Cool-Season Sea Level Anomalies and Storm Surges along the U.S. East Coast: Climatology and Comparison with the 2009/10 El Niño

WILLIAM V. SWEET AND CHRIS ZERVAS
NOAA/National Ocean Service, Center for Operational Oceanographic Products and Services, Silver Spring, Maryland

(Manuscript received 18 November 2010, in final form 28 January 2011)

ABSTRACT

Climatologies of sea level anomalies (>0.05 m) and daily-mean storm surges (>0.3 m) are presented for the 1960–2010 cool seasons (October–April) along the East Coast of the United States at Boston, Massachusetts; Atlantic City, New Jersey; Sewells Point (Norfolk), Virginia; and Charleston, South Carolina. The high sea level anomaly and the number of storm surges, among the highest in the last half century during the 2009/10 cool season, are comparable during strong El Niño cool seasons. High numbers of daily storm surges occur in response to numerous East Coast extratropical cool-season storms and have a positive correlation with the El Niño phase of the El Niño–Southern Oscillation (ENSO). Patterns of anomalously high sea levels are attributed to El Niño–related changes to atmospheric pressure over the Gulf of Mexico and eastern Canada and to the wind field over the Northeast U.S. continental shelf.

1. Introduction

Sea levels vary on many time and space scales. Important short-period variations occur when water levels differ significantly from those driven by localized tidal dynamics. Along the East Coast, these events are a cause for concern whether they are multiday storm surges from regional East Coast extratropical cool-season storms, commonly referred to as nor’easters, or as more localized impacts from hurricanes. Both types of storm surges can cause extensive flooding, erosion, and damage to coastal infrastructure. Longer-period and lower-amplitude sea level anomalies occur as significant variability about the seasonal mean and are recorded by the National Oceanic and Atmospheric Administration (NOAA; Zervas 2009). These events are less noticeable but, when elevated, effectively raise the level of the spring–neap tidal cycle (Sweet et al. 2009) and compound the impacts of incident storm surges and associated waves during high tide (Zhang et al. 2001). Short- and long-period low-water events also occur and pose risks to the maritime industry as the likelihood of ship groundings increases.

Global climate indices are one measure of atmospheric and oceanic patterns that have an effect on regional-scale storm-surge and sea level variability. Along the U.S. East Coast, the interannual changes within atmospheric centers of action associated with the North Atlantic Oscillation (Hurrell and Deser 2009) affect transport within the Gulf Stream system (DiNezio et al. 2009) and adjacent coastal sea levels (Hong et al. 2000; Papadopoulos and Tsimplis 2006; Kolker and Hameed 2007). El Niño–Southern Oscillation (ENSO) is also associated with ocean-atmosphere variability along the East Coast. Unlike the direct oceanic forcing of seasonal sea levels along the Pacific Coast (Chelon and Davis 1982), ENSO alters weather patterns that impact the East Coast. For instance, ENSO influences the frequency and landfall of hurricanes in the Atlantic (Gray 1984; Bove et al. 1998), though direct impacts from their wind and storm surge are both infrequent and quite localized. Much more common and widespread are East Coast impacts from extratropical cool-season wind storms, whose frequency and storm tracks are modified by ENSO. From 1951 to 1998, Hirsch et al. (2001) found that an average of 12 storms normally impact the East Coast during the October–April period and an average of 15 occur during El Niño
conditions. Eichler and Higgins (2006) also found more storms from 1950 to 2002 along the East Coast during cool seasons of El Niño and an increased storm track over the Great Lakes during La Niña. In terms of storm surge, Zhang et al. (2000) found highest frequencies along the East Coast during cool seasons with large interdecadal variability during the twentieth century, whereas from 1959 to 2007, Colle et al. (2010) observed that highest frequencies in New York City also tended to coincide with strong El Niño events.

This paper focuses on cool seasons (October–April) from 1960 to 2010 along the U.S. East Coast and highlights an unusual set of storm-surge and sea level observations made during the 2009/10 cool season. The atmospheric conditions during the 2009/10 cool season follow a pattern common to other strong El Niño periods and contribute to high seasonal sea level anomalies observed at NOAA water-level stations (http://tidesandcurrents.noaa.gov/sltrends). Specifically, this study investigates 1) short-term variability composed of daily-mean storm surges (height above tide) and setdowns (height below tide) and 2) longer-term variability of mean sea level over the entire cool season. This study builds upon previously derived East Coast extratropical storm climatologies that show an increased frequency during El Niño conditions by providing quantitative statistics that correlate storm-surge frequency with El Niño [sea surface temperature (SST) anomalies in Niño region 3.4]. To interpret the climatology of cool-season mean sea levels, atmospheric pressure over the Gulf of Mexico and eastern Canada and the wind field over the Northeast U.S. continental shelf are examined to diagnose the conditions inherent to cool-season sea level variability.

2. Data and methods

Hourly water-level observations and tide predictions are available for NOAA water-level stations at http://tidesandcurrents.noaa.gov (Fig. 1). The observations include both tidal and nontidal components of variability. Each tide station has a unique tide prediction that quantifies the astronomical forcing, composed of 37 harmonic constituents that include two long-term constituents representative of the localized, long-term mean-seasonal response to meteorological forcing (Gill and Schultz 2001). The observations and tide predictions were averaged over a 24-h period and subtracted to create a daily residual series, or a detided series representing the height relative to the predicted tide. Since the NOAA tide predictions do not include the local relative sea level trend, the daily residuals are detrended by a best-fit line to remove the local sea level rise (Table 1, column 1).

In this study, storm surge and setdown refer to daily residuals >0.3 m (~1 ft) and <−0.3 m, and they are tallied per month and per cool season (1 October–30 April). The 0.3-m storm-surge threshold is used because it is 1) a height at high tide capable of flooding many low-lying East Coast coastal areas (Sweet et al. 2009), 2) approximately each stations’ 1960–2010 mean daily positive residual plus two standard deviations, and 3) a height whose cool-season frequency has a high common correlation with the cool-season mean Niño-3.4 SST anomaly (Fig. 3). Storm-surge events are tallied as nonconsecutive daily storm surges per cool season. A high sea level anomaly is defined to be when the average sea level over a cool season is >0.05 m and a low sea level anomaly occurs when the average sea level is <−0.05 m.
Highest and lowest sea level anomalies are designated in Table 2 as the nonconsecutive sea level anomalies common to Atlantic City, New Jersey, and Sewells Point, Virginia (i.e., 1997/98, but not 1996/97). The selected stations are geographically representative of the regional coastal-ocean response from frontal-to-seasonal forcing. The correlation matrices (not shown) of daily and monthly water levels from 1960 to 2010 are $0.7$ and $0.8$ for station pairs from Boston, Massachusetts, to Sewells Point, though lower, $0.55$ and $0.75$ between Sewells Point and Charleston, South Carolina, likely from changes in forcing and coastline orientation.

Time series of National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis (Kalnay et al. 1996) 1000-mb winds, sea level pressure (SLP), and Niño-3.4 region ($5^\circ$N–$5^\circ$S, $170^\circ$–$120^\circ$W) SST anomalies are available at www.esrl.noaa.gov. The Oceanic Niño Index (ONI), which is the 3-month running mean of the Niño-3.4 region SST anomaly, is available at www.cpc.noaa.gov and used to quantify ENSO following NOAA’s operational definitions of El Niño and La Niña. Monthly ONI values are averaged over each cool season to designate strong ($>1^\circ$C) and moderate–weak ($0.5^\circ$–$1^\circ$C) El Niño and moderate–weak ($-0.5^\circ$ to $-1^\circ$C) and strong ($<-1^\circ$C) La Niña conditions (Table 2), a method that identifies periods similar to previous studies (Hirsch et al. 2001; Eichler and Higgins 2006). Using other indices, such as the Multivariate ENSO Index (MEI), which has a $>0.9$ correlation with the ONI, gives slightly different ENSO-event magnitudes and correlations ($<0.02$) derived in this study, but do not affect our findings or conclusions.

### Table 1. Sea level trends ±95% confidence interval (CI; mm yr$^{-1}$) between 1960 and 2010; number of cool-season storm-surge events (nonconsecutive days) for active years and the 1960–2010 mean ±1 standard deviation; and correlations of the 1960–2010 cool-season number of storm surges and setdowns with the cool-season mean Niño-3.4 region SST anomaly and the mean $2.5^\circ$ ($45^\circ$–$42.5^\circ$N, $70^\circ$–$67.5^\circ$W) northeasterly (NE)–southwesterly (SW) wind component with station sea level. Correlations $>0.23$ are at the 95% significance level. Years refer to the midpoint (15 Jan) of the cool season.

<table>
<thead>
<tr>
<th>Trend</th>
<th>Events</th>
<th>Correlations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1960–2010 ±95% CI</td>
<td>1973</td>
<td>1983</td>
</tr>
<tr>
<td>Boston</td>
<td>2.42 ±0.24</td>
<td>13</td>
</tr>
<tr>
<td>Atlantic City</td>
<td>4.48 ±0.30</td>
<td>16</td>
</tr>
<tr>
<td>Sewells Pt.</td>
<td>4.86 ±0.32</td>
<td>13</td>
</tr>
<tr>
<td>Charleston</td>
<td>2.95 ±0.26</td>
<td>9</td>
</tr>
</tbody>
</table>

### Table 2. Cool seasons classified as weak to moderate ($0.5^\circ$–$1^\circ$C) and strong El Niño ($>1^\circ$C), as weak to moderate ($-0.5^\circ$ to $-1^\circ$C) and strong ($<-1^\circ$C) La Niña by cool-season mean ONI values, and having highest and lowest sea level anomalies that are nonconsecutive and common to Atlantic City and Sewells Point. Years refer to the midpoint (15 Jan) of the cool season.

<table>
<thead>
<tr>
<th>El Niño</th>
<th>La Niña</th>
<th>Sea level anomaly</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>Weak–moderate</td>
<td>Weak–moderate</td>
</tr>
</tbody>
</table>
also the findings of Zhang et al. (2000). The frequency of storm surges and setdowns is higher (and amplitude larger as to reach the 0.3-m criteria) in the mid-Atlantic highlighted by the Sewells Point and Atlantic City series (Fig. 1a).

The time series for the 2009/10 cool season illustrate the differences in geographical response to local and regional forcing (Fig. 1b). The 2009/10 cool season was particularly active, especially at Atlantic City and Sewells Point, where a large storm surge from a powerful mid-Atlantic nor’easter occurred in mid-November 2009. The 2009/10 cool season was very energetic in the number of daily storm surges (>0.3 m) at all locations. The 2009/10 cool season also had a noticeable positive shift in each station’s mean sea level, which raised actual storm-tide elevations (surge height plus tide elevation, not shown). In fact, the 2009/10 cool season had some of the highest values in the last half century (Fig. 2): Boston, Atlantic City, and Sewells Point had the highest number of daily storm surges; and Boston and Sewells Point had the highest cool-season sea level anomaly. The 2009/10 cool-season values at Charleston, though not as extreme, largely follow a similar pattern. In terms of discrete storm-surge events (Table 1, column 2), 2–3 times the 1960–2010 mean occurred during the 2009/10 cool season.

b. Correlations of storm surges and setdowns with ENSO

The cool-season time series of the 1960–2010 distribution of storm surges and setdowns (Fig. 1a) are shown in Fig. 2. A pattern is evident of highest sea level anomalies (Table 2) and numerous daily storm surges occurring during cool seasons of strong El Niños, such as the 1972/73, 1982/83, 1997/98, and 2009/10 seasons. Correlations between cool-season number of daily storm surges and ENSO (cool-season mean Niño region 3.4 SST anomaly) quantify El Niño’s effect upon the likelihood of an increased number of daily storm surges along the East Coast (Table 1, column 3a). However, the opposite (more setdowns and lowest sea level anomalies associated with strong La Niña) is not true. For instance, the 1976/77, 1980/81, 1989/90, and 1994/95 cool seasons had lowest sea level anomalies and numerous daily setdowns, but they were not La Niña seasons (1976/77 and 1994/95 were actually weak El Niños). Correlations using the number of cool-season setdowns (Table 1, column 3b) confirm that setdown frequency is unrelated to the La Niña phase of ENSO.

Correlations for various storm-surge height thresholds are shown in Fig. 3 to ascertain the degree of association with ENSO. The correlations, which have a highest common value between sites at the 0.3-m threshold, reveal an important (>0.4 correlation) ENSO association with daily storm-surge frequencies between the 0.2- and 0.5-m thresholds. In all cases, the high number of storm surges during strong El Niño cool seasons effectively establishes the correlations in an otherwise variable signal. At thresholds ≥0.6 m, the correlations decrease as a greater number of cool seasons with applicable daily storm surges reduce to 0. For instance, Charleston had no storm surges above 0.6 m, whereas the other sites had only ≥33% of 1960–2010 cool seasons with nonzero values, thereby reducing the strong El Niño contribution to the correlations. If just the cool seasons with positive SST anomalies are utilized, the storm-surge correlations (Table 1, column 3a; Fig. 3) are all ~0.1 higher.

c. Mean sea level and atmospheric variability

A comparison of the distributions of daily-mean residuals for cool seasons with highest and lowest sea level anomalies (Fig. 4) reveals substantial shifts in the mean
(quantified in Fig. 2). The shape of the distributions remains near-normal under both circumstances with similar variance, though there is some skew ($\leq 0.03$ m) or minor difference between the means and medians (not shown) related to the ratio of extreme cool-season storm surges and setdowns. The distributions during the highest sea level anomaly seasons (shown in red hues) occurred during strong El Niños, but the lowest sea level anomaly seasons (shown in green hues) did not occur during strong La Niñas. It is evident that another forcing mechanism, one associated with El Niño, but not necessarily its relationship with cool-season storm frequency, is related to the mean sea level shifts.

To aid in the diagnosis of the low-frequency forcing linked to the mean sea level shifts, the 1960–2010 cool-season composite of mean SLP over North America and the wind field over the northwest Atlantic are shown in Fig. 5. The SLP maps (Fig. 5a) highlight the zonal subtropical atmospheric high (~1020 mb) along $30^\circ$N and lower SLP (~1000 mb) along $60^\circ$N associated with the Aleutian and Icelandic low pressure centers. The regional wind field (Fig. 5b) is characterized as moderate ($\geq 3$ m s$^{-1}$) westerlies with more of a northerly component in the higher latitudes and a southerly component in the lower latitudes over the ocean.

Maximum correlations between the 1960–2010 time series of cool-season sea levels to those of SLP and the zonal and meridional components of the wind (Figs. 5c–e) emphasize particular regions where forcing is highly linked to the observed East Coast sea level variability. Spatial correlations with each station’s sea level series (shown only for Atlantic City) are all quite similar in pattern and magnitude. The SLP–sea level correlations (Fig. 5c) are positive (0.4 to 0.5) for eastern Canada and strongly negative ($= -0.6$) for the Gulf of Mexico and the southeastern U.S. The wind–sea level correlations are highest east of Boston for the Gulf of Maine region, $< -0.7$ in the zonal (Fig. 5d) and $< -0.5$ in the meridional component (Fig. 5e). The correlations indicate that East Coast (shown for Atlantic City) sea levels rise as the difference in SLP gradient between the Gulf of Mexico and eastern Canada weakens (Fig. 5a) and the mean wind field (Fig. 5b) becomes less westerly and more northerly (enhanced northeasterly forcing, negative orientations) over the Gulf of Maine region. On the contrary, cool-season sea levels drop as the meridional SLP gradient further strengthens and the winds become more westerly and less northerly (enhanced southwesterly forcing, positive orientations) in response.

The highest correlations from Fig. 5d are found in the region of $45^\circ – 42.5^\circ$N, $70^\circ – 67.5^\circ$W. The 1960–2010 mean wind vectors in this region, illustrated in Fig. 5b, have an approximate axis of minimum variance of $315^\circ – 135^\circ$ with a northwesterly (oriented toward $135^\circ$) mean and standard deviation of 2.3 and 0.4 m s$^{-1}$. The wind field’s approximate axis of maximum variance, which is $45^\circ – 225^\circ$ with a southwesterly (positive orientation toward $45^\circ$) mean and standard deviation of 1.3 and
0.7 m s\(^{-1}\), is correlated with each station’s cool-season sea level series (Table 1, column 3c). As illustrated for Atlantic City and Sewells Point (Fig. 5f), there is a clear relationship between diminished southwesterly (or enhanced northeasterly) wind forcing over the Gulf of Maine region and sea level rise and increased southwesterly forcing and sea level fall along the East Coast. These results are similar to a previous study of monthly sea level variability along the U.S. East Coast (Sweet et al. 2009) and share the interpretation that Ekman-induced variability from northeasterly winds in this region affects both on-shore and alongshore transport and sea levels along much of the U.S. Atlantic coastline.

d. Atmospheric variability and ENSO phase

Cool-season mean Niño-3.4 SST from 1960 to 2010 is correlated with SLP and the wind components (Figs. 6a–c) to examine how ENSO-related variability affects SLP and the wind field over the regions where forcing is linked to sea level change along the U.S. East Coast (Figs. 5e–e). Over the eastern United States and Canada, the ENSO–SLP correlation map (Fig. 6a) is spatially similar to the SLP–sea level correlation map (Fig. 5c). For instance, there is the high degree of correlation (\(>0.6\)) within the Gulf of Mexico (Fig. 6a). However, the ENSO–SLP correlation is considerably weaker (\(<0.3\)) for eastern Canada. The ENSO–wind correlations (Figs. 6b,c) are also relatively weak (\(<-0.4\)) for the Gulf of Maine region, but indicate a limited tendency for either enhanced northeasterlies during El Niño or southwesterlies during La Niña.

The correlation maps in Figs. 6a–c imply that SLP changes occur during both La Niña and El Niño over the Gulf of Mexico (higher correlation). On the contrary, the lower ENSO–SLP correlations for eastern Canada and ENSO–wind correlations for the Gulf of Maine region suggest that these regions are less responsive to teleconnected forcing during both ENSO phases. This concept is supported through observations (Fig. 6d) that show strong El Niños concurrent with diminished southwesterly (or slight northeasterly) forcing over the

Fig. 5. The 1960–2010 cool-season composites of mean (a) SLP, and (b) vector winds showing magnitude (contours) and direction (arrows). The 1960–2010 cool-season (c) SLP and the (d) zonal and (e) meridional wind components correlations with Atlantic City’s 1960–2010 cool-season sea levels (\(>0.23\) are at the 95% significance level). (f) The cool-season sea level at Atlantic City and Sewells Point correlations with the northeasterly–southwesterly component of the wind from 45° to 42.5°N and 70° to 67.5°W. Years refer to the midpoint (15 Jan) of the cool season. Images are from www.esrl.noaa.gov/psd.
Gulf of Maine region (45°–42.5°N, 70°–67.5°W), but that little or no relationship is apparent during La Niña periods.

In terms of sea level variability, cool seasons with highest sea level anomalies occur under diminished southwesterly forcing (Fig. 5f) during strong El Niños (Fig. 6d). Figure 6e illustrates the relationship between highest and lowest East Coast sea level anomalies, wind forcing over the Gulf of Maine region (wind vectors shown in zonal and meridional components), and ENSO. During strong El Niños, cool seasons are characterized by mean northerly to northwesterly winds (along the axis of minimum variance with an enhanced northeasterly contribution along the axis of maximum variance) and highest sea level anomalies. However, strong La Niña conditions are not historically associated with a combination of enhanced southwesterly winds and lowest sea level anomalies. The unusually high 2009/10 cool-season sea level anomaly reflects that the northeasterly component was the highest (~0.5 m s⁻¹) of the 1960–2010 period.

Composite maps (Fig. 7) illustrate the atmospheric conditions during cool seasons with highest and lowest sea level anomalies and strong El Niños and La Niñas (shown in Fig. 6e and listed in Table 2). The SLP and wind-field anomalies are shown in Fig. 7a during cool seasons common to both highest sea level anomalies and strong El Niños (1972/73, 1982/83, 1986/87, 1997/98, and 2009/10). Most noticeable is the large region of very low (<−3 mb) SLP anomalies over the northeast Pacific. Of direct relevance to the regions of highest SLP–sea level correlation (Fig. 5c), the SLP anomalies are high (>−1.5 mb) over the northeast Pacific, slightly elevated (<−1 mb) over parts of the northwest Atlantic, but mostly neutral over the SLP–sea level regions of highest correlation. The resultant wind field has high (>1.4 m s⁻¹) northeasterly anomalies over the Gulf of Maine region where the highest wind–sea level correlations exist (Fig. 5d,e). During strong La Niñas (Fig. 7b), the conditions are different, but they are not entirely opposite those during the strong El Niños. The SLP anomalies are high (>2 mb) over the northeast Pacific, slightly elevated (<1 mb) over parts of the northwest Atlantic, but mostly neutral over the SLP–sea level regions of highest correlation. The wind field has weak (<0.6 m s⁻¹) and mostly southerly anomalies over the Gulf of Maine.
region. As expected, conditions during lowest sea level anomalies (Fig. 7c) are mostly opposite those during the highest sea level anomalies and strong El Niños. The SLP is slightly higher (<1 mb) over the Gulf of Mexico, but it is quite low (>−2 mb) over eastern Canada, giving rise to strong (>1 m s⁻¹) southwesterly anomalies over the Gulf of Maine region.

4. Concluding remarks

The number of daily storm surges (>0.3 m) and discrete storm-surge events and the sea level anomaly (>0.05 m) that occurred along the U.S. East Coast (Fig. 2) during the 2009/10 cool season were among the highest of the last half century. The 2009/10 number of daily storm surges and discrete events were nearly 3 times greater than each station’s 1960–2010 mean, with highest incidence of storm-surge events (17, each ~2 days in duration) occurring along the mid-Atlantic at Sewells Point and Atlantic City. A very high (>0.1 m) sea level anomaly existed at Sewells Point, Atlantic City, and Boston during the 2009/10 cool season and effectively raised the level on top of which the storm surges occurred. The anomalies are clearly visible as prolonged periods of very high sea level within the series of interannual monthly variability tracked by NOAA (http://tidesandcurrents.noaa.gov/sltrends).

The circumstances during the 2009/10 cool season are unique to strong El Niños, such as those of 1972/73,
1982/83, and 1997/98 periods. A primary atmospheric response to El Niño is a strengthening and shift in position of the subtropical jet stream during the Northern Hemisphere winter (Arkin 1982). Composite images of 200-mb winds (not shown, http://www.esrl.noaa.gov) reveal that the jet stream during the 2009/10 and other strong El Niño cool seasons is more zonally oriented over the southern United States and much stronger over the southeastern United States compared to periods of strong La Niña and lowest sea level anomalies (Table 2). A general southwest–northeast progression of storms along the East Coast during strong El Niños has been documented through a combination of SLP, wind, and precipitation data analyses (Hirsch et al. 2001; Eichler and Higgins 2006) and is attributed to storms following the cyclonic shear side of the jet stream’s wind maxima. During strong El Niños, the high number of cool-season storm surges is recognized as a response to frequent, localized northeasterly wind forcing from a high number of nor’easters following an active East Coast storm track. The $\sim 0.5$ correlation derived in this study between cool-season storm-surge occurrences and ENSO (cool-season mean Niño region 3.4 SST anomaly) quantifies the likelihood. However, the frequency of daily water-level setdowns ($< -0.3$ m) and related low sea level anomalies of importance to shipping interests are unrelated to the La Niña phase of ENSO.

The high regional sea level anomaly during the 2009/10 and other strong El Niño cool seasons (Table 2) is attributed to the same atmospheric patterns that established the East Coast storm track. Cool-season sea levels along the East Coast respond to changes in SLP over the Gulf of Mexico–southeastern United States and eastern Canada and wind patterns over the Gulf of Maine region (Figs. 5c–e). A pattern of unusually high SLP over eastern Canada and lower SLP over the Gulf of Mexico and southeastern United States during strong El Niño cool seasons (Fig. 7a) not only alters the jet stream location and increases the number of nor’easters entering (short-period northeasterly forcing over) the Gulf of Maine region, but it also drives a lower-frequency northeasterly component to the surface winds over this region. The resultant mean northeasterly wind component over the Gulf of Maine region was at a 1960–2010 high during the 2009/10 cool season, and so were many East Coast sea levels (Figs. 2 and 5f). Northerly–northeasterly wind forcing is parallel to most of the mid-Atlantic and New England coastline and the observed coastal sea level rise patterns might stem from both an Ekman-related on-shelf pressure gradient and related southwestward geostrophic transport over the Mid-Atlantic Bight and Scotian continental shelves (Han 2007; Lentz 2008). Although the atmospheric patterns and presumably the transport processes during lowest sea level anomalies (Fig. 7c) are mostly opposite those of the highest sea level and strong El Niño periods, the ENSO relationship is only one directional. Strong La Niña conditions are not associated with wind- and SLP-pattern reversals in the regions needed for lowest cool-season sea level anomalies to develop (Fig. 7b).

Of concern is the increasing susceptibility of the U.S. East Coast to the deleterious combination of sea level rise from climate warming and anomalously high sea level stands frequently punctuated by storm-surge events during strong El Niños. In the near future, regional sea levels along the U.S. mid-Atlantic and New England coasts are projected to rise from a slowdown of the Atlantic meridional overturning circulation (Yin et al. 2009) that will superimpose upon an expected acceleration in overall global rise rates (Rahmstorf 2007). Land subsidence is also causing relative sea level to rise, with highest rates along the U.S. East Coast within the mid-Atlantic region (http://tidesandcurrents.noaa.gov/sltrends) that is both highly developed and storm prone. In this study, relative sea level trends were removed (Table 1, column 1) to compare storm-surge and sea level anomaly magnitudes over the last half century. If the trends remained, the 2009/10 cool-season sea level and storm-tide elevations are higher than past comparable events. Though this study does not quantify maximum storm-tide elevations, the results help establish an El Niño–related propensity for localized flooding. More research is needed to realize the local-to-regional synergy between coastal geomorphology, storm-surge and wave climatologies (Ruggiero et al. 2001; Zhang et al. 2001) and their important El Niño–related variability along the East Coast.

Findings from this study help interpret how high seasonal sea levels associated with El Niño–related interannual variability are manifested along the U.S. East Coast. An outcome of this study is the development of statistical measures of the total effect of a cool season’s storm surges at a coastal location. The seasonal sea level anomaly, the number of daily storm surges, and the number of storm-surge events in a season may better represent the cool-season’s cumulative effect on the land–ocean interface than the highest and lowest water levels reached by the largest storm surges of the season. These indices are applicable to a spectrum of coastal planning efforts by providing useful insights when assessing coastal erosion, marsh habitat health (Kolker et al. 2009), and vulnerable coastal infrastructure (Zhang et al. 2001).

Acknowledgments. The authors are grateful for the suggestions made by John Boon of William and Mary’s.
Virginia Institute of Marine Sciences, Steve Gill of NOAA’s National Ocean Service, and two anonymous reviewers.

REFERENCES


