yr (1933–2000) of NOAA tide gauge data (Sandy Hook, New Jersey station number 8531680, which is a reference gauge for Wachapreague station number 8631044).

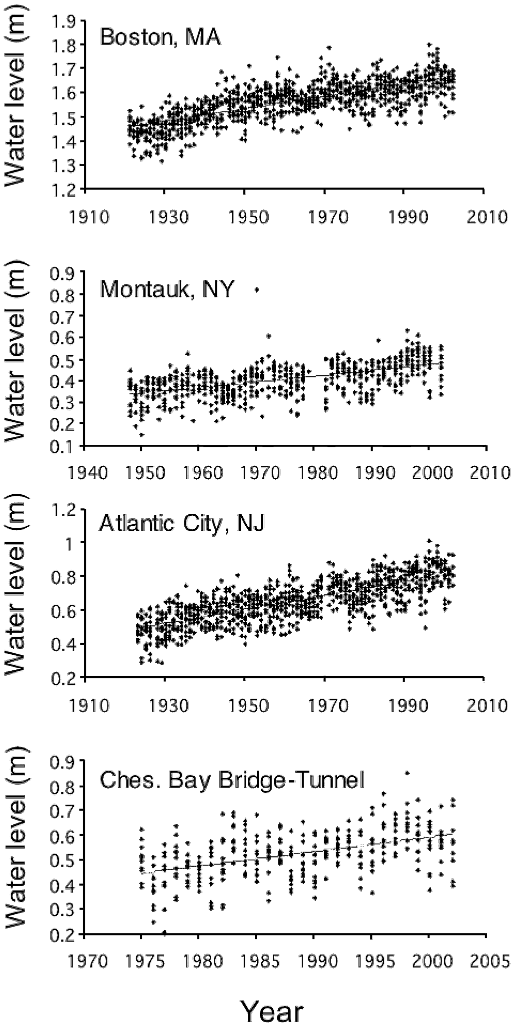

FIGURE 4. Comparison of relative sea-level rise rates along the Atlantic Coast based on monthly mean tide heights (datum mean low low water). Raw data obtained from National Oceanic and Atmospheric Administration's (NOAA) National Ocean Service (<http://www.co-ops.nos.noaa.gov/> (31 July 2006]). Annual RSLR rates, regression equations, r^2 values, and P-values are: Boston: rate = 0.26 cm/yr, $y = -3.48 + 0.00257x$, $r^2 = 0.55$, $P < 0.01$; Montauk: 0.26 cm/yr, $y = -4.76 + 0.0026x$, $r^2 = 0.31$, $P < 0.01$; Atlantic City: 0.41 cm/yr, $y = -7.4 + 0.0041x$, $r^2 = 0.58$, $P < 0.01$; Chesapeake Bay Bridge-Tunnel: 0.59 cm/yr, $y = -11.2 + 0.0059x$, $r^2 = 0.23$, $P < 0.01$.

considering the current conditions, the SET results (past 3–4 yr) suggest that, except for Nauset Marsh, sediment elevations are not keeping pace with the current rates of RSLR, with deficits varying from ca. 2.5–4.1 mm/yr (Table 3). All values of RSLR and marsh elevation change (except E. B. Forsythe NWR) indicated significant ($P < 0.05$) positive levels of change using least-squares regression analyses.

Estimates of flooding frequencies at the New Jersey and Virginia sites, based on our temporary tide-gauge recordings suggest a significant increase in marsh flooding (>20 cm above marsh surface) in both areas during the May–July period over the past ca. 70–90 yr (Fig. 5). This analysis however, accounts only for water-level changes, assuming a steady-state in marsh surface. Correcting the marsh elevation changes back to the early 1900s based on our core accretion accumulation rates is crude at best, but we considered it necessary to attempt to estimate both marsh and water surface changes, even if a subsidence component was not estimable; the results (Fig. 5) still reveal a significant increase in flooding in Virginia, but a non-significant ($P > 0.05$) increase in New Jersey.

WATERBIRD IMPACTS

The effects of marsh inundation and flooding frequency for the waterbirds in these regions are numerous. In the short term, the effects will be expressed most dramatically for the species that are marsh nesters (Table 4). For those species with reasonable breeding estimates available, we calculated the number and percentages of the Atlantic Coast populations that reside in the most vulnerable region from New Jersey to Virginia (Table 5). For both Forster's Terns and Laughing Gulls (*Larus atricilla*), a large majority of their populations nest in this region and, thus, their populations are highly vulnerable.

At the intermediate time scale (1–2 decades), changes in marsh morphology and vegetation are expected with negative effects on populations of nesting species, but some positive effects on feeding waterfowl and shorebirds (Table 6). Also, at longer (>50 yr) time scales, with loss of most lagoonal marshes, waterfowl and shorebirds may enjoy some benefit, however, nesting habitat loss will be dramatic, and large changes in estuarine productivity may result (Table 7).

HYPOTHETICAL SEA-LEVEL-RISE SCENARIO: A CASE STUDY AT ATLANTIC COUNTY, NEW JERSEY

We digitized a total of 2,402.5 ha of saltmarsh habitat from the four randomly selected marsh locations in Atlantic County, New Jersey and, of the total area digitized, roughly 10% was categorized as pannes or pools, i.e., shorebird feeding habitat. According to the National Wetland Inventory maps, the total area of saltmarsh for Atlantic County was approximately 17,974.5 ha. Hence, if we assume that the four randomly selected subsamples are accurate

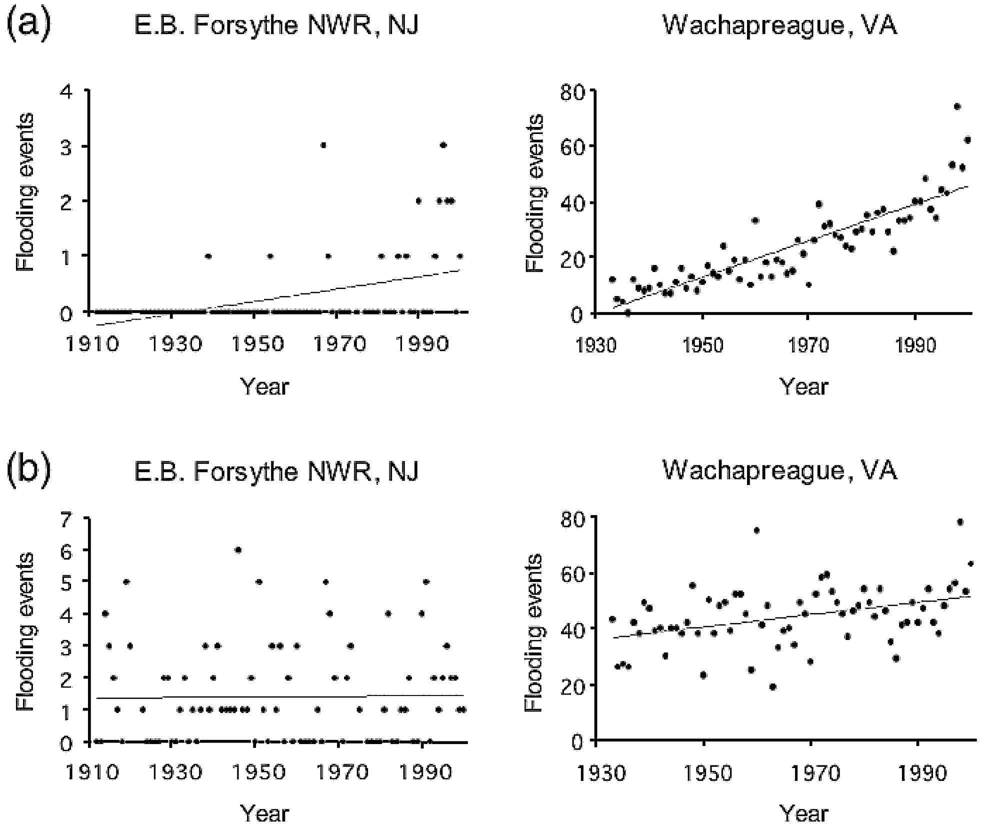

FIGURE 5. Frequency of marsh flooding events (>20 cm inundation) during May–July for E.B. Forysthe NWR, New Jersey, and Wachapreague, Virginia. The first scenario (a) represents annual marsh flooding frequency for each site assuming a static marsh elevation measure (based on year 2000) in relation to NOAA water levels. The second scenario (b) represents flooding frequencies calculated using a marsh elevation estimate hindcasted by subtracting annual accretion for each year. Averaged accretion rates were 3.8 and 3.5 mm/yr for E. B. Forsythe NWR (N = 2) and Wachapreague (N = 2), respectively. Forsythe flooding frequencies were calculated using 89 yr of NOAA tide gauge data (1912–2000); 68 yr (1933–2000) of data were used for Wachapreague. Regression equations, r^2 values, and P-values are: (a) Forsythe: $y = -20.9 + 0.010x$, $r^2 = 0.19$, $P < 0.001$; Wachapreague: $y = -1260.0 + 0.653x$, $r^2 = 0.77$, $P < 0.001$; and (b) Forsythe: $y = -1.3 + 0.001x$, $r^2 = 0.001$, $P > 0.05$; Wachapreague: $y = -388.3 + 0.220x$, $r^2 = 0.16$, $P < 0.001$.

TABLE 3. SHORT-TERM TRENDS (3–4 YR) IN MARSH ELEVATION CHANGE BASED ON SURFACE ELEVATION TABLE (SET) SITES COMPARED WITH RELATIVE SEA-LEVEL RISE (RSLR).

Location	Number of sites	Elevation change (mm/yr)	Relative sea-level rise (RSLR) (mm/yr)[a]
Nauset Marsh, Massachusetts	4	3.4[b]	2.6[b]
Absecon, New Jersey	3	1.7[b]	4.1[b]
E. B. Forsythe NWR, New Jersey	3	-1.1	4.1[b]
Wachapreague, Virginia	3	2.1[b]	3.9[b]
Mockhorn Island, Virginia	2	1.4[c]	3.9[b]

[a] RSLR rates same as those in Table 2, except for Nauset Marsh where seven additional years were added since the Roman et al. (1997) report using NOAA tide gauge data (Boston, MA station number 8443970).

[b] $P < 0.01$, regression analysis H_0: if no superscript, assume change = 0.

[c] $P < 0.05$, regression analysis H_0: if no superscript, assume change = 0.

Table 4. Short-term (seasonal) effects of sea-level rise on Atlantic Coast waterbirds and habitat.

	Biological effect on waterbirds	
Effect	Direct	Indirect
Storm flooding	Nest losses[a]: AMOY, BLSK, CLRA, COTE, FOTE, GBTE, LAGU, SESP, STSP	A. Renesting energetics costs (adult survival?). B. Shift nest sites. C. Fitness of late season fledglings (immature survival?).

[a] Species codes: AMOY = American Oystercatcher; BLSK = Black Skimmer; CLRA = Clapper Rail; COTE = Common Tern; FOTE = Forster's Tern; GBTE = Gull-billed Tern; LAGU = Laughing Gull; SESP = Seaside Sparrow; STSP = sharp-tailed sparrow.

Table 5. Estimates of number of nesting waterbirds along the Atlantic Coast [a].

Species	States (N)	Total[a]	N (and %) in mid-Atlantic[b]	N (and %) in marshes[b, c]
Laughing Gull	10	136,774	97,032	97,032
(*Larus atricilla*)			(0.71)	(1.00)
Common Tern	13	51,389	4,702	1,657
(*Sterna hirundo*)			(0.09)	(0.35)
Forster's Tern	6	6,449	5,255	5,255
(*Sterna forsteri*)			(0.81)	(1.00)
Gull-billed Tern	5	1,127	631	61
(*Larus nilotica*)			(0.56)	(0.09)

[a] Maine—Georgia (13 states). Colony estimates (in pairs) based on 1993–1995 inventories based on unpublished censuses coordinated by state biologists.

[b] New Jersey–Virginia.

[c] Percent of total mid-Atlantic (New Jersey–Virginia) populations located in marshes.

Table 6. Intermediate (1–2 decades) effect of sea-level rise on Atlantic Coast waterbirds and habitats (+ indicates positive effects, - indicates negative).

Effect	Ecological change	Effects on waterbirds[a]
Changes in marsh morphology and/or vegetation	A. Vegetation community shift (*Spartina patens* to *S. alterniflora*)	SESA, STSP nesting habitat (-).
	B. Enhanced ponding in interior marshes	Shorebirds (15+ species) ABDU, BWTE feeding habitat (+).
	C. Erosion of marsh island perimeters	AMOY, BLSK, COTE, FOTE, GBTE nesting habitat (-).

[a] Species codes: ABDU = American Black Duck; AMOY = American Oystercatcher; BLSK = Black Skimmer; BWTE = Blue-winged Teal; COTE =

Table 7. Long-term (>50 yr) effects of sea-level rise on Atlantic Coast waterbirds and habitat.

Effect	Ecological Change	Effects on waterbirds [a]
Inundation of marsh Islands	A. Emergent marshes convert to tidal flats	Migrant shorebirds, wintering waterfowl feeding habitat (+); Tern, LAGU, sparrow, rail nesting habitat (-); move to alternative habitat?
	B. Potential loss of nursery area for forage fish, shellfish	Reduced K for waterbirds; shifts to impoundments (increase in competition)?
	C. Redistribution of marshes latitudinally	Winter redistributions of ABDU, other waterfowl, shorebirds.

[a] Species codes: ABDU = American Black Duck; LAGU = Laughing Gull.

representations of the habitat in the County, the area of pannes and pools should be roughly 10% of the entire saltmarsh area, or 1,797.5 ha.

We calculated a maximum density of 51.7 shorebirds/ha during autumn 2000 at our survey location in Atlantic County (see Appendix 1 for species lists). Assuming that this number is also representative of the feeding densities throughout the county, we can estimate that 92,928 shorebirds (51.7 shorebirds/ha × 1,797.5 ha) are using the pannes and pools as feeding habitat at any given time during peak autumn migration. Supposing that this habitat is no longer available due to sea-level rise, E. B. Forsythe NWR offers one of the only local viable alternatives, with three impoundments totaling ca. 541 ha. The maximum density of shorebirds in the impoundments during autumn 2000 was 17.5 shorebirds/ha (J. Coppen, E. B. Forsythe NWR, unpubl. data). Presuming no yearly population changes of shorebirds, that density would increase 10-fold to 189 shorebirds/ha, assuming that shorebirds were unable to utilize their natural feeding habitat due to sea-level rise and all shifted to impoundments.

DISCUSSION

Relative Sea Levels and Saltmarshes

As reported earlier (National Academy of Science 1987), we showed a gradient in RSLR from New England to the mid-Atlantic region. A number of factors may account for this geographic variation, including deep subsidence associated with crustal dynamics and isostatic rebound differences (Kaye and Stuckey 1973, Douglas 1991). Local variation may be pronounced as well; to wit, our findings of major accretion estimate differences from cores only about 1 km apart at our Mockhorn Island site (Table 2). At another lagoonal marsh site within 20 km of our Wachapreague, Virginia site, an earlier estimate of 1.5–2.1 mm/yr was reported from two cores at Chimney Pole Marsh (Kastler and Wiberg 1995), putting that estimate far below the 5.4 and 16.0 values we obtained. Altogether, these data and others suggest marsh inundation has been occurring for some time, at least in Virginia. Knowlton (1971) found a 17% loss of cordgrass marsh from the period 1865–1965 comparing coastal geodetic survey maps. This variation also suggests that it may be quite problematic to model large-scale marsh changes without having a large number of additional samples.

In contrast to the Virginia data, Roman et al. (1997) claimed that, at least on Cape Cod, marshes were easily keeping pace with sea-level rise; however, our SET data suggest that marsh elevation change from 1998–2002 is more modest than the core data taken by Roman et al. (1997) suggest. One factor that might account for this difference was mentioned by Roman et al. (1997); storm-driven sand from the nearby barrier spit may provide infrequent but significant sources of surface accretion that was reflected in the longer-term cores but not in our SET results. In general, the northern New England marshes may be safer than marshes further south because recent tide-gauge data reveal a slower rate of RSLR over the most recent 40 yr compared to the entire record (ca. 80 yr) for the Boston, Portland, and Eastport, Maine stations (Zervas 2001). No other tide gauge (N = 60 examined) showed any other significant change comparing the recent data with the entire record (Zervas 2001). However, the greater tidal amplitudes in New England, relative to the mid-Atlantic, may offset any differences in RSLR, resulting in similar flooding vulnerabilities and decreasing their attractiveness as nesting sites on the marsh surface.

Morris et al. (2002) underscore the complications of marsh responses to sea-level rise along the southeastern US coast. They present an optimality model showing sea level as a constantly moving target (subject to interannual, annual, decadal, and longer temporal cycles). In this model, marsh vegetation is always adjusting toward a new equilibrium, and lag times are important. Thus, comparing short-term SET rates with long-term core data is fraught with peril since subsurface processes such as root production, decay, and compaction have not had time to occur. They further point out large geographic differences, with southeastern marshes being sediment-rich compared to mid- and north Atlantic marshes. Absolute elevation differences of the marshes are also critical in assessing vulnerability to RSLR (Morris et al. 2002:2876).

The increases in flooding frequency we documented in Virginia during the breeding season of waterbirds raises concerns about the future ability of some species to sustain their populations. Even though the small increase in flooding we suggest in New Jersey was not significant by one analysis, we feel that throughout the mid-Atlantic, waterbird habitat will become increasingly flooded as average global sea-level rise is expected to accelerate in the next 100 yr. The best estimate of an ca. 48-cm increase (Intergovernmental Panel on Climate Change 2001) representing a much higher rate than the global average of ca. 15 cm over the past century ± our estimates of 39–41 cm (3.9–4.1 mm/yr rates) for Virginia and New Jersey, respectively, over the past century (Table 2). In addition to mean water-level changes, storm frequencies have been predicted to increase by 5–10% along the Atlantic, with possible increases in intensity of storms as well (Giorgi et al. 2001). In addition to strong directional winds and normal lunar-seasonal cycles (Fig. 1), a long-term metonic or nodal cycle of 18.6 yr may also play a role in coastal flooding of marshes (Kaye and Stuckey 1973). Stumpf and Haines (1998) report that, with metonic, or lunar-nodal, cycles coupled with an annual tidal signal, some Gulf Coast wetlands may experience discrepancies of up to 5 cm from predicted tidal charts. In the mid-Atlantic region, this suggests that increases in water levels, and hence marsh flooding, probably occurred more often in the mid-1970s and again the early 1990s (Panel D, Fig. 1). Unfortunately, we were unable to locate any long-term data on breeding success by any marsh-nesting birds to confirm this prediction. However, Eyler et al. (1999) did find high nest flooding losses of marsh-nesting Gull-billed Terns during the 1994–1996 breeding seasons in Virginia. For long-lived marsh specialists such as Laughing Gulls that might breed for up to a decade, an intriguing question arises: does evidence exist for any long periodicities in reproductive effort that might be associated with these tidal cues?

WATERBIRD IMPACTS

The effects of slow inundation of lagoonal marshes along the Atlantic Coast are widespread. For waterbirds, the most vulnerable group is the marsh-nesting species, most notably those species that are saltmarsh-habitat specialists such as Laughing Gulls, Forster's Terns, Clapper Rails, and Seaside Sparrows, sharp-tailed sparrows, and Coastal Plain Swamp Sparrows. Forster's Terns appear to be the most vulnerable at present given their saltmarsh specialization (Storey 1987) and their large proportion of breeding range within the mid-Atlantic. Although we have some recent estimates of nesting populations of some of the colonially nesting species (Table 5), no large-scale surveys are available for most nesting species of cryptic passerines or rails. The status of the two species of sharp-tailed sparrows and the Coastal Plain Swamp Sparrow is currently under investigation by a number of biologists along the mid- and north Atlantic coasts (J. Taylor and R. Dettmers, USDI Fish and Wildlife Service, pers. comm.; Greenberg and Droege 1990, Greenberg et al. 1998). At present then, we have little idea of the extent to which populations of these cryptic species of sparrows and rails are threatened at the regional or Atlantic Coast scale. Nest losses of all these affected species will no doubt result in frequent renesting efforts that may often be relatively unsuccessful (e.g., Roseate Terns, [*Sterna dougallii*], Burger et al. 1996; Common Terns, Nisbet et al. 2002). Numerous anecdotal reports are also available of entire season nesting failure of Laughing Gulls, Gull-billed Terns, and Black Skimmers in coastal Virginia due to repeated flooding washout events (R. M. Erwin, unpubl. data; B. R. Truitt, The Nature Conservancy, unpubl. data). This occurred in most colonies during the mid-1990s and again in 2001–2002, with almost no young-of-the-year terns or skimmers seen in August roosts (B. R. Truitt, unpubl. data). Increased reproductive effort in a given season may prove costly to adult survival as well (Cam et al. 1998 and references therein); thus, both fecundity and survival may be adversely affected.

Abandoning marsh islands is another option. However, even if marshes are able to expand along the mainland or the backside of the barrier islands as the sea rises (Brinson et al. 1995), the ability of these marsh-nesters to shift to new breeding areas may be limited. First, in many developed coastal areas, the extent of bulkheads, sea walls, and other human structures may severely restrict the area of any significant long-term marsh transgression (Titus et al.1991). Second, even with marsh development, these newer marshes may become ecological traps as mammalian predators including red foxes (*Vulpes vulpes*), raccoons (*Procyon lotor*), and feral cats (*Felis domesticus*) will have easier access to nesting birds than when they nested on islands (Erwin et al. 2001). All of these carnivorous mammals have increased in the Atlantic coastal region as humans continue to increase along the coast and barrier island regions (Erwin 1980, Burger and Gochfeld 1991)

At the intermediate-time scale, changes in vegetation with smooth cordgrass invading areas now dominated by the higher marsh saltmeadow cordgrass (*Spartina patens*) and beach salt grass will presumably result in loss of breeding habitat for the marsh sparrows that depend on high marsh grasses and low marsh shrubs such as marsh elder (*Iva frutescens*). As sea levels encroach into marshes and cause more frequent flooding, many species will simply suffer reduced breeding habitat or shift to alternative habitats. Some colonial species such as Common Terns, Black Skimmers, and Gull-billed Terns have shifted to manmade habitats, e.g., an abandoned parking lot at the Hampton Roads, Virginia, bridge-tunnel complex (Erwin et al. 2003) but such sites are obviously limited. Specialized species such as rails, Forster's Terns, Laughing Gulls, and Seaside Sparrows may be strongly affected. For shorebirds and waterfowl especially, habitats that are flooded too deeply for feeding in large marshes may cause a larger proportion to shift to agricultural fields nearby if conditions are proper (Rottenborn 1996), to manmade public impoundments or, may force them to shift to other regions. Very large concentration of birds within impoundments raises questions about both the capacity of the prey base to sustain the populations, as well as the potential for disease under artificially high densities (Combs and Botzler 1991). In any event, either being forced into much higher densities in smaller habitat areas, or shifting to more distant regions will probably take a toll in the population levels of a number of species.

Finally, over the long term, with more unvegetated flats and open water replacing marsh islands, wintering waterfowl and migrant shorebirds may benefit by having more feeding habitat available. Especially for diving species such as bay and sea ducks, the newly created shallow water should provide good additional foraging habitat (Perry and Deller 1996). However, less marsh may force changes in distribution during breeding, migration, and even wintering seasons. American Black Ducks may be forced to winter further north as mid-Atlantic marshes decrease in area, especially if marsh loss is not as severe or rapid in coastal regions north of New Jersey. Again, this probably comes with a cost in terms of survival and population size.

Effects on Faunal Communities and the Estuary

Although we have focused our attention here on the potential effects of sea-level rise on the waterbird community, numerous ecological impacts are expected to occur along many coastal regions of the US and elsewhere. As examples, Reid and Trexler (1992) argue that, in just five southeastern US states, almost 500 rare and imperiled species use the coastal zone below the 3-m contour, and that human density is increasing in the coastal zone of all of these states. Similarly, Daniels et al. (1993) reveal the potential effects of sea-level rise in South Carolina, where 52 endangered or threatened plant and animal species were found in the 3-m contour. They argue that species as varied as American alligator (*Alligator mississippiensis*), loggerhead turtle (*Caretta caretta*), shortnose sturgeon (*Acipenser brevirostrum*), and Wood Stork (*Mycteria americana*) will be threatened by salt-water intrusion, flooding, inundation or erosion of feeding or nesting habitat if predictions prevail.

At the ecosystem level, major state changes would be expected to occur as estuaries once dominated by emergent cordgrass marsh become dominated by open water where primary productivity is dominated by macroalgae, submerged aquatic plants, or phytoplankton (Hayden et al. 1991, Valiela et al. 1997). Not only would major changes in primary productivity occur, but secondary production may also be greatly affected. The loss of the detrital food web within emergent marshes would have major implications for all trophic levels, to nearshore coastal production, and might severely jeopardize nursery areas for commercially important fisheries (Bertness 1999).

Research Needs

As has been pointed out above, we need much more information on the densities and distributions within saltmarshes of most waterbird species, especially those depending on the marshes for breeding. We have some estimates for the large, conspicuous colonial waterbirds, but very little large-scale data exist for the cryptic rails and marsh sparrows. As in most wildlife studies, few long-term monitoring efforts have been directed at assessing any demographic parameters, especially fecundity and survival; at best, annual population estimates are obtained for breeding adults for some species. In addition, we need more accurate global positioning system data to describe and model marsh elevations and topography, especially as they relate to tidal means and ranges. Having these data may allow us to construct more accurate models that will project various sea-level rise scenarios to landscapes that are relevant to bird habitat use (Galbraith et al. 2002). Or conversely, as Morris et al. (2002) suggest, marshes in sub-estuaries may have their own characteristic pattern of surface and sub-surface dynamics that strongly limit extrapolation.

ACKNOWLEDGMENTS

We thank the organizers, especially S. Droege and R. Greenberg, for inviting us to participate in the symposium. Many individuals assisted in establishing the SETs and helping with measurements, but we especially thank C. Roman, E. Gwilliams, and J. Lynch for their help. The staffs of Cape Cod National Seashore, E. B. Forsythe NWR, the Virginia Institute of Marine Sciences, and the University of Virginia's Virginia Coast Reserve Long-Term Ecological Research project (NSF Grant # DEB 0080381) provided much logistical support for the project. Funding was provided by the Global Change Program within the US. Geological Survey. Waterbird breeding estimates were kindly provided by state wildlife biologists in Maine, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, Delaware, Maryland, Virginia, North Carolina, South Carolina, and Georgia. We also thank S. Kress of the National Audubon Society for northern New England data and B.R. Truitt, The Nature Conservancy, and B. Williams for records from coastal Virginia. S. Droege and two anonymous reviewers provided constructive comments on an earlier draft.

APPENDIX 1. RANKING OF SHOREBIRD SPECIES OBSERVED AT OUR SURVEY LOCATION (LBNJ) AND THE IMPOUNDMENTS AT E. B. FORSYTHE NATIONAL WILDLIFE REFUGE, NEW JERSEY ON THE PEAK SURVEY DATE FOR EACH LOCATION (15 AUGUST 2000 AND 31 AUGUST 2000, RESPECTIVELY). SPECIES ARE LISTED IN DECREASING ORDER.

LBNJ bird survey site		E. B. Forsythe impoundments	
Common name	Scientific name	Common name	Scientific name
Semipalmated Sandpiper	*Calidris pusilla*	Semipalmated Sandpiper	*Calidris pusilla*
Semipalmated Plover	*Charadrius semipalmatus*	Semipalmated Plover	*Charadrius semipalmatus*
Short-billed Dowitcher	*Limnodromus griseus*	Black-bellied Plover	*Pluvialis squatarola*
Black-bellied Plover	*Pluvialis squatarola*	Least Sandpiper	*Calidris minutilla*
Willet	*Catoptrophorus semipalmatus*	Short-billed Dowitcher	*Limnodromus griseus*
American Oystercatcher	*Haematopus palliatus*	Western Sandpiper	*Calidris mauri*
Greater Yellowlegs	*Tringa melanoleuca*	Greater Yellowlegs	*Tringa melanoleuca*
Whimbrel	*Numenius phaeopus*	Willet	*Catoptrophorus semipalmatus*
		Lesser Yellowlegs	*Tringa flavipes*
		Stilt Sandpiper	*Calidris himantopus*
		Killdeer	*Charadrius vociferus*
		Ruddy Turnstone	*Arenaria interpres*
		American Oystercatcher	*Haematopus palliatus*
		Wilson's Phalarope	*Phalaropus tricolor*