Storm induced Semidiurnal Perturbations to Surges in the US Eastern Seaboard

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ABSTRACT

Tide-surge interactions can affect the timing and the value of the maximum water levels observed in a given coastal region, and need further understanding for accurate flood risk predictions. The analysis of 18-year long tidal gauge records along the US East coast has revealed the appearance of semidiurnal perturbations to storm surges in the South Atlantic Bight. A total of 71 events with perturbation amplitudes higher than 0.15 m and durations longer than one day were identified. These perturbations were triggered by the passage of tropical storms and cold fronts, and appeared during positive storm surge events. As a consequence of the storm induced forcing, observed tides were delayed and partially dissipated with respect to the predictions. Such delay and dissipation resulted in a semidiurnal signal on the surge. Perturbations associated with the passage of tropical cyclones and hurricanes were characterized by higher amplitudes and longer durations than winter storm events. Regression analysis shows that parallel-to-shore winds in the shelf region between Cape Hatteras and the South Atlantic Bight are highly correlated with the generation of the semidiurnal perturbations. Increased bottom
friction resulting from enhanced wind-driven alongshore currents is suspected to be the primary factor delaying and dissipating the astronomic tides.

Keywords: Storm surge; surge residuals; astronomic tide; semidiurnal perturbation; continental shelf waves; tropical storms.

INTRODUCTION

The US eastern coast has been frequently affected by hurricanes and the associated extreme surges. Hurricanes Isabel (2003), Katrina (2005), Ike (2008), Irene (2011), and Sandy (2012) all left their names in the US catastrophic coastal flooding history. Coastal regions are becoming more vulnerable to climate change-induced hurricane/storm hazards (i.e. Talke et al. 2014; Houston & Dean 2011). According to Talke et al. (2014), three of the nine highest recorded water levels in the New York Harbor region since 1844, have taken place in the last four years. Knutson (2010) indicated that storm activity on a global scale will be enhanced by a consistently warming climate. Correspondingly, there is an imperative need for better understanding and predicting flooding threats to coastal communities.

Total water levels measured at a given coastal point are influenced both by storm surge and astronomic tides. For simplification, many coastal flooding studies consider a linear superposition of the astronomic (or predicted) tides and the storm surge, disregarding their possible nonlinear interactions (e.g. the Nivmar system, Fanjul et al. 2001; NOAA system, Glahn et al. 2009). Since the pioneer studies of Proudman (1955a,
it is known that tide-surge interactions can be relevant, especially in shallow waters and estuaries. They can affect the arrival time and the peak value of the water levels, and consequently the flooding threat.

Physical mechanisms causing tide-surge interactions have been extensively analyzed because of the need to determine the maximum water levels during extreme storms such as for flooding defense purposes (e.g. Proudman, 1957; Rossiter, 1961; Wolf, 1978; 1981). Most of these studies have focused on the British East Coast, at the North Sea and the English Channel, characterized by its exceptionally high tidal range (e.g. Prandle & Wolf, 1979, Horsburgh & Wilson, 2007; Idier et al. 2012). However, relevant surge-tide interactions have been identified in many other coastal regions, including the Orissa coastline in the Bay of Bengal (Ali, 1980; Murty et al. 1986; Sinha et al. 1996; 2008; Nayak et al. 2012), the Fujian coast in China (Zhang et al. 2010), the Gulf of Suez at the northern end of the Red Sea (Rady et al. 1994; 1998), the northern Gulf of Mexico during the passage and landfall of hurricanes (Rego & Li, 2010), and the South Atlantic Bight in the US East coast during the passage of hurricanes Sandy and Irene (Valle-Levinson et al. 2013).

One of the consequences of tide-surge interactions is the appearance of periodic oscillations (with the same period as the main astronomic tidal component) in the storm surge, often known as ‘semdiurnal residuals’ or ‘semdiurnal surges’. As explained by Horsburgh & Wilson (2007), a change in the amplitude and/or phase of the astronomic tide due to external forces (e.g. increased water levels, wind, atmospheric pressure) can result in an oscillation of the surge level of the same period as the main astronomic tidal component. While investigations of the tide-surge interactions in the North Sea indicated
that the maximum residual occurs during the rising tide, other studies (i.e. Proundman, 1957) found that the maximum residual can also happen during a falling tide.

The physical processes responsible for the emergence and characteristics of the semidiurnal perturbations to the surge (hereafter referred to as “Sepes”) are site specific. Most of the studies point to nonlinear bottom friction and shallow water effects as the main mechanisms responsible for such interactions (e.g. Zhang et al. 2000; Rego and Li, 2010; Idier et al. 2012). In the South Atlantic Bight however, and based on a momentum balance analysis derived from numerical results, Coriolis accelerations, linked to along-shelf wind stress, were suggested to lead the generation of Sepes over other factors (Valle-Levinson et al. 2013). Nayak et al. (2012) indicated that nonlinear tide-surge interactions depend on the steepness of the continental shelf slope. However, the site they were analyzing was greatly influenced by setup induced by wave-breaking. Besides geographic effects, the characteristics of atmospheric forcing (parametric pressure and wind) also can play a role in tide-surge interactions. Mercer et al. (2002) showed that the atmospheric pressure contributes the most in triggering the barotropic waves in the Grand Bank of Canada. Other studies (e.g. Morey et al. 2006; Rego & Li, 2010) demonstrated the dominating role of wind forcing in promoting periodic oscillations of the storm surge.

The evidence of tide-surge interactions in the South Atlantic Bight can be traced back to decades ago, when Overland and Myers (1976) reported vigorous tide-surge interactions in Cape Fear estuary during Hurricanes Hazel (1954), Diane (1955), and Helene (1958) via numerical simulations. Valle-Levinson et al. (2013), through tidal gauge data analysis and numerical simulations, reported the presence of Sepes in the South Atlantic Bight during the passage of Hurricane Sandy (2012). These perturbations...
contributed to over 50% of the surge height and propagated like continental waves along
the US eastern coast. The authors mentioned that similar semidiurnal oscillations were
observed during Hurricane Irene (2011). Valle-Levinson at al. (2013) pointed out that the
quasi-standing tidal wave behavior in the South Atlantic Bight (Blanton et al., 2004)
could be an important factor for the emergence of Sepes in the area. The existence of
along-shelf propagating waves during Hurricane Sandy was also reported by Chen et al. (2014) who, by combining satellite altimetry and tide gauge measurements, analyzed the
sea surface elevations along the US east coast.

Whether other tropical cyclones and meteorological conditions can produce Sepes
along the US east coast remains unclear. Therefore it is necessary to examine tidal gauge
records together with the historical storm events in the South Atlantic Bight to better
understand the nature of these oscillations. The main goal of the present study is to
ascertain where and when Sepes can occur and, more importantly, how they are
generated.

The following sections, begin with a description of the data sources considered and
the methodology developed. Results illustrate the relevance of tide-surge interactions in
the South Atlantic Bight and the associated atmospheric and oceanic conditions that
favour such interactions. The relationship between Sepes and tidal characteristics, and the
association between Sepes and atmospheric forcing (wind, atmospheric pressure deficit)
are discussed and summarized in the last two sections.
DATA SOURCES AND METHODOLOGY

The occurrence of Sepes along the US eastern coast and the correlation with the meteorological conditions was studied using data collected from a variety of sources. Water level, atmospheric pressure, and wind velocity measurements along the US eastern coast were obtained from the NOAA program “Tides and Currents” (tidesandcurrents.noaa.gov), and the NOAA’s National Data Buoy Center (ndbc.noaa.gov). A total of 20 tidal gauges, spread out from Virginia Key (FL) to Montauk (NY), were selected to cover most of the US eastern coast (Figure 1). Sea level observations were collected at 6-minute temporal resolution between 1996 and 2014. Daily weather maps from the National Center for Environmental Prediction were also used to explore weather conditions.

A methodology based on harmonic analysis, data filtering, and wavelet analysis was developed to detect the occurrence of Sepes. The main steps followed in the methodology are shown in Figure 2. At each of the considered tidal gauges, the storm surge (‘non-tidal residuals’ in other studies, i.e. Horsburg & Wilson, 2007) was computed by subtracting the harmonic tidal prediction from the observed water levels. The T_Tide Matlab toolbox (Pawlowicz et al., 2002) was used to determine the predicted (or astronomic) tides. The appearance of Sepes was detected computing the continuous wavelet transform to the surge signal and determining the time series of amplitude of the M2 tidal constituent of the surge signal. The energy at this specific frequency component can also be isolated from the surge signal applying a moving window harmonic analysis. Both methods were compared during the development of this methodology. Although the results were similar, the harmonic analysis technique was very dependent on the selected moving
window size and in some events was not able to correctly separate the low frequency surge signal (with periods larger than 13 hours) from the M2 harmonic. This was the main reason why the continuous wavelet transform technique was chosen as the most appropriate technique for the current analysis. In this study, the Matlab toolbox derived by Grinsted et al. (2004) was used, and a Morlet wavelet (with a non-dimensional frequency = 6) was selected to compute the continuous wavelet transform. Sepes events were identified by applying the “Peaks Over a Threshold” technique to the M2 surge amplitude time series, derived directly from the surge continuous wavelet transform. The threshold was defined as an amplitude of 0.15 m and a duration of 1 day.

As described in the Introduction, the M2 component of the storm surge can result from a phase and/or amplitude difference between observed and predicted tide. To analyze these phase and amplitude differences, it is necessary to extract the low-frequency surge signal from the observations. In the present study, the low-frequency surge (with periods longer than 13 hours) was determined by applying a low-pass filter (Rosenfeld, 1983) to the water level observations.

Although the data analysis was conducted with the annual time series, Figure 2 shows a ten-day sample during the passage of Hurricane Floyd in 1999 at the Fort Pulaski (GA) tidal gauge to clearly illustrate the main steps followed in the methodology. The storm surge (after subtracting the low frequency surge) revealed a very well-defined 12.42-hour oscillation (dashed black line in Figure 2.f), with a maximum amplitude of ~0.4 m centered on September 16th.

This procedure was applied to the 20 tidal gauges along the US Eastern Coast, and using the Peaks Over a Threshold technique was used to identify all Sepes events with
amplitudes larger than 0.15 m and a minimum duration of 1 day. The maximum tidal amplitude and phase differences between the high-pass observed tides (observed total water level – low frequency surge) and predicted tides were calculated to analyze the astronomic tidal phase lag and amplitude reduction/amplification during Sepes. For each tidal cycle, during a Sepes event, we computed the tidal range and the exact time of zero-crossing tidal levels. Figure 4.a shows an example of the observed and predicted tides, and depicts the points selected for the phase difference computation. In this particular example, the observed tide is lagging behind the prediction. A negative phase difference would represent an observed tide that occurred in advance to the predicted tide. The tidal amplitude change was computed in a similar way, evaluating the difference between the high-pass observed tidal and the predicted tidal range (Figure 4.b). A negative change in tidal amplitude during a Sepes event represents tidal attenuation, while a positive value indicates tidal amplification.

The resulting time series at each station were used to reconstruct the Sepes amplitude Hovmöller diagrams. These are often used to explore the propagating characteristics of a variable and clearly reveal where and when Sepes appeared. Figure 5 depicts the Hovmöller diagram of the Sepes amplitude during Hurricane Floyd. In this specific event, the maximum Sepes occurred on September 15\textsuperscript{th} at Fort Pulaski (GA) and Charlotte (NC) stations.

Daily weather maps from NOAA were used to determine the meteorological conditions associated with Sepes. Atmospheric pressure and wind velocity Hovmöller diagrams were also constructed to investigate the link between atmospheric forcing and the amplitude and duration of the Sepes, only for those storms producing semidiurnal
perturbations. For a pair of stations, e.g. Hatteras (NC) and Duck (NC), data gaps for the
time of interest were filled with the Standard Meteorological Data package from the
nearby NDBC buoy stations (http://www.ndbc.noaa.gov/). The synoptic history of each
Tropical storm (TS) includes meteorological statistics and trajectories. The Tropical
Cyclone Reports (formerly known as Preliminary Reports) from the National Hurricane
Center (http://www.nhc.noaa.gov/data/#tc), as well as the International Best Track
Archive for Climate Stewardship (IBTrACS) Data (Knapp et al., 2010), were used to
provide information on the tropical storms.

RESULTS

There were 71 Sepes events with amplitudes higher than 0.15 m and persisting for at
least one day between the years 1996 and 2014. Of the 71 events, 29 happened during the
winter, 13 during the spring, and 29 occurred during hurricane season (May to October).
Figure 6 shows the annual Hovmöller diagrams of the Sepes amplitude from the year
1996 to the end of the 2014 hurricane season. Thin and bright color strips in the diagram
framed in yellow boxes show the occurrence of Sepes. For example, at least four Sepes
events occurred in 1996’s hurricane season. Sepes were consistently largest at Fort
Pulaski, Georgia (GA) station (in the 576 km ’y’ axis "Alongshore distance"). The years
with most Sepes were 1996, 1999, 2004, and 2007. The Sepes with the largest spatial
influence coincided with the passage of Hurricane Sandy in 2012 which extended along
the coast between central Florida up to the north of New Jersey. However, this was an
exceptional case and in most events, Sepes’ influence region was confined to the Sought
Atlantic Bight.
Further statistical analysis conducted in Fort Pulaski showed that *Sepes* during hurricane season are more persistent and intense than during non-hurricane seasons (Figures 7.a and 7.b). The mean duration during non-hurricane seasons was 25 hours, while during hurricane seasons it could be as long as 42 hours. T-statistic test further showed a significant difference exists in *Sepes* duration from hurricane season to non-hurricane season (P-value less than 0.001). As illustrated in Figure 7.a, the amplitudes of *Sepes* also show a seasonal trend. The maximum amplitude was on average 0.24 m during hurricane season and 0.18 m during non-hurricane season. There was a positive correlation between *Sepes* duration and amplitude during both non-hurricane and hurricane seasons (Figures 7.c and 7.d). The square of correlation coefficient $r^2$ was 0.79 and 0.60 respectively. During non-hurricane season *Sepes* were usually weaker and shorter, and most of the events lasted up to 20 hours with amplitudes < 0.2 m. The decrease of correlation between the duration and the amplitude for the hurricane season was explained by the heavy tail values. During the hurricane season, over 10 percent of the *Sepes* lasted over 48 hours with a mean amplitude above 0.2 m. In other words, the hurricane season contained more extreme events.

Daily weather maps from NOAA showed that long-lasting and extreme *Sepes* were mostly triggered by tropical cyclones. From the 32 hurricane season *Sepes*, 21 were caused by tropical storms. The longest *Sepes* event was induced by the 2005 Hurricane Ophelia, which persisted over 166 hours. Short-lasting and weak *Sepes* were mostly related to the passage of cold fronts and/or high precipitation events along the South Atlantic Bight coast. As the most intense and persistent *Sepes* occurred from tropical
cyclones, further analysis was conducted to identify the atmospheric characteristics producing these strong tide-surge interactions.

Since 1996, the IBTrACS dataset indicates that 85 tropical cyclones affected the US east coast. The majority of these storms were independent from each other. Out of the 85 Atlantic Tropical Cyclones, 21 caused Sepes > 0.15 m at Fort Pulaski, GA. Hurricane Dennis in 1999, although not very influential at Fort Pulaski, generated significant Sepes nearby and was also considered in the statistical analysis. Figure 8 summarizes the main characteristics of these 22 tropical storms. Figure 8.a illustrates the number of tropical cyclones produced Sepes each year. Half of these 22 tropical cyclones reached hurricane status during their existence, and most of the hurricanes reached major hurricanes status based on the Saffir-Simpson’s category. The tropical cyclone’s IBTrACS history revealed that these 22 tropical storms shared similarity in meteorological statistics and trajectories (Figure 8.b). Except for a few Gulf of Mexico tropical storms, most of the tropical storms were originated in West Africa, and they reached their peak intensity when they arrived to the Caribbean countries. Their wind power decreased to tropical storm or Category One Hurricane status as they passed by the South Atlantic Bight and most of their trajectories went parallel or next to the US eastern coast.

Judging from their landfall locations, these 22 tropical storms could be divided into three types. The first type went parallel to the South Atlantic Bight coast and struck between the states from North Carolina to New York. The second type clustered tropical storms originating close to Puerto Rico, Jamaica, and Bermuda that afterward made landfall in the south or east of Florida. The third type developed in the Gulf of Mexico or the Caribbean Sea, headed northeastward, and then northwest Florida. The six most
severe *Sepes* were originated from the passage of Hurricane Floyd (1999), Sandy (2012), Gabrielle (2001), Jeanne (2004), Ophelia (2005) and Tropical Storm Tammy (2005). They produced the largest *Sepes* at Fort Pulaski, GA station, with maximum amplitudes ≥0.25 m and durations >48 hours. Among them, Floyd, Sandy, and Ophelia were Type 1 storms, Tammy and Jeanne were Type 2, and Gabrielle was Type 3. These six *Sepes* events are described in detail next.

**Type 1: North Atlantic Hurricanes parallel to the South Atlantic Bight coast**

The first type of storm formed 12 of the 22 tropical storm-induced *Sepes* and usually produced the highest *Sepes* amplitudes. In the analysis, 7 out of the 12 storms encompassed *Sepes* with amplitude > 0.20 m. Most of these tropical cyclones developed from a tropical wave off the west coast of Africa and traveled across the Atlantic Ocean, intensifying to hurricane status. Figure 9.d shows the intensity and track of the type 1 tropical cyclones producing the most severe *Sepes* events: Hurricane Floyd (1999), Hurricane Ophelia (2005), and Hurricane Sandy (2012).

*Hurricane Floyd (1999)*

Floyd reached Category 4 Hurricane Status between September 12th-13th when hovering over the Bahamas. When Floyd’s eye was near the Bahamas, *Sepes* began to appear on September 12th (Figure 9.a), and lasted for the next 62.1 hours. At Fort Pulaski, *Sepes* emerged two days ahead of Floyd’s core, simultaneously with a persistent 10 m/s southwestward wind. On September 14th, with the passage of Floyd’s central low, the atmospheric pressure dropped, the southwestward winds strengthened, and *Sepes* amplitude increased to 0.28 m. Development of *Sepes* extended from North Florida to
North Carolina (see Figure 2.c to identify the locations). The low-frequency storm surge (water elevation induced by atmospheric forces without considering the astronomic tide) was as high as 0.59 m. The observed tide lagged behind the predictions by about 74.5 minutes, and the amplitude was about 0.15 m smaller (Table 1).

Table 1. Tidal and Sepes characteristics associated with six representative tropical storms.

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<td></td>
<td>Floyd</td>
<td>Gabrielle</td>
<td>Jeanne</td>
<td>Ophelia</td>
<td>Tammy</td>
<td>Sandy</td>
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<tr>
<td>Sepes amplitude (meters)</td>
<td>0.28</td>
<td>0.26</td>
<td>0.25</td>
<td>0.25</td>
<td>0.27</td>
<td>0.28</td>
</tr>
<tr>
<td>Dissipation in tidal amplitude (meter)</td>
<td>0.15</td>
<td>0.13</td>
<td>0.17</td>
<td>0.13</td>
<td>0.17</td>
<td>0.15</td>
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<tr>
<td>Delay in phase (minutes)</td>
<td>74.51</td>
<td>38.68</td>
<td>33.95</td>
<td>44.95</td>
<td>62.52</td>
<td>40.63</td>
</tr>
<tr>
<td>Maximum surge (meters)</td>
<td>0.59</td>
<td>0.57</td>
<td>0.34</td>
<td>0.54</td>
<td>0.91</td>
<td>0.43</td>
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<tr>
<td>Duration of Sepes (hours)</td>
<td>62.10</td>
<td>40.80</td>
<td>67.60</td>
<td>166.40</td>
<td>49.40</td>
<td>54.20</td>
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Hurricane Ophelia (2005)

Hurricane Ophelia (2005) was a slow-moving hurricane that battered the coast of North Carolina. It aroused from a mixture of a cold front and a low-pressure trough between Florida and Bermuda (refer to the blue line east of Florida in Figure 9.d). Due to Ophelia’s slow motion nearby the shore during September 7th-13th, the mid-South Atlantic Bight coast (from Fernandina Beach, FL to Charleston, SC) was affected by persistently southwestward winds. Appearance of Sepes were evident from September 6th and maintained an amplitude of at least 0.15 m for the next 166.4 hours. The peak amplitude occurred on September 7th, and it was not until the 12th when Ophelia moved up to the north, and the magnitude decreased. During this long-lasting event, the
maximum storm surge was 0.54 m and the observed tide at Fort Pulaski lagged behind the predicted by 45 minutes. The observed tidal amplitude was 0.13 m smaller than the predicted (Table 1). Just a few days after Ophelia’s passage, another Sepes event was detected. Although its amplitude was ~0.15 m, it lasted for almost a week (September 18th -23rd). Whether this event was related to a post-hurricane effect or a particular atmospheric condition needs further investigation.

Hurricane Sandy (2012)

Hurricane Sandy (2012) brought the most destructive and deadliest storm surge in US history. Sandy originated from the south of the Caribbean Sea and reached Category Three status while whirling over Cuba. Sandy made landfall on October 29th a few kilometers south of Atlantic City (New Jersey) as a Category Two Hurricane. Sepes appeared on October 22nd at Fort Pulaski, and amplified by the passage of Sandy from October 26th to 28th. Sepes were unusually high with a maximum amplitude of 0.28 m and extended from the north of Cape Hatteras, NC (1123 km in Figure 6.d) to the south of West Palm Beach, FL (306 km in Figure 9.d). Hurricane Sandy was moving close to the FL coast with a distance between the hurricane eye and the shore of 507 km. Its diameter was over 1,850 km, meaning that the coastal region was entirely covered with Sandy’s wind field. Even though Sandy’s eye was the furthest from the coast among the three described Type 1 storms and its wind intensity was only Category One during October 27th-28th, Sandy’s wind shear stress in the south-southwest direction extended over the whole shelf region between Cape Hatteras and south Florida. At Virginia Key (0 km) the intensity was about 20-25 m/s. At the same time, the atmospheric pressure dropped below 1000 mb. The central low-pressure system kept decreasing while Sandy
traveled northwestward. The appearance of *Sepes* was mostly associated with the wind shear of Sandy (Figure 9.c) and lasted until October 29\textsuperscript{th}. When Sandy moved to New Jersey the amplitude decayed gradually. The maximum storm surge at Fort Pulaski was 0.43 m and the observed tide lagged behind the predicted tide by 40.63 minutes. The observed tidal amplitude was 0.15 m smaller than the predicted tidal elevation (Table 1).

Type 2: Hurricanes making landfall at FL from the North Atlantic

These hurricanes shared similar trajectories as Type 1, with the main difference being that they made early landfalls in Florida. After impacting the coast, several of them continued northeastward (such as Hurricane Jeanne, 2004) and others gradually faded while propagating inland (e.g. Tropical storm Tammy, 2005).

*Hurricane Jeanne (2004)*

Jeanne became a Category Three Hurricane and made landfall on the east coast of Florida (99 km in Figure 12.c) early on September 26\textsuperscript{th}, with maximum winds of 54.0 m/s and minimum central pressure of 950 mb. After Jeanne made landfall, it moved parallel to the US eastern coast but on the inland side. Jeanne induced *Sepes* emerged on September 25\textsuperscript{th} that lasted 67.6 hours (almost three days) with maximum amplitudes (0.25 m) observed on the landfall. The onset of *Sepes* coincided with south-southwestward winds that covered a large area of the US east coast. These winds influenced the coast from Virginia Key, FL to Wilmington, NC (km 0-1123 in Figure 11.d) between September 23\textsuperscript{rd} and 26\textsuperscript{th} (Figure 10.a). The *Sepes* amplitude was enhanced with Jeanne’s landfall while the wind at Fort Pulaski was shifting from southwestward to northwestward, and the atmospheric pressure was decreasing from 1100 to 1000 mb. The
maximum storm surge at Fort Pulaski reached 0.34 m. The observed tide was delayed 34.0 minutes and the amplitude was 0.17 m smaller with respect to the prediction.

*Tropical storm Tammy (2005)*

Tropical storm Tammy moved steadily along the shore, 37 km east off the Florida coast. It made landfall on the northeast Florida coast near Atlantic Beach at 23:00 UTC early on October 6th. Measured Tammy’s maximum wind speed was 23.1 m/s and its lowest pressure 1001 mb.

According to the National Hurricane Center, the short-lived Tropical storm Tammy caused minor damage to Florida. However, Tammy induced significant Sepes with a maximum amplitude of 0.26 m. They appeared on October 3rd and 4th when Tammy was still just an elongated region of relatively low atmospheric pressure over the Bahamas, with no closed circulation. The Sepes amplitude was over 0.15 m at 2100 UTC on October 4th and was maintained for the next 49.4 hours. Sepes amplification coincided with a rotation in wind stress just south of Fort Pulaski, GA. The wind field was quite similar to that of Hurricane Jeanne. As shown in Figure 10.b, the mid-South Atlantic Bight coast (571 – 1123 km) was affected by west-to-southwestward winds before the incidence of the tropical storm. This was followed by perpendicular-to-shore winds when the tropical storm made landfall near Fernandina Beach, FL (571 km). The maximum amplitude of Sepes was observed when perpendicular-to-shore winds were blowing over southeastern Georgia. During this period of Tammy’s influence, the maximum storm surge was 0.91 m, the observed tide was delayed by 62.5 minutes and its amplitude was reduced by 0.17 m with respect to the prediction.
Type 3: Hurricanes originating in the Gulf of Mexico and making landfall at FL

Besides the conventional North Atlantic tropical storms, some cyclones that originated in the Gulf of Mexico, such as Tropical storm Josephine (1998), Hurricane Gabrielle (2001), Tropical storm Barry (2007), and Tropical storm Debby (2012), also produced Sepes in the South Atlantic Bight. Among them, Hurricane Gabrielle (2001) was the strongest in terms of both wind intensity and Sepes intensity.

Hurricane Gabrielle (2001)

Gabrielle (2001) made landfall on Florida’s west coast near Venice at about 1200 UTC on September 14th, with a maximum wind speed of 30.9 m/s and a minimum central pressure of 983 mb. After landfall, Gabrielle continued northeastward, crossing Florida peninsula during the next 18 hours at a slow forward speed of 3 m/s and then weakening into a tropical storm.

Gabrielle induced Sepes at 2200 UTC on September 14th, simultaneously with increased southwestward winds along Georgia’s coast (km 571 to 764 in Figure 11.b). Sepes maximized to 0.26 m on October 15th when Gabrielle moved to the east coast of Florida, and decreased on September 16th as Gabrielle was moving off the South Atlantic Bight. The total duration of the Sepes was 40.8 hours. Southwestward winds migrated northward along the US eastern coast (500–1600 km), which was related with Gabrielle’s parallel-to-shore trajectory (Figure 11.a & b). During this period, the surge reached 0.57 m. The observed tidal lag was 38.7 minutes with respect to the predictions, and the tidal amplitude was reduced by 0.13 m.
DISCUSSION

Tidal characteristics

During the six most extreme tropical cyclones induced Sepes, the observed tide was delayed and attenuated with respect to the predicted tide. Further investigation proved that this was the case in most Sepes (including non-hurricane seasonal events). Sepes amplitude was correlated with a) phase lag and b) tidal amplitude reduction. With one exception, all events were characterized by phase delays longer than 20 minutes (Figure 12.a). The exceptional case represented a post-hurricane event following the 2001 Hurricane Gabrielle, in which the observed tide moved in advance of the predicted tide by about 3 minutes. So as an exception to the positive trend between the tidal amplitude reduction and Sepes amplitude (Figure 12.b), there were four events with an amplified tidal amplitude. These four cases, three of which were winter events, were associated with the passage of cold fronts perpendicular to the South Atlantic Bight coast. In general, there were fewer “off-track” points during hurricane season than non-hurricane season, which means that the hurricane season events (mostly tropical storms) were most likely to show phase delays and decreased tidal amplitude.

Sepes amplitude during hurricane seasons can be best predicted by

\[ \eta_{\text{Sepes}} = 0.1718 + 0.29175 \times 10^{-2} A - 0.23429 \times B + 0.010045 A \times B \\
- 0.28415 \times 10^{-4} A^2 + 0.34431 B^2 \]  

(1)

where \( \eta_{\text{Sepes}} \) is the amplitude of Sepes in meters, \( A \) is the phase differences in minutes and \( B \) is the tidal amplitude reduction in meters. Statistical analysis indicates that Sepes amplitude is more related to the phase difference (P-value: 2.05e-07) than to the tidal
amplitude reduction (P-value: <0.005). The combined influences are illustrated in Figure 12.c, on the basis of Eq.1. The figure shows that the relationship between the phase lag and amplitude reduction is nonlinear, while the relationship between the amplitude reduction and the Sepes intensity is essentially linear. In addition, both tidal properties interact to enhance the amplitude of the Sepes. For example, at 20 minutes of a phase lag, the Sepes amplitude increases by only 0.12 m with each unit of tidal amplitude reduction. In contrast, the Sepes amplitude increases by 0.57 m per unit of tidal amplitude reduction for a phase delay of 70 minutes. Compared with a simple linear regression model, by including the interaction ($A \times B$) and polynomial terms ($A^2$, $B^2$), the data is better fitted. The square of correlation coefficient $r^2$ increases from 0.44 to 0.50, which means more of the sampling data can be explained by Eq.1.

For most of the cases, maximum Sepes occurred in a falling tide (ebb tide), consistent with Proudman (1955b). Hurricane Bonnie (1998) and Hurricane Frances (2004) were exceptional, in the sense that the maximum Sepes occurred at the peak and the trough of the predicted tides respectively. Moreover, besides one event that was triggered by a winter cold front with negative surge, all other Sepes showed positive storm surges.

**Meteorological characteristics**

Sepes raised directly from the phase and amplitude differences between the observed and predicted tides, and for this reason there must be a physical forcing or driver during these events that modifies the predicted tidal propagation. Further exploration of the possible correlation between atmospheric forcing and Sepes’ intensity was conducted including both hurricane and non-hurricane seasonal events. Atmospheric variables included maximum central pressure deficit, wind speed, and wind direction (all measured
at 41008 NDBC Buoy station). Figure 13.a shows a scatterplot matrix with linear correlations between the maximum values of Sepes amplitude, wind speed, parallel-to-shore wind, perpendicular-to-shore wind, and atmospheric pressure deficit during the 71 Sepes events. Parallel winds were representative of winds blowing over the shelf region between the north border of Florida and Cape Hatteras, NC. They were defined negative toward 226 degrees from true north, while perpendicular-to-shore winds were defined negative toward inland. Wind speed and parallel-to-shore winds were most influential on Sepes amplitude. The correlation coefficient ‘r’ between wind speed and parallel-to-shore wind with Sepes amplitude is as high as 0.56 and -0.44, respectively. Circles in the scatter plot between parallel-to-shore wind and Sepes amplitude can be divided into two clusters (second square of the third row from the bottom of Figure 13.a). The big cluster at top left of the scatter plot illustrates the winds blowing southwestward (< 0 m/s), and the small one at right bottom depicts the winds going northeastward (> 0 m/s). The two clusters show that Sepes amplitude increased as southwestward winds increased (from -10 to -20 m/s), and became lowest when winds blew northeastward (0 to 5 m/s).

The overall correlation between the perpendicular-to-shore wind and Sepes amplitude was small (correlation coefficient ‘r’ of 0.046). However, when the wind blew inland, Sepes amplitude also increased with wind speed. This positive correlation could be related with the Sepes induced by Type 2 storms.

Pressure deficit is not as influential as wind speed on the Sepes amplitude. The overall correlation between the pressure deficit and Sepes amplitude was 0.21. However, the correlation coefficient between the wind speed and pressure deficit was 0.54. This correlation seems to arise from hurricane-induced Sepes events because pressure deficit
and wind strength are highly correlated during hurricanes (Holl and 1980; 2008; Holland et al. 2010). Accordingly, for events with pressure deficits > 15 mb, there was a positive relationship between Sepes amplitude and atmospheric pressure deficit (third square of the first row from the bottom of Figure 13.a). Most of the pressure deficit values were < 10 mb such that the overall correlation between Sepes amplitude and pressure deficit remained small (‘r’ = 0.21). This is because Sepes often arose ahead of the influence of the Hurricane’s pressure center.

Other influences

This analysis showed that the slow translation was common in the tropical cyclones producing Sepes. A slow hurricane translation (under 5 m/s) was observed during all six representative tropical storms. The most persistent Sepes happened during Hurricane Ophelia (2005). According to NOAA’ preliminary report, Hurricane Ophelia was famous for its erratic and slow movement in the vicinity of the North Carolina coastline. The report also mentioned the slow movement was similar in hurricanes Bonnie (1998) and Dennis (1999), which were both associated with Sepes amplitude > 0.22 m as identified in this study.

Although statistical analysis suggested that Sepes could happen at any moon phase (or any type of astronomic tide), extreme tidal conditions, such as spring tides, could enhance the Sepes intensity. In spring tides, a given phase difference would produce higher Sepes amplitudes. For example, Hurricane Sandy (2012) happened during spring tides (full moon period) and the astronomic tidal amplitude was as 1.12 m at Fort Pulaski (GA) station. The resulting Sepes amplitude were larger than normal (0.28 m).
The Sepes induced by tropical storms were related to positive surges. In this analysis, 70 out of the 71 storm events produced Sepes higher than a threshold (0.15 m) were associated with positive surges at Fort Pulaski. Most of the Sepes were produced because the observed tide was damped and delayed with respect to the predicted tide. The tidal amplitude attenuation and the delay should have resulted from increased bottom friction, which can be caused by a water depth reduction or an increase of current velocities. Because all the events (with only one exception) were associated with positive surges, the increase of bottom friction could only be explained by increased current speeds. This was in agreement with the high correlation between wind intensity parallel to the shelf and Sepes amplitude, as those winds should produce increased along-shelf currents. The effect Coriolis accelerations in modifying astronomic tides in the South Atlantic Bight (Valle-Levinson et al., 2013) was also linked to increased along-shelf currents driven by southwestward winds. Determination of Coriolis effects on Sepes will require implementation of numerical simulations with momentum balance analysis.

In addition to tropical storms, cold fronts also produced extreme Sepes events (both during hurricane and non-hurricane seasons). In this analysis, the largest Sepes amplitude (0.30 m) of hurricane season was associated with a cold front that affected the South Atlantic Bight coast on October 8th, 2010. During non-hurricane seasons, the largest Sepes event had a 0.22 m (on average) amplitude that began on November 13th, 2001 and lasted for almost four days. This Sepes was associated with a complex atmospheric condition that combined the passage of a cold front and a low-pressure system in the near-shore region of South Atlantic Bight during November 12th -18th. These cold fronts could bring intense south-southwestward wind that might be the primary trigger of Sepes.
Furthermore, winter Sepes events were also found coincided with high precipitation rates at the South Atlantic Bight. The effect of precipitation on Sepes needs exploration in future work.

**SUMMARY AND CONCLUSION**

Tidal gauge records covering most of the US east coast were analyzed from 1998 to 2014 to evaluate the relevance of tide-surge interactions. The analysis was performed by applying a methodology that combined harmonic and wavelet analysis and data filtering techniques, designed to extract the time series of the amplitudes of semidiurnal perturbations to storm surges (Sepes).

The analysis revealed that Sepes were evident in the South Atlantic Bight and most prominent at Fort Pulaski (Georgia) station. These perturbations could be triggered by tropical storms, and by the passage of cold fronts (occasionally with high precipitation rates in the area). However, the extreme Sepes were mostly associated with major hurricanes. Since 1996, 71 events were identified as producing Sepes with amplitudes > 0.15 m and durations of at least one day. Statistical analysis showed a high correlation between duration and intensity, and that winter events were, in general, less intense and shorter than those produced by tropical cyclones.

Regression analysis between atmospheric factors (wind intensity and atmospheric pressure deficit) and Sepes at Fort Pulaski (GA) station, revealed that wind intensity was more important than atmospheric pressure deficit. The Sepes primarily occurred during parallel-to-shore winds in the coastal region of the South Atlantic Bight, but could also appeared with winds perpendicular to shore associated during hurricane landfalls. In addition, the passage of a cold front caused Sepes with 0.30 m amplitudes in October.
2010. *Sepes* could last up to 166 hours, and it can significantly modify the timing and the height of the water levels associated with the passage of tropical cyclones.

Almost all of the largest *Sepes* appeared during positive surges because parallel-to-shore winds drove increased along-shelf currents. The increase of the current speed should have enhanced bottom friction, resulting in tidal amplitude reduction and phase delay. Further analysis is required with values of current velocities on the shelf to ascertain the influence of Coriolis accelerations.

Tide-surge interactions in the South Atlantic Bight were forced to affect the timing of and the height of the maximum water levels. Such interactions should be considered in operational storm surge forecasting systems. In future work, thresholds of meteorological forcing, geometric boundary conditions, Coriolis effects, and shallow water influence will be investigated through numerical simulations based on the COAWST modeling system (Warner et al., 2010). Further research is also needed to determine dynamic mechanisms associated with cold fronts that produced *Sepes*.

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Figure 1. Location of the tidal gauges (red dots) and buoy stations (green triangles) used for data collection and analysis.

Figure 2. Steps followed to extract the surge signal (solid orange in b) from the observed total water levels (solid green in a); and separate the low-frequency surge (solid cyan in c) from the observed total water levels; as well as determine the Sepes amplitude (solid magenta in d) from the surge signal. The high-frequency oscillations of the surge signal (dashed black in d) was obtained by subtracting the low-frequency surge from the surge signal. The high-pass observed tide (dashed red in c) was obtained by subtracting the low-frequency oscillations of surge signal from the observed total water levels that reveals the astronomic tidal oscillation in observed water levels. The specific time series shown in the figure corresponds to the measurements taken at Fort Pulaski (GA) during the passage of Hurricane Floyd in 1999.

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Figure 9. Hovmöller diagrams of atmospheric pressure (colors) and wind vectors for hurricanes a) Floyd (1999), b) Ophelia (2005), and c) Sandy (2012), along with the Sepes amplitude at Fort Pulaski, GA station (km 764 from the origin in the ‘y’-axis). The light blue line indicates the time series of Sepes amplitude at Fort Pulaski, GA station; d) the IBTrACS trajectories and wind speeds for the 3 hurricanes, along with landmarks (in km) of the tidal gauges, for instance, Fort Pulaski, GA station (located 764 km from the Virginia Key tidal gauge, FL in the Hovmoller diagrams).

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Figure 11. Hovmöller diagrams of atmospheric pressure (colormap) and wind vectors for a) Hurricane Gabrielle (2001), along with the Sepes amplitude at Fort Pulaski, GA station (which is located 764 km to the origin in ‘y’-axis); and b) IBTrACS trajectories and wind
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**Figure 12.** a) Scatter plot of phase lag (in minutes) and Sepes amplitude for the hurricane season (red circles) and all 71 Sepes events (triangles); b) Scatter plot of tidal amplitude reduction (in meters) and Sepes amplitude for the hurricane season (red circles) and all 71 Sepes events (triangles); c) Fitted response surface for Sepes amplitude by considering tidal phase lag and amplitude reduction, for events during the hurricane season.

**Figure 13.** a) Scatterplot matrix depicting the relationship between pairs of the variables among the the maxima of Sepes amplitude, wind speed, parallel-to-shore wind, perpendicular-to-shore wind, and atmospheric pressure deficit for the 71 Sepes events; b) rose wind depicting the wind direction distribution during the Sepes events of hurricane seasons; c) rose wind illustrating the wind direction distribution during the Sepes events of non-hurricane seasons. The variables are written in a diagonal line from top left to bottom right and each variable is plotted against each other in a). The scatterplot matrix is automatically ordered and colored by the correlation coefficients with red depicting the highest correlation coefficients, and yellow representing the lowest.