NOAA Technical Report NOS CO-OPS 051

ELEVATED EAST COAST SEA LEVEL ANOMALY: June – July 2009

Silver Spring, Maryland
August 2009

noaa National Oceanic and Atmospheric Administration

U.S. Department Of Commerce
National Ocean Service
Center for Operational Oceanographic Products and Services

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National Ocean Service
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U.S. Department of Commerce

The National Ocean Service (NOS) Center for Operational Oceanographic Products and Services (CO-OPS) provides the National infrastructure, science, and technical expertise to collect and distribute observations and predictions of water levels and currents to ensure safe, efficient and environmentally sound maritime commerce. The Center provides the set of water level and tidal current products required to support NOS' Strategic Plan mission requirements, and to assist in providing operational oceanographic data/products required by NOAA's other Strategic Plan themes. For example, CO-OPS provides data and products required by the National Weather Service to meet its flood and tsunami warning responsibilities. The Center manages the National Water Level Observation Network (NWLON), a national network of Physical Oceanographic Real-Time Systems (PORTS) in major U. S. harbors, and the National Current Observation Program consisting of current surveys in near shore and coastal areas utilizing bottom mounted platforms, subsurface buoys, horizontal sensors and quick response real time buoys. The Center: establishes standards for the collection and processing of water level and current data; collects and documents user requirements which serve as the foundation for all resulting program activities; designs new and/or improved oceanographic observing systems; designs software to improve CO-OPS' data processing capabilities; maintains and operates oceanographic observing systems; performs operational data analysis/quality control; and produces/disseminates oceanographic products.

Cover photo of local flooding at Carolina Beach, NC due to the elevated sea levels during the east coast anomaly on June 22, 2009.

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August 2009

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NOTICE

ELEVATED EAST COAST SEA LEVEL ANOMALY:
JUNE – JULY 2009

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EXECUTIVE SUMMARY

NOAA sea level stations managed by the Center for Operational Oceanographic Products and Services (CO-OPS) recorded higher than normal sea levels (SL) along the U.S. East Coast in June and July 2009. Near-peak levels in the latter half of June coincided with a *perigean-spring* tide, an extreme predicted tide when the moon is closest to the Earth during a *spring* tide. This tidal event added to the observed SL anomaly, produced minor coastal flooding, and caught the attention of many coastal communities because of the lack of coastal storms that normally cause such anomalies.

In terms of SL heights, the event was not very abnormal as many locations have higher levels in the late-summer. June – July 2009 SL heights are anomalous because of their unexpected timing and geographic scope. The SL event is anomalous in terms of its 'residual' values unaccounted for within the predictions of the earth-moon-sun tides and normal seasonal cycles of the winds and atmospheric pressure, ocean currents, and heating/cooling of coastal waters. The mean residual SL values for June 2009 were significant (> 0.2 m) from North Carolina to New Jersey, substantial (> 0.1 m) from Florida to Maine, and the most extreme to occur simultaneously over the entire East Coast during a spring/summer period as far back as 1980.

There are two probable mechanisms responsible for the June – July 2009 high SL residuals. The first is northeasterly (NE) wind forcing. In June 2009, winds over the entire geographic area from Cape Hatteras, NC to the Gulf of Maine had a moderate NE wind component, whose transport caused coastal SL to rise. South of Cape Hatteras, winds were primarily southwesterly (SW). The other mechanism is the changing transport of the Florida Current, which is measured in the Florida Straits before it supplies the Gulf Steam off of Cape Hatteras, NC. When the Florida Current / Gulf Stream transport is low, the eastward-rising cross-current slope relaxes and raises coastal SL. In June 2009, the SL residual rise was concurrent with a noted decrease in transport of the Florida Current.

The June – July 2009 SL event decays in mid-July 2009 as the SL residuals diminish. During this period, transport of the Florida Current sharply increases and the winds oscillate between SW and NE along the East Coast.

The June – July 2009 SL anomaly is unique in that the NE winds were not at a multi-year high or the Florida Current transport at its low. But the coupled effect of the two forces created SL residuals that were at highest levels all along the East Coast. Highest SL residuals between North Carolina and New Jersey highlight the region of greatest overlap of the two forces.

ELEVATED EAST COAST SEA LEVEL ANOMALY: JUNE – JULY 2009

PURPOSE

The purpose of this report is to describe and document a significant anomaly in the elevations of sea level along the East Coast during June and July of 2009. Oceanographers and web-services personnel in the NOAA Center for Operational Oceanographic Products and Services (CO-OPS) started receiving dozens of inquiries from the general public in early June when they noticed the tides were running higher than predicted over several days. The peak number of inquiries was associated with the peak elevations of the event in late June 2009. During that time period (June 20-25), the sea level anomaly coincided with extreme predicted tides caused by increased tide-producing forcing due to the near conjunction of the moon's perigee (moon closest to the earth in the monthly orbit) and *spring* tide (a new moon). These *perigean-spring* tides, which cause water levels a few centimeters above normal *spring* tides, can cause minor coastal flooding even in the absence of a coastal storm or sea level anomaly. The amplitude and the extent of the anomaly caught everyone by surprise, because there was no coastal storm or strong weather front present that would normally cause these types of anomalies.

The following text was used as an alert on the Center for Operational Oceanographic Product and Services web-site (http://tidesandcurrents.noaa.gov):

"Observed tides have risen above predicted elevations along the entire U.S. East Coast from Maine to Florida since June. From June 19 thru June 24, water levels were between 0.6 to 2.0 feet above normal depending upon location. As of July 1, anomalies continued running lower at 0.3 to 1.0 ft. above normal. It is not unusual for smaller regions and estuaries along the East Coast to experience this type of event this time of year; however, it is significant that the geographic extent of this event covers the entire East Coast. The Center for Operational Oceanographic Products and Services (CO-OPS) will continue to monitor this event and will provide further information on the causes, amplitudes, geographic extent, and the duration of the event."

This sea level anomaly event should not be confused with a change in the relative trends in mean sea level determined from the NOAA tide stations. This event is of much shorter duration and would only affect relative sea level trends if the anomalies started occurring with increasing frequency and longer duration.

INTRODUCTION

Water levels vary over many time scales, from tidal forcing to longer-term sea level rise associated with climatic changes. Non-tidal changes vary in duration and magnitude and can be storm driven, or reflect seasonal, annual, inter-annual, and decadal sea level changes. Seasonal changes occur primarily from changes in wind forcing and atmospheric pressure, ocean-currents, and density (heating/cooling) of the shelf waters. Inter-annual and longer variability can cause significant changes in the timing and magnitude of the normal seasonal/annual patterns. Often, multiple forcing mechanisms work in tandem and create feed-back loops making it difficult to discern the specific response from a particular forcing parameter. In order to support the CO-OPS mission of providing reliable measurements and accurate predictions of water levels and establish longer-period (i.e., weekly and longer) sea level heights and trends, it is necessary to assess the sea level responses that occur from mechanisms forcing change.

This document presents data from a sampling of NOAA stations (Figure 1) to highlight the extent and magnitude of an elevated sea level anomaly that occurred June – July 2009 along the U.S. East Coast. Important to this study are the concepts of observations and predictions of water level and their differences or 'residuals'. Water level observations are a measurement made by NOAA stations and are analogous to 'lines in the sand', or the heights at which water is located at a given time. Tide predictions are a product provided by CO-OPS that quantify through harmonic analysis the site-specific time and height of the periodic motion driven by the interaction of the earth-moon-sun system. There are two long-period tidal constituents inherent to NOAA predictions that are important to this study. They are the 365-day period Sa (solar annual) and 183-day period Ssa (solar semiannual) harmonic constituents, which have a theoretical tide-producing force origin with small amplitudes. However, in practice, they are used in an attempt to capture the periodicity of the sea level response that results from seasonal meteorological forcing. These constituents are derived from an observed-mean annual sea level signal and are usually computed from 5 to 19 years of data, depending on the station. Thus, the tidal predictions are unable to account for either inter-annual variability or the intra-annual variations that deviate from the mean annual sea level prediction. The residuals, or the portion of the observations unaccounted for by the predictions, will reflect all non-tidal variability induced by the forcing mechanisms described above. In this report, the June – July 2009 sea level anomaly is highlighted in terms of residual values.

The document is laid out in the following manner. Examples of six-minute observations, tidal predictions and residual data provided at the CO-OPS website (http://tidesandcurrents.noaa.gov) are shown to highlight the event. Time series of daily observations from multiple stations along the East Coast are used to illustrate the magnitude of the event as would be witnessed by a local observer. Site-specific predicted and residual cycles since 2006 are shown at two locations to assess the timing and magnitude of the June – July 2009 event. To put the event in geographical perspective, the June 2009 monthly averaged sea level data from East Coast stations with >30 years of data are de-trended by the site-specific seasonal signal and relative sea-level trend (Zervas, 2001). For historical perspective, the East Coast stations are then grouped into a northern or southern region and their monthly de-trended averages are shown since 1980. Time series of wind collected at two NOAA buoys and of the transport strength of the Florida Current are shown and correlated to sea levels at multiple stations to highlight likely forcing factors involved in the event. Time series of atmospheric pressure at multiple NOAA stations are also included to determine the influence of the inverse barometer effect. Products derived from sea surface height (SSH) data from satellite altimetry measurements are shown to better discern the regional influence of the anomalous conditions. Lastly, reasons for inter-annual variability of the forcing mechanisms are described in context of the literature and on-going research efforts.

Figure 1. NOAA stations, NOAA buoys, and Florida Current transport measurement site.

METHODS AND DATA

Water levels are obtained from the CO-OPS website located at http://tidesandcurrents.noaa.gov. Water level data are relative to mean sea level (MSL), which is a tidal datum currently in effect for the 1983-2001 National Tidal Datum Epoch (NTDE). Throughout this report, the term 'sea level (SL)' will be used to describe longer period (> 7 days) water levels and are shown relative to the MSL datum. Also reported are the tidal predictions reported relative to the same MSL datum. Predicted values are based upon 37 harmonic constituents derived by averaging > 5, 1-year least-squares harmonic analyses of observed hourly water level heights. The residual values are the difference between the observed and predicted values. Time series of water levels from five NOAA stations are investigated to highlight the June – July 2009 SL event: 1) Nantucket, MA, 2) Atlantic City, NJ, 3) Duck, NC, 4) Charleston, SC, and 5) Trident Pier at Cape Canaveral, FL. Time series of atmospheric pressure during the event are also shown, but of the five stations, they are only available at the Nantucket, Duck and Trident Pier locations.

In order to place the magnitude of the June – July 2009 SL anomaly into a long-term perspective, a 'de-seasonalized' and 'de-trended' monthly series are shown. The cycle removed from the de-seasonalized series is composed of average heights relative to MSL for each month over the entire series. Generally, this seasonal cycle is very close to the predicted values based upon harmonic constituents. However, since the predictions are computed from harmonic constituents averaged over time periods of 5 to 19 years and the seasonal cycle is computed over the series length, slight differences occur (Figure 2). The de-trended series also includes the removal of the series-long (> 30 yr) linear fit that represents the site-specific relative SL rise (Zervas, 2001).

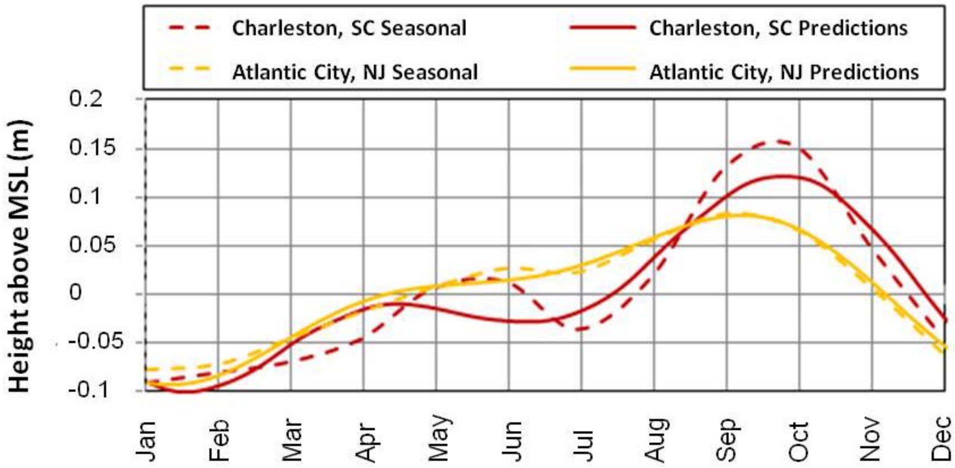


Figure 2. Illustration of SL predictions based on 5 to 19 years of data and the seasonal SL cycle determined by averaging values from each month over the entire series (> 30 years).

Time series of winds are shown for the NOAA buoy 41004 (Edisto), which is located 41 nm southeast of Charleston, SC (Figure 1). Wind is also shown for buoy 44008 (Nantucket), which is located 54 nm southeast of Nantucket, MA. Both sets of wind velocity vectors are rotated to direction of maximum (minimum) variance of the Edisto time series for consistency, namely 45°/225° (135°/315°) from true north. These wind observations are thought to be representative of large regions for application to the analyses presented here. Comparisons to the large-scale wind field of the SeaWinds satellite microwave scatterometer sensor (QSCAT) at www.remss.com attest to their general agreement. Throughout the document, wind directions will be referred to in the standard meteorological sense, i.e., from the direction of flow. Time series of the transport strength of the Florida Current (FC) is shown as measured between Florida and the Bahamas near 27°N (Figure 1). A detailed history of cable measurements of the Florida Current can be found in Larsen (1992). Also, merged daily composites of regional-scale dynamic ocean topography and SL anomaly are shown. These data are derived from satellite altimetry and gridded to 0.3 degrees and an accuracy of ~4 cm. The absolute dynamic height is relative to the 1993-1999 mean SSH adjusted for the geoid and calibrated by *in-situ* based climatology as well as the SL anomaly, which is a date-specific SSH anomaly from the 1993-1999 SSH mean. Further documentation is available at www.aviso.oceanobs.com/duacs.

Daily time series of water level observations, predictions, and residuals, atmospheric pressure, wind data, and FC transport have been lowpass filtered by a cosine Lanczos filter (Emery and Thompson, 2004). Lowpass filtered data series have cutoff frequencies (half amplitude) of 39-hour, 7-day, 30-day, and 90-day and are appropriately labeled within the text. Filtered data have been truncated at the beginning and end by half the cutoff frequency (i.e., 15 days for the 30-day filter). The cross correlation function is computed between various 30-day lowpass series using the MATLAB (Mathworks, 2009) function XCOV, which is the cross covariance between the de-meaned time-series. Coefficients are normalized between -1 and 1 and imply strong inverse (negative) and direct (positive) correlations. Coefficients are shown at the corresponding lead/lag phases and are significant at the 99% confidence level. The cross correlation function was used instead of a frequency-based coherence function since it can handle the occasional large gaps in the data sets. Coherency analyses and spectral analyses of continuous SL, wind and FC data segments confirm significant energy and coherence in the 25 – 50 day band, validating the usage of the 30-day lowpass filter series used in the correlation analyses (Maul *et al.*, 1990).

FINDINGS

Sea levels during June 2009 were consistently > 0.2 m above predicted tidal elevations along most of the eastern U.S. seaboard. Examples from Charleston, SC and Atlantic City, NJ show a series of 6-minute water level measurements available on the CO-OPS website (Figure 3a). It can be seen that on ~6/22/09, water levels were at their highest values. In fact, near-peak residual values for the June – July 2009 event, which topped 0.4 m at both locations, occurred within a couple days of 6/22/09, when a *perigean-spring* tide was occurring. It is important to note that while the observations and predictions both gradually increased due to the tidal event, the residual values remain relatively constant. Water levels were indeed high, but the effects of the *perigean-spring* tide are included in the predictions, and thus the residual increase is in response to other underlying forcing mechanisms.

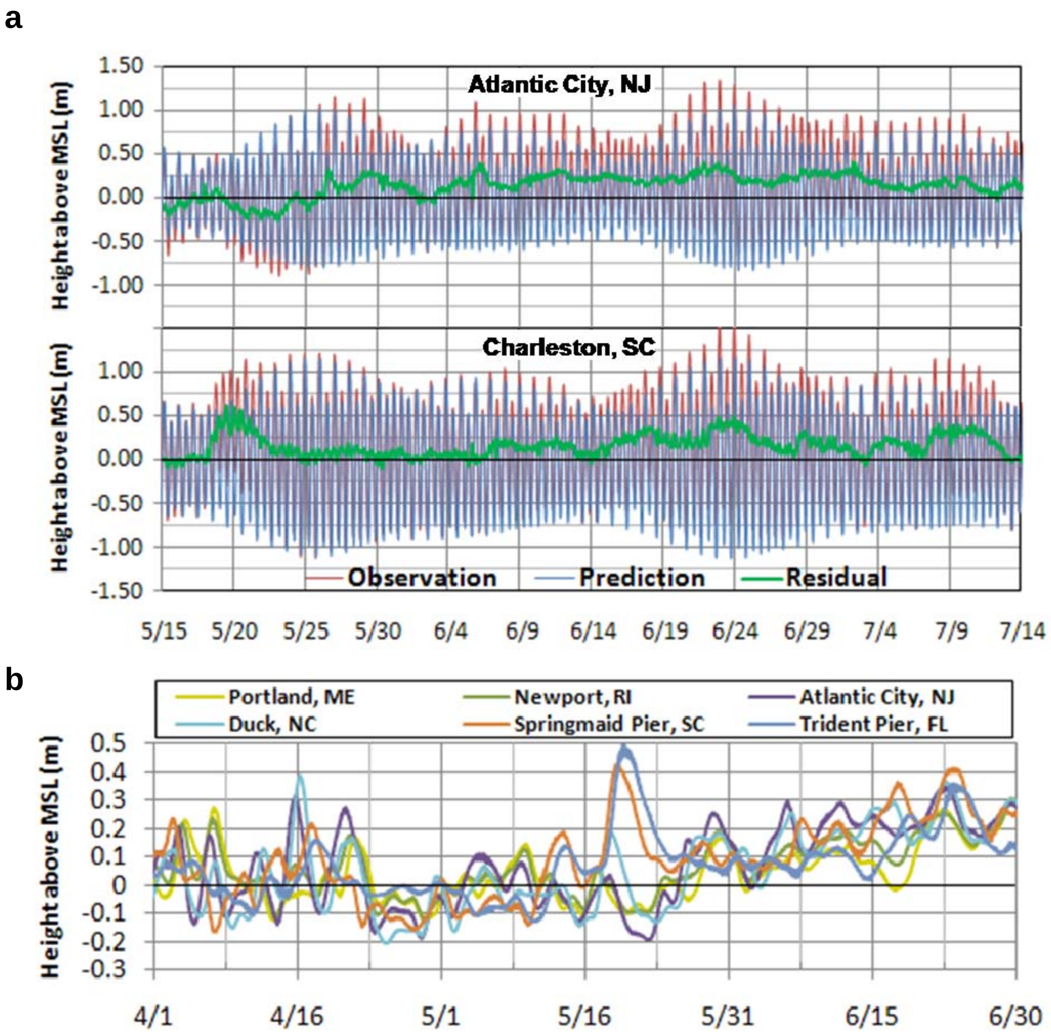


Figure 3. a) Plot of 6-min data from Atlantic City, NJ and Charleston, SC between May 15 and July 14, 2009 and b) 39-hour lowpass filtered series of observations along East Coast.

The SL rise associated with the June – July 2009 event begins in approximately late May, as shown by multiple de-tided observations along the East Coast (Figure 3b). The de-tided series closely match the residual (observed – predicted) series over this short time period. It is important to comment on the large spike in water levels in mid-May shown at Springmaid Pier in Myrtle Beach, SC and Trident Pier located at Cape Canaveral, FL (Figure 3b) and in the residual at Charleston, SC in Figure 3a. This multi-day spike is not considered as part of the widespread SL anomaly. A slow-moving cold front produced a strong NE wind between May 19 and 23, 2009 that temporarily raised water levels ~0.4 m from South Carolina to Florida. This event will be further discussed in later sections.

Observations, Predictions and Residuals

Since water levels are persistent across the tidal cycle, multi-day averages and lowpass filtered values of observations, predictions and residuals are investigated. Figure 4 is a plot of monthly mean SL observations from January 2000 to July 2009 from five stations along the East Coast. Common to most stations is a SL that is highest (> 0.2 m) in late summer, lowest in late winter (< -0.1) and has a secondary high in late spring that is more prevalent towards the south. The June 2009 SL values are not particularly abnormal in terms of their overall magnitude, though the middle Atlantic stations at Duck, NC and Atlantic City, NJ are close to their respective series high. The June 2009 SL values are anomalous in that many have already achieved heights similar to their respective historical late-summertime highs. That is, the high-water values are occurring earlier than expected. Comparison of the site-specific SL predictions will determine magnitudes of the anomalies in terms of their residuals.

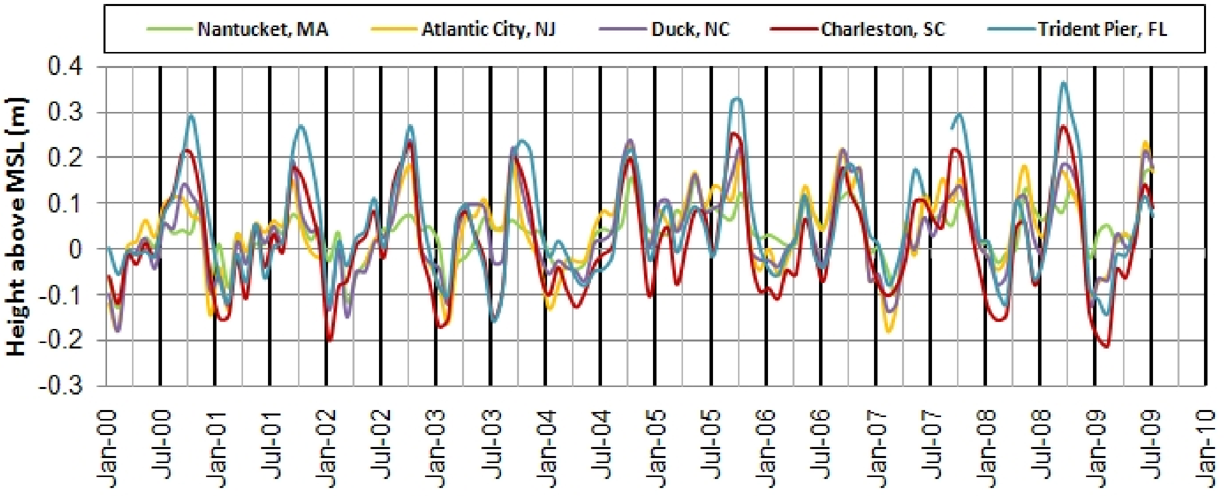


Figure 4. Monthly mean SL observations at East Coast stations from January 2000 to July 2009.

Figure 5 shows the 30-day lowpass filter series of SL at Charleston, SC and Atlantic City, NJ from January 2006 to July 2009. The predictions, which reflect the site-specific Sa and Ssa constituents, represent the periodic intra-annual SL variability. The changes occur primarily in response to seasonal meteorological and oceanic forcing. The predictions include effects from the steric cycle of seasonal heating and cooling of the coastal waters that cause SL to be higher in late summer and lower in the late winter. The predictions at Charleston have a slightly larger range and contain a more noticeable double peak than the predictions at Atlantic City. Both locations have predictions that are lowest in February, highest in October, a lessened peak in April/May with a subsequent low in June/July. The residual series show a positive anomaly associated with the June - July 2009 event peaking at ~0.25 m at both locations in the latter half of June. Actual SL observations with equal or greater magnitudes have occurred in the last three years at both locations. A few noted high SL events occurred in September 2006 at both locations and in September/October of 2007 and 2008 at Charleston, SC. The residuals, although, were less since the predictions are both locations are higher in September/October.

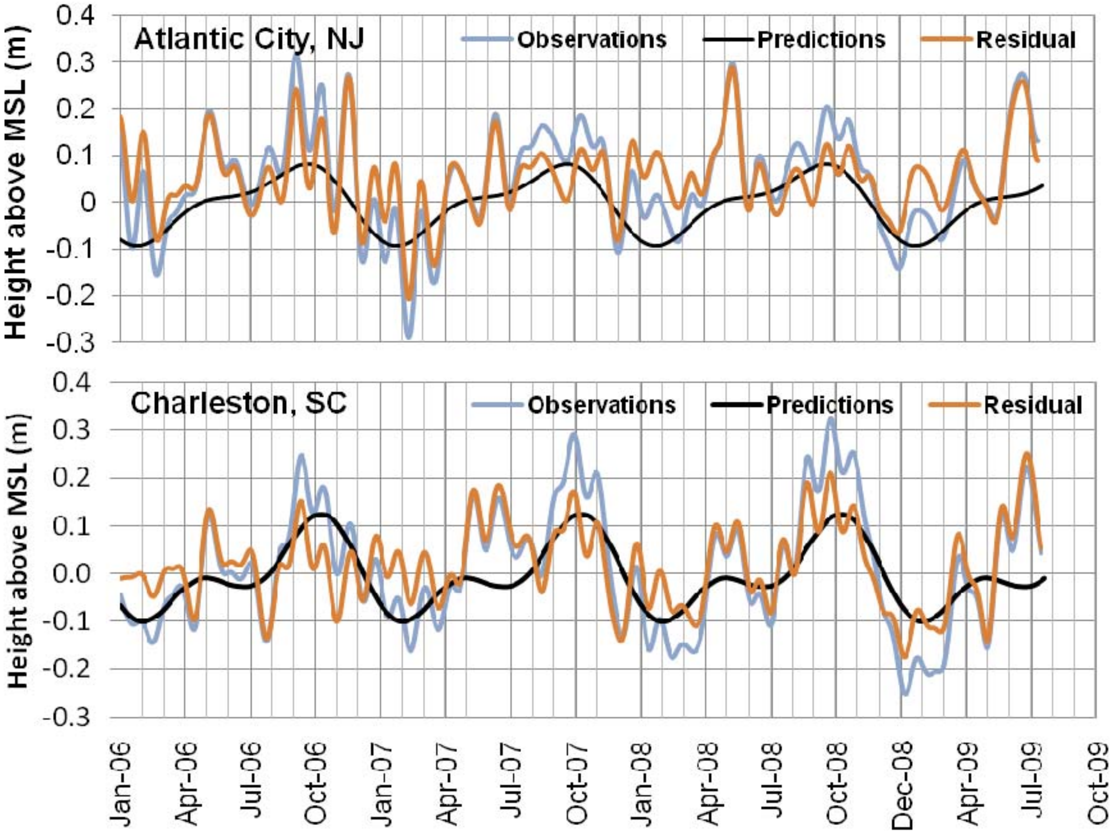


Figure 5. 30-day lowpass filter of SL observations, tidal predictions and residuals at Atlantic City, NJ and Charleston, SC from January 2006 to mid-July 2009.

A Spatial and Temporal View of the De-trended Series

Monthly mean SL values are examined at long-term NOAA stations (> 30 years) to determine the geographical extent of the June – July 2009 SL anomaly along the East Coast and compare it with previous events. Data were obtained relative to the MSL datum for the 1983-2001 NTDE. The series have the average seasonal SL cycle, derived over the entire data series from each station, removed to create a 'de-seasonalized' SL series. The 'de-seasonalized' series are quite close to the longer-period SL predictions at a particular station (see Figure 2). The June 2009 mean SL values with the seasonal cycle removed are displayed in red in Figure 6. The highest June SL values (> 0.2 m) are from Sandy Hook, NJ to Chesapeake Bay Bridge Tunnel (CBBT), VA although the SL values are substantial (> 0.1 m) from Eastport, ME to Vaca Key, FL.

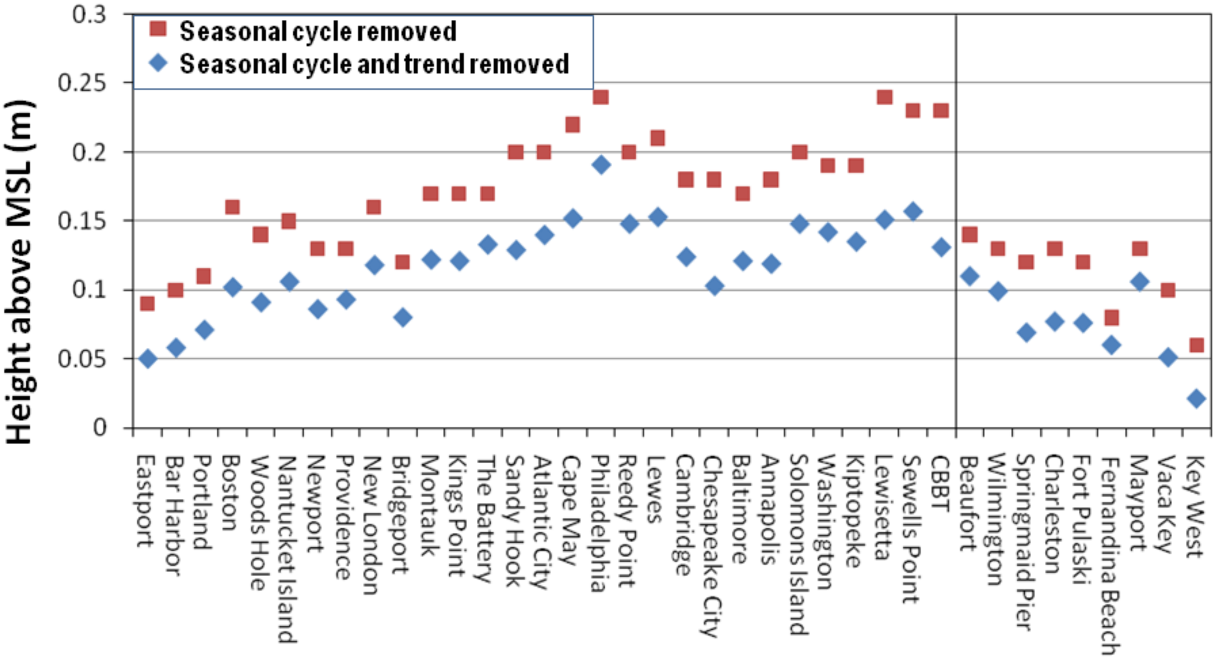


Figure 6. June 2009 mean SL observations adjusted for the long-term average seasonal SL cycle (red) and the long-term relative SL rise (blue). The vertical line shown on the plot separates the two regional groups.

Absent in the predictions and thus inherent to the residual (observed – predicted) values is the long-term relative SL rise that has occurred since 1992, or the middle of the 1983-2001 NTDE. In the subsequent 17 years, SL rise has averaged ~3 mm/yr on the East Coast, resulting in an average rise of ~0.051 m. In Figure 6, each station in blue is further de-trended by its long-term relative SL rise. This de-trended value is a better representation of the true magnitude of the anomaly, independent of the time elapsed since the establishment of the NTDE.

The de-trended SL series are highly correlated between neighboring stations along the coastline (not shown). A time series of the averages from 1980 for the two regional groups of stations – north of Cape Hatteras (Eastport to CBBT) and south of Cape Hatteras (Beaufort to Key West) is shown in Figure 7. The average de-trended SL series north and south of Cape Hatteras are somewhat correlated with each other (0.50). Some months have large values north and south of Cape Hatteras, and in some months, large values exist in one region but not the other.

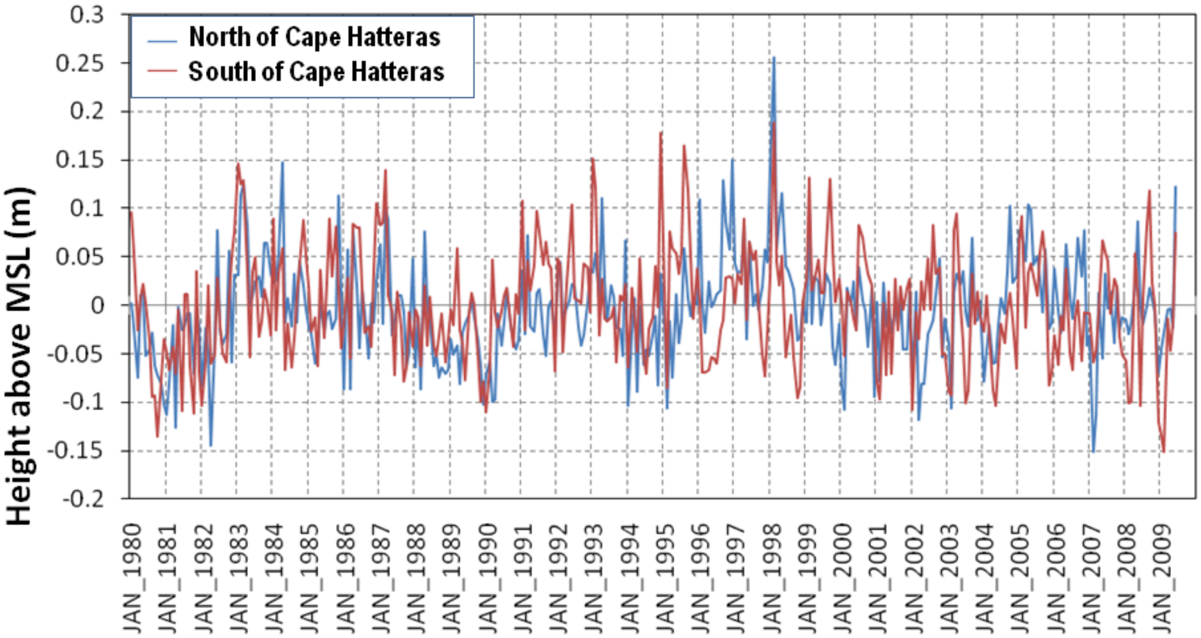


Figure 7. Average of the mean monthly SL observations adjusted for the average seasonal cycle and long-term relative SL rise for 29 stations north of Cape Hatteras (Eastport to CBBT in blue) and 9 stations south of Cape Hatteras (Beaufort to Key West in red).

The de-trended SL series allows an unbiased comparison of the June 2009 values to previous events. The greatest values in both regions occurred in January and February 1998 when a series of long-lasting, slow-moving winter storms significantly raised SL along the entire East Coast (Deitemyer, 1998). Similar events occurred in January-March 1983, March 1987, and February 1999. On the other hand, winter storms in some years have significantly affected SL in one of the regions but not the other. There are only a few instances where large de-trended values occur in summer (Figure 7). There are large values only in the north for September 1996 and large values only in the south for August 1995 and September 1999. The June – July 2009 values are the highest shown to simultaneously occur within both regions during the spring/summer period.

Wind Forcing, Atmospheric Pressure and Sea Level Response

The 30-day lowpass filtered residuals for five stations along the East Coast show the magnitude and widespread extent of the June – July 2009 SL event (Figure 8). It can be seen that the southwesterly/northeasterly (SW/NE) component of the wind has a particularly strong effect on SL along the East Coast. Northeasterlies (negative) are largely oriented alongshore and cause an Ekman-driven convergence along the coast and SL to rise (positive). On the other hand, SW (positive) winds cause a divergence away from the coast or set down of SL. The winds offshore at the Nantucket buoy establish a stronger negative correlation to SL than the winds offshore of Edisto (Figure 8 legend in parentheses) most likely due to the fact that Nantucket is further offshore and less influenced by boundary effects from land.

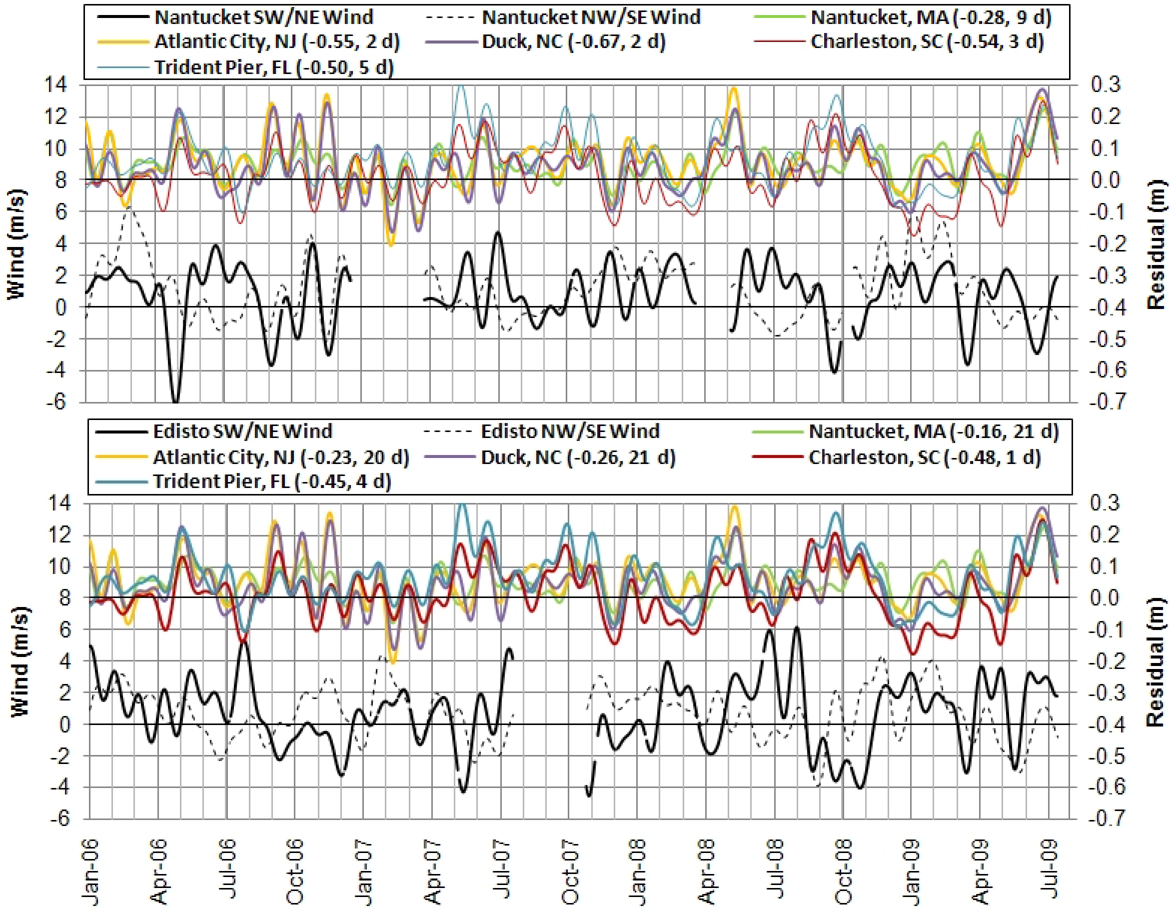


Figure 8. 30-day lowpass filtered SL residual time series and southwesterly/northeasterly winds (SW/NE) and northwesterly/southeasterly winds (NW/SE) at NOAA buoys 44008 Nantucket and 41004 Edisto. Correlation coefficients and phase lead (+) of the SW/NE winds to the SL residual (shown in parentheses).

Near the beginning of May 2009, the winds at the Edisto buoy turn to become a NE wind; it should be noted, though, that the 30-day lowpass series primarily reflects the strong 5-day NE wind event in mid-May mentioned earlier. Residuals quickly respond at the nearby stations, increasing > 0.25 m at Trident Pier, FL and Charleston, SC. Interestingly, even while the winds reverse and become SW at the start of June, the residuals rise by ~0.15 m to a value of ~0.25 m by mid-June under continued SW wind forcing at Edisto. In contrast, the winds at the Nantucket buoy are SW in May, becoming NE winds by the start of June. The NE wind peaks in mid-June and become SW by July. The residuals at Duck, NC, Atlantic City, NJ and Nantucket, MA all rapidly respond to the Nantucket winds. Residuals increase by > 0.25 m from mid-May to mid-June at all locations under NE wind forcing, with highest levels of ~0.3 m observed at Duck.

A few other NE wind events put the current event into perspective. The NE winds that occurred around October 2008 and March 2009 had magnitudes of > 3 m/s at both locations, which are similar to speeds of the June 2009 NE wind event (Figure 8). During the October 2008 event, Charleston, SC and Trident Pier, FL had SL observations slightly higher than during the June – July 2009 event (Figs. 4 and 8). During the March 2009 event, SL was lower at each location. However, in both occasions the residuals were lower due to the fact that the predictions normal for these time periods are also higher. There are two other NE wind events worth noting that exceeded the speeds during June 2009 and that happened at nearly the same time of year. During May of 2007, a NE wind > 4 m/s occurred at the Edisto buoy and during May/June of 2006, a NE wind of ~6 m/s occurred at the Nantucket buoy (Figure 8). Neither event registered at both buoys, similar to the June 2009 NE event. In both cases, except the response at Trident Pier, FL in May 2007 that reached ~0.3 m, the SL residuals were considerably less than the values reached during the June – July 2009 SL event. These results hint at the important contribution of another forcing mechanism upon the SL response during the June – July 2009 SL event.

A higher resolution view of the winds and SL residuals from April to July 2009 are shown in Figure 9. In most cases the winds lead the SL signal by a couple days, though the 7-day filter makes this comparison approximate. A pattern similar to that described for Figure 8 emerges. The winds oscillate between SW and NE at the Nantucket buoy, and the residuals show a strong inverse response, though somewhat muted at Nantucket, which is probably related to its position seaward towards the shelf break. The > 0.3 m residual increase in the last quarter of May 2009 at Duck and Atlantic City from a multi-day NE wind at the Nantucket buoy remain elevated as the wind reverses to a light SW wind at the start of June. An even stronger NE wind event at the Nantucket buoy in early July causes only a slight (~0.02) rise in water levels, indicating another factor causing a general drawdown of SL during this period. The strong NE winds at Edisto on and around ~5/19/09 mentioned earlier forces a rapid, slightly lagged rise of residuals at Charleston and Trident Pier. It is important to note that SL continues to rise at Charleston and Trident Pier in June under greatly diminished wind forcing in the opposite direction.

Also shown in Figure 9 are time series of atmospheric pressure collected at the NOAA stations. Inverse barometer effects from atmospheric pressure changes are such that an increase (decrease) of one millibar in pressure results in a fall (rise) of one centimeter in water level. The pressure changes need to be of a sufficient period (> 4 days) to allow SL to adjust (Wunsch *et al.*, 1969; Garrett and Toulany, 1982). Atmospheric pressures are very similar between Duck and Nantucket, and these two series have a larger range and variability than at Trident Pier. Of interest to the June – July 2009 SL event is the drop of ~15 mbar that occurs in the last week of May at Duck and Nantucket. During this period, the winds turn from SW to NE and SL residuals rise at Duck and Atlantic City by > 30 cm, or twice the amount attributed to the inverse barometer effect. At Nantucket, the residuals rise by ~20 cm. During the first half of June, atmospheric pressure remains relatively constant at all locations, though SL residuals at Atlantic City and Duck rise by > 10 cm and > 20 cm at Charleston. In mid-June, the most notable drop in atmospheric pressure occurs, ~25 mbar at Nantucket, ~15 mbar at Duck, and ~5 mbar at Trident Pier. The SL residuals rise by ~25 cm at Nantucket, > 10 cm at Atlantic City, a > 5 cm at Duck and a > 20 cm rise occurs at Trident Pier and Charleston, though initiating prior to the pressure drop. From late June into mid-July, pressure rises by ~10 mbar at Duck and Nantucket and ~5 mbar at Trident Pier. During the same period, the overall drop in SL residuals is ~20 cm at Duck, Atlantic City and Nantucket and > 30 cm at Trident Pier and Charleston.

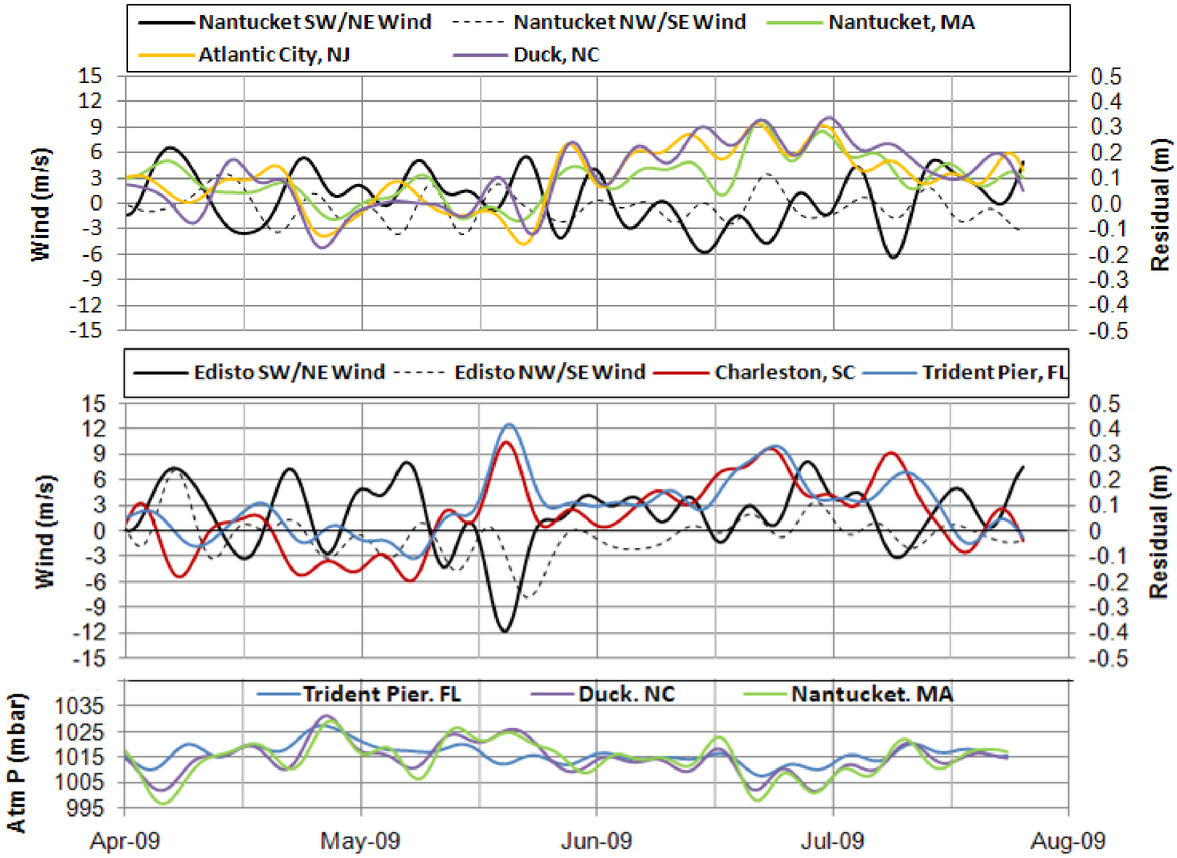


Figure 9. 7-day lowpass filtered SL residual, southwesterly/northeasterly (SW/NE) and northwesterly/southeasterly winds (NW/SE) and atmospheric pressure at sea level.

Florida Current Transport and Sea Level Response

There are two distinct patterns of seasonal SL predictions along the East Coast (i.e., Figure 2). The shape of the predictive curves reflects the summation of the forcing specific to an individual station. Stations north of the Chesapeake Bay tend to have SL that steadily increases from spring until early fall and then decreases until late winter, driven primarily by the steric cycle of seasonal heating and cooling of the water column (see http://tidesandcurrents.noaa.gov/sltrends). As shown in Figure 2, the SL prediction at Charleston, SC has a more pronounced 'lower' high peak in the late spring than occurs at Atlantic City, NJ. The existence of a double peak reflects the annual variability in transport strength of the Florida Current (FC), which largely supplies and becomes the Gulf Stream off of the coast of the Carolinas. Figure 10a shows the seasonal cycle of the FC composed of its 90-day lowpass filtered series between June 2000 and June 2009, whose values have been grouped by month and subsequently averaged. Also shown are the SL predictions at East Coast stations that are largely inverse to the FC signal.

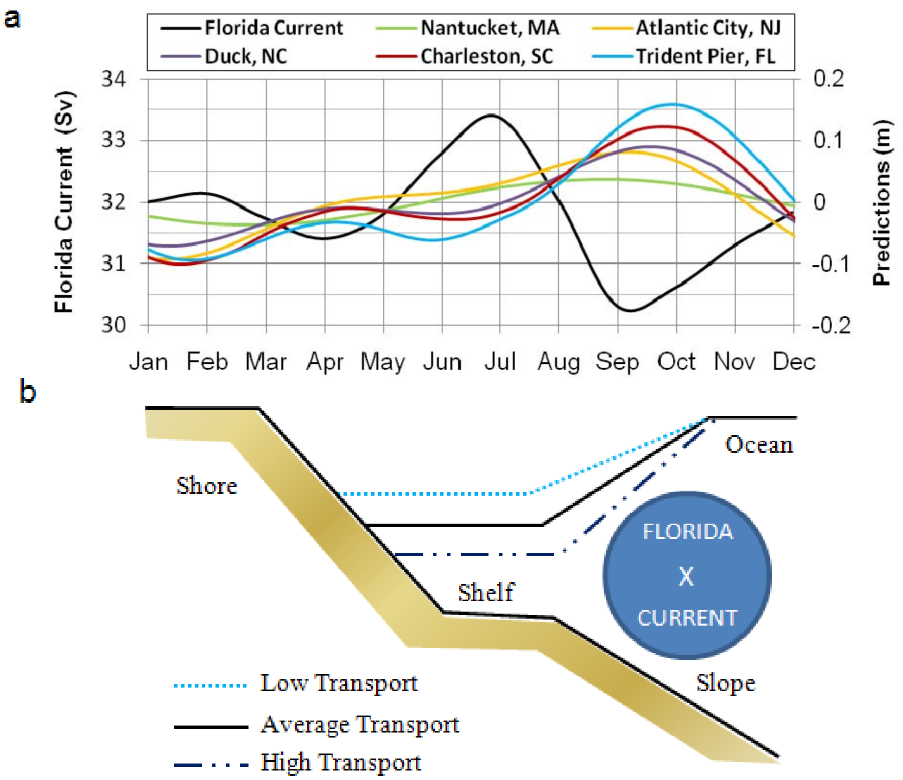


Figure 10. a) The June 2000 – June 2009 average seasonal cycle of FC transport based on a 90-day lowpass filtered series and SL predictions above MSL and b) diagram showing cross-shore sea slope with low, average, and high FC transport (adaption of Figure 2 in Noble and Gelfenbaum, 1992).

The 2000 – 2009 FC average transport cycle is maximum during the summer and greatly diminished during the fall (Figure 10a), similar to other findings (Blaha, 1984; Noble and Gelfenbaum, 1992; Baringer and Larsen, 2001). Typical FC transport values range on the order of 20 – 40 Sv in the Florida Straits, with annual, inter-annual and decadal variability normally < 5 Sv (Baringer and Larsen, 2001). The inverse response of the predicted coastal SL to the FC transport is a dynamic adjustment to the changing geostrophy of the current system. Cross-current sea-slope changes of > 0.25 m seasonally occur within the Florida Current / Gulf Stream that extend across the continental shelf to the shore with a relatively small decay (Noble and Gelfenbaum, 1992), affecting SL from Florida to Delaware (Blaha, 1984; Ezer, 2001). For instance, when the FC is strong, the cross-current gradient steepens and effectively lowers SL along the coast (Figure 10b). The opposite occurs when the FC weakens. The influence of the FC is greatest at Trident Pier, FL (of the stations shown) such that it has lower predictions in June and higher values in October (Figure 10a). The influence of the FC upon predictions gradually lessens northward as the Florida Current / Gulf Stream heads offshore near Cape Hatteras, NC.

Figure 11a shows the 30-day lowpass filtered series of FC transport and SL residuals along the East Coast. The FC seasonal cycle (Figure 10a) has not been removed because it is a small part of the total variance and not well determined with only nine years of data (Meinen *et al.*, submitted). High (low) residual SL along the eastern seaboard occurs during periods of low (high) FC transport. For example, high FC transport in December 2008 coincided with a large SL residual decrease along much of the East Coast. Conversely, the transport of the FC during the June – July 2009 SL event drops in mid-May from ~32 Sverdrup (Sv, 10^6 m^3/sec) to a low of ~27 Sv in the latter half of June (Figure 11a). As the FC transport drops, the residual SL at all locations rise nearly (< 1 day) in phase. The FC regains strength in July, increasing to ~35 Sv in mid-July with the residuals all steadily falling ~0.2 m to < 0.1 m in the process. The correlation coefficients of the FC to the SL residuals are negative (low transport = high SL residual) and decrease to the north as would be expected as the Florida / Gulf Stream current system moves further offshore (Figure 11a legend in parentheses).

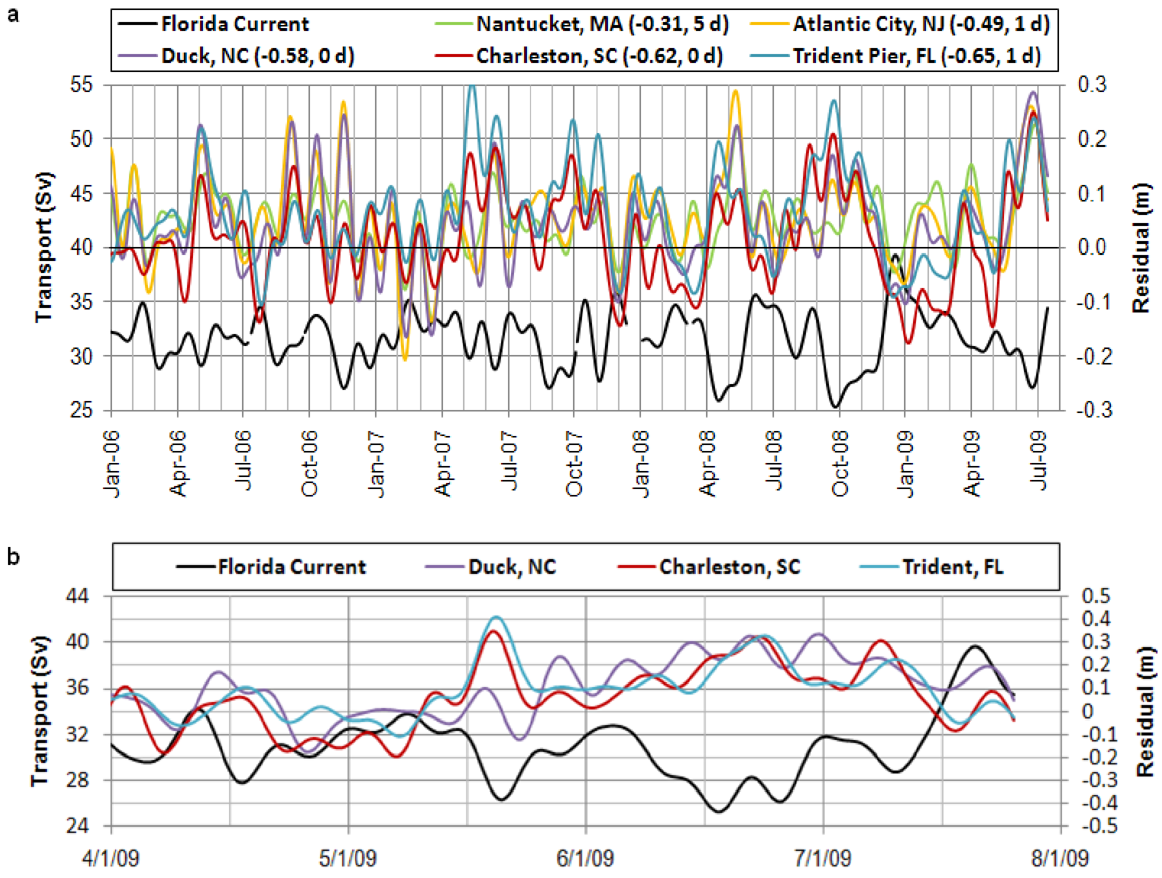


Figure 11. a) 30-day lowpass filtered series of FC transport and SL residual time series at NOAA stations with correlation coefficients and phase lead (+) of the FC (shown in parentheses) and b) 7-day lowpass filtered series since April 2009.

The 7-day lowpass filtered series in Figure 11b show a higher resolution view of the SL responses at Trident Pier, Charleston and Duck. The series show a strong inverse relationship, though the Duck SL series (and the stations to the north) contain additional variability associated with wind forcing captured at the Nantucket buoy (Figure 9). The residual rise at Charleston and

Trident Pier and FC slow down that occurs on ~5/21/09 in Figure 11b coincides with the strong NE wind of ~5/19/09 at the Edisto buoy (Figure 9), suggesting that short-period NE winds can act to slow the FC transport. The strong rebound of FC transport strength from ~29 to 40 Sv that occurs around the second week of July 2009 is coincident to a large drop in residual values, > 0.25 m at Charleston and Trident Pier.

A few historical periods with low FC transport offer comparison to the June – July 2009 SL event. The FC transport was lower during the months of April (26 Sv) and October (25 Sv) in 2008 than the low during the June – July 2009 SL event (27 Sv). During these two earlier events, the station residuals were quite high (Figure 11a). During April 2008, the winds were NE at Edisto at ~2 m/s, but data was missing at Nantucket. Residuals were slightly higher at Atlantic City, NJ by ~0.02 m, but elsewhere slightly lower. During October 2008, there was slightly higher NE forcing (~4 m/s) at both locations compared to the June – July 2009 event. Residuals at Trident Pier were slightly higher (~0.02) than the June – July 2009 SL event, but the other residuals were much (~0.05 m) less. Again, since the predictions are slightly higher during April and much higher during October, the residuals during these periods generally happen to be less (Figure 10a).

Satellite Perspective of Event

Images of absolute dynamic ocean topography and SL anomaly derived from merged sea surface height (SSH) altimetry for times of recent high FC transport (see Figure 11a) on 12/10/08 and low transport on 10/1/08 are compared to the June – July 2009 SL event (6/21/09 image) in Figure 12. Measurements of the dynamic topography allow investigations of general circulation patterns of geostrophic flows. The dynamic topography shows generally a sharper gradient across the FC within the South Atlantic Bight (Florida to North Carolina) during the period of high FC transport than during the low-transport periods. A weaker (stronger) eastward-rising gradient is indicative of weaker (stronger) northward geostrophic flows.

The SL anomaly in Figure 12 illustrates the SSH variability due to changing currents from seasonal and inter-annual forcing. During the high-transport period of 12/10/08, anomalously low (0 to -0.2 m) SL/SSH occurs over much of the East Coast. Conversely, during the low FC transport period of 10/1/08 and 6/21/09, anomalously high SL/SSH of < 0.4 m and < 0.2 m occur, respectively, over the East Coast. It is important to note that the satellite images of SL anomalies do not have a seasonal correction applied. Thus, an observer might have measured higher sea heights on 10/1/08. However, the SL residuals shown in Figure 11a, which have the mean seasonal series removed via predictions, correctly report a higher magnitude during the June – July 2009 event.

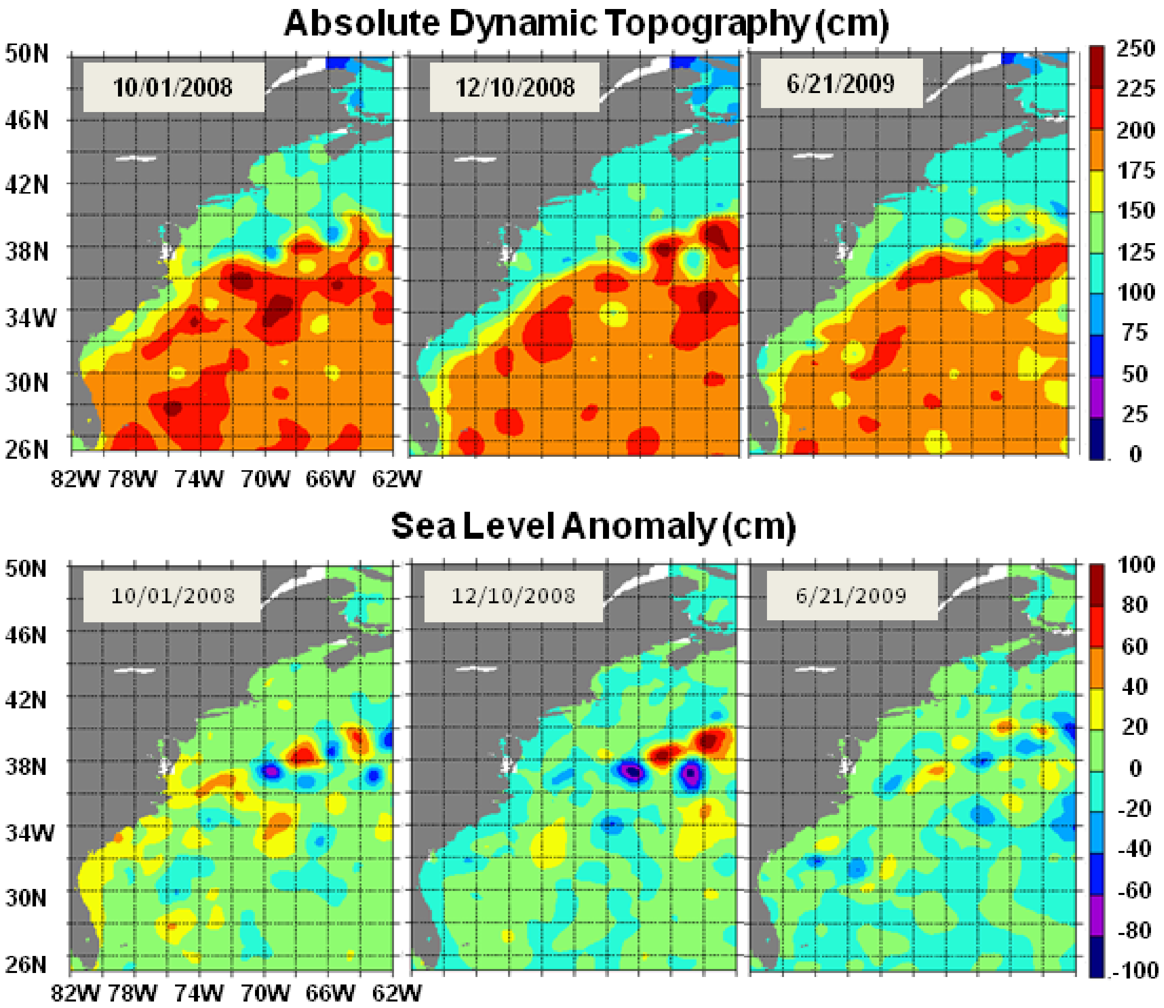


Figure 12. Merged satellite altimetry of absolute dynamic topography (cm) and SL anomaly (cm) along the eastern U.S. coast and western Atlantic during periods of low (October 2008 and June 2009) and high (December 2008) Florida Current transport (http://www.aviso.oceanobs.com/duacs).

Figure 12 also provides inference about the geostrophic currents present during each described FC transport stage. With low FC transport on 10/1/08 and 6/21/09, the dynamic topography has a negative gradient (eastward decline) between the coast and the landward-edge of the Gulf Stream in the area north of Cape Hatteras to Long Island, NY. This suggests a southward-flowing current along the shelf landward of the Gulf Stream (Csanady, 1978). A near-shore current flowing southward is required by geostrophy to have a higher SL closer to shore than seaward of the current. However, during high FC transport on 12/10/08, this southward current appears non-existent and not recognizable through the satellite images of dynamic topography.

SUMMARY DISCUSSION

Magnitude of Event

Sea level (SL) along much of the eastern U.S. was higher than normal for much of June and July 2009, enough to cause significant attention from coastal communities and gain noticeable media attention. At the height of the event in the latter half of June 2009, the event was exacerbated by the simultaneous occurrence of a *perigean-spring* tide (Figure 3a). In terms of observed SL, this event was not extremely abnormal. In fact, SL in many of these locations has exceeded levels observed during the June – July 2009 event numerous times over the last decade (http://tidesandcurrents.noaa.gov). The June – July 2009 SL event is anomalous in terms of its timing and magnitude compared to the site-specific predictions that CO-OPS produces at the NOAA tidal stations (Figure 5). The 'residual' values, which represent the height unaccounted for by the predictions, were anomalously high from early June into July 2009 from Florida to Maine (Figure 6). When the site-specific SL is further normalized through adjustments that 'de-seasonalize' and remove the long-term relative SL rise (climate-related) from the series-long (> 30 years) record, the high-water anomaly is unique in that it occurs over large regions both north and south of Cape Hatteras, NC. Close inspection of the regional averages, defined as north of Cape Hatteras (Eastport, MA to Chesepeake Bay Bridge Tunnerl [CBBT]) and south of Cape Hatteras (Beaufort, NC to Key West, FL), reveal that the June – July 2009 SL event is the most extreme high-water event to occur in both regions simultaneously during spring/summer period since 1980 (Figure 7). The other events that matched or exceded the de-trended values of June 2009 in both regions occurred during the late winters of 1983, 1987, 1998, and 1999. The June – July 2009 SL event was highest (> 0.2 m) from Sandy Hook, NJ to Chesapeake Bay Bridge Tunnel (CBBT), VA although the values were substantial from Eastport, ME to Vaca Key, FL.

Inverse Barometer Effect

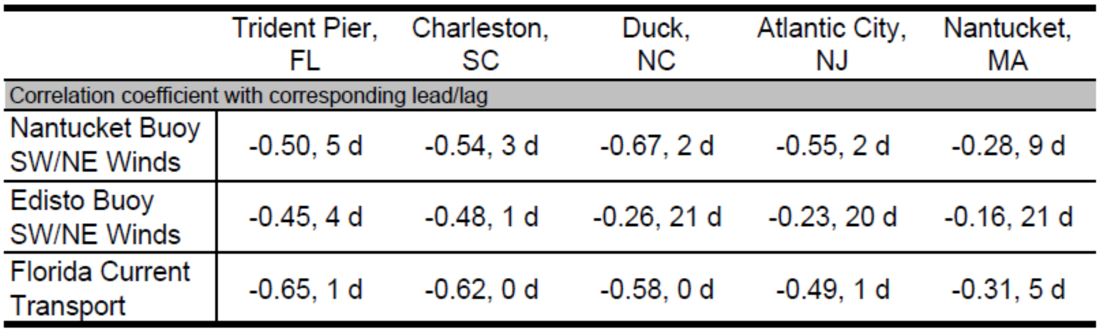
There are multiple mechanisms contributing to the high SL residuals during the June – July 2009 SL event. Intrinsic to SL variability are inverse barometric effects from localized changes in atmospheric pressure. This force causes SL to rise (fall) as the overlying atmospheric pressure decreases (increases). The inverse barometer effect is in addition to any wind-forced transport that may result from large-scale atmospheric pressure differences and their wind fields. During the June – July 2009 SL event, the correlation coefficient between the 7-day lowpass filtered atmospheric pressure and SW/NE winds at Nantucket NOAA station and offshore buoy, respectively, is 0.45 with little phase lag (not shown). This relationship implies that often times, high (low) pressure on land is associated with SW (NE) winds at the buoy, which act to reinforce the SL response (i.e., SW winds cause SL to drop as does higher atmospheric pressure). However, the relationship often is reversed due to the distance between stations and the size and position of non-stationary pressure systems causing a particular wind field. The effects of changing atmospheric pressure were not directly removed from the SL residuals since the residuals are already adjusted for a mean seasonal signal of atmospheric pressure inherent to SL predictions. In order to make an adjustment would require deriving an anomalous series from a seasonal mean signal of atmospheric pressure. Over this June – July 2009 SL event, though, the absolute changes in atmospheric pressure are considered to cause an approximate change in SL.

Changes in SL residuals from the inverse barometer effect during the June – July 2009 SL event were most prominent at Nantucket, i.e., the 25 cm SL residual rise from a ~25 mbar drop in pressure in mid-June (Figure 9). However, at the other locations, SL residual responses contained much smaller influences from atmospheric pressure variability. For instance, the ~20 cm SL residual increases in the first half of June at Charleston, Duck and Atlantic City occur under relatively stable atmospheric pressure. Also, SL residuals decrease in early July with an overall drop of ~20 cm at Duck, Atlantic City and Nantucket and > 30 cm at Trident Pier and Charleston during a period when atmospheric pressure rises by only ~10 mbar at Duck and Nantucket and ~5 mbar at Trident Pier. Thus, it can be seen that other forcing mechanisms are primarily driving the SL residual variability observed during the June – July 2009 SL event.

Effects of Wind Forcing

The first is wind forcing. Winds recorded at offshore NOAA buoys ~40 nm southeast of Charleston, SC and ~50 nm southeast of Nantucket, MA both had fairly persistent and moderate northeasterly (NE) component during the months of May and June, respectively (Figure 8). Though, it should be pointed out that the NE winds at the Edisto buoy in Figure 8b were primarily concentrated over a 5-day event in mid-May (Figure 9). The direction of this wind component is alongshore and acted to raise SL via Ekman transport, which is 90 degrees to the right in the northern hemisphere. The absolute magnitude of the correlations between the 30-day lowpass filtered southwesterly/northeasterly (SW/NE) winds and the stations' residual SL values (observed – predicted) are highest (> 0.5) between the winds at the Nantucket buoy and residuals at the mid-Atlantic stations of Charleston, SC, Duck, NC, and Atlantic City, NJ (Table 1). In this area, the wind forcing leads the SL response by < 3 days, a timeframe typical of a regional wind-forced response (Emery and Thomson, 2004). The high-resolution view of the 7-day lowpass filtered winds and residuals clearly reveal that since April 2009, the two series are inversely related (Figure 9). However, the magnitude of the SL response varies to similar winds and indicates that another mechanism is also affecting the residual SL values.

Table 1. Summary of correlations between 30-day lowpass filtered series. A negative value implies an inverse relationship and the phasing is shown in days (d) and positive values indicate that the wind and Florida Current transport lead/force a SL response at the NOAA stations.



	Trident Pier, FL	Charleston, SC	Duck, NC	Atlantic City, NJ	Nantucket, MA
Correlation coefficient with corresponding lead/lag					
Nantucket Buoy SW/NE Winds	-0.50, 5 d	-0.54, 3 d	-0.67, 2 d	-0.55, 2 d	-0.28, 9 d
Edisto Buoy SW/NE Winds	-0.45, 4 d	-0.48, 1 d	-0.26, 21 d	-0.23, 20 d	-0.16, 21 d
Florida Current Transport	-0.65, 1 d	-0.62, 0 d	-0.58, 0 d	-0.49, 1 d	-0.31, 5 d

Effects of Florida Current Transport

The other mechanism is the changing strength of the Florida Current (FC) transport. The FC is measured *in-situ* between Florida and the Bahamas near 27°N. The FC flows northward along the shelf break of the Southeast US and largely supplies the Gulf Steam near Cape Hatteras, NC. Variability in the 30-day lowpass filtered FC transport strength has a high negative correlation (< -0.6) to SL ~south of Cape Hatteras, but is still considerable north of it (Table 1). The dynamics are such that when the FC transport is high, its cross-stream slope is steep, which causes a drop in SL landward to the coast (Figure 10b). The opposite occurs when the FC transport is low. Changes of SL to the longer-period (30-day lowpass series) fluctuations in the FC transport occur quickly (< 1 day) as shown in Table 1. The geographical extent of the influence of the FC transport is hinted at by the correlation coefficients whose absolute magnitudes progressively decrease to the north (Table 1) similar to findings of Blaha (1984) and Ezer (2001). Similarly, the changing influence of the FC transport is observable and inherent to the long-term seasonal SL cycles at NOAA stations (Figure 10a). The FC signal causes a double peak in the seasonal cycle, compared to a single peak which would be expected from normal seasonal heating/cooling of the water column. When the FC transport is highest in July, stations approximately south of Atlantic City, NJ have a low in their seasonal SL cycle (Figure 10a). When the FC transport is low in October, the stations have an enhanced high. These seasonal SL patterns are quite different than those approximately north of Atlantic City, NJ, where the signals are more controlled by the steric cycle, peaking in late August and at a minimum in early February.

During the June – July 2009 SL event, the formation of the high SL residual coincided with a noted decrease in FC transport strength (Figure 11). At the peak of the event, the FC transport bottomed out at ~26 Sv and the residuals peaked at values > 0.25 m (7-day lowpass series in Figure 11b). Changes within the two signals are nearly concurrent to one another, especially at the more southern stations (Figure 11 and Table 1). The June – July 2009 SL event decays at all locations in early July, when the residuals became greatly reduced and even negative with the onset of a strong transport increase (~10 Sv) of the FC (Figure 11b), even while the winds oscillate between SW and NE (Figure 9).

Wind and FC Transport Interactions

Short-period winds appear to influence the transport strength of the FC measured within the Florida Straits during the June – July 2009 SL event. The 7-day lowpass filtered series highlights a strong NE wind event at the Edisto buoy commencing on ~5/19/09 (Figure 9b) and a subsequent drop ~2 days later in FC transport (Figure 11b). The 7-day filter makes exact phasing of these series difficult. However, both the filtered (and unfiltered, not shown) residuals at Trident Pier and Charleston and the NE wind peaked ~2 days prior to the low of the FC transport (Figure 11b). Historical investigations have noted similar interactions. Lee *et al.* (1985) and Lee and Williams (1988) found that short-term variations in FC transport with periods of < 10 days were correlated to local northerly/southerly winds. For instance, a NE (SW) wind causes a landward (seaward) Ekman transport that diminishes (strengthens) the cross-stream sea slope and slows (accelerates) the northward geostrophic transport of the current. In addition, multi-year correlations and phasing between the January 2006 – June 2009 30-day lowpass filtered SW/NE wind components at Edisto (0.40, 7 days) and Nantucket (0.54, 3 days) and the FC transport suggest that longer-period NE (SW) winds may have caused a decrease (increase) in FC transport. This finding is weakly supported by our results, but in agreement with findings by Lee and Williams (1988) who concluded that the primary contribution to the annual FC transport cycle was from weather events longer than five days, though the winds used in the their study were regional over the Straits of Florida. Another study found a strong relationship between monthly variability in the easterly trade winds over the Caribbean and the seasonal FC transport patterns (Lee *et al.*, 1996).

The correlation coefficients between the SW/NE winds at Edisto (0.40) and Nantucket (0.54) and the FC transport suggest a quasi-independent contribution from both forces to the SL residual along the coast. It is realized, although, that the two forces are somewhat mutually correlated and a more complicated multivariate correlation analysis is required to determine the specific contribution from each forcing mechanism. However, a couple points are worth noting. During the June – July 2009 SL event, longer-period NE winds were not at their displayed series-long highest value (Figure 8) nor was the FC transport strength at its lowest value (Figure 11a). On the other hand, the SL residuals were at widespread highs, hinting at the importance of the coupled effect of the two forcing mechanisms. The fact that the highest de-trended (seasonally and long-term relative SL rise) SL values were located within the mid-Atlantic areas from Virginia to New Jersey is supportive of the overlapping effect of the two forcing mechanisms (Figure 6). High correlations of SW/NE winds at Nantucket (-0.67) and FC transport (-0.58) to the SL residuals at Duck, NC (Table 1), highlight this region as heavily influenced by both forces.

Satellite Altimetry

Satellite altimetry data offers an interesting view of the June – July 2009 SL event in terms of other recent high- and low-transport periods of the FC (Figure 12). Snapshots of sea surface height (SSH) derived products during the June – July 2009 event (June 21, 2009) and another low-transport event in October 2008 reveal a somewhat weakened cross-stream gradient in the dynamic topography, high SL anomalies along the East Coast, and the presence of a southward-flowing current from Long Island, NY to Cape Hatteras, NC. During a high-transport period in December 2008, the opposite conditions generally occurred. More analysis needs to be performed to see if this type of relationship is persistent and statistically significant for multiple, discrete periods of high- and low-FC transport. It is plausible that variability within the Florida / Gulf Stream system might substantially affect coastal SL within the mid-Atlantic Bight (North Carolina to Massachusetts) by regulating the strength of the southward flow normal along the shelf (Csanady, 1978) and the higher coastal SL it requires due to geostrophic constraints.

Future Work

The bigger question exists as to what causes the inter-annual variability in both winds and FC transport that caused the June – July 2009 SL event. On-going research is trying to decipher the complexities involved. Some recent findings have shown that multi-year FC variability is highly anti-correlated to variability in the North Atlantic Oscillation (NAO) though with ~18 month lags between signals (Baringer and Larsen, 2001) that makes the relationship less obvious to the observer. The NAO is a climatic phenomenon defined by fluctuations in the differences of sea-level atmospheric pressure between the Icelandic Low and the Azores high that affects the westerly wind strength over the northern Atlantic. The NAO also modifies the wind-stress curl over regions of the subtropical Atlantic, which appears to be an important factor driving the FC transport rates (Dinezio *et al.*, 2009). Continued work focusing on the inter-connections between the wind and currents and their effects upon coastal SL will be critical to addressing and ultimately better predicting intra-annual and inter-annual SL anomalies along the East Coast.

The unexpected anomalous SL event during June – July 2009 will lead to further applied research in detecting and reporting out on similar events as they occur in the future. CO-OPS is investigating various types of new products to alert the public and to explain events to them.

ACKNOWLEDGMENTS

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