Atlantic Coastal Sea Level Variability and Synoptic-Scale Meteorological Forcing

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ABSTRACT: Anomalous sea levels along the mid-Atlantic and South Atlantic coasts of the United States are often linked to atmosphere–ocean dynamics, remote- and local-scale forcing, and other factors linked to cyclone passage, winds, waves, and storm surge. Herein, we examine sea level variability along the U.S. Atlantic coast through satellite altimeter and coastal tide gauge data within the context of synoptic-scale weather pattern forcing. Altimetry data, derived from sea level anomaly (SLA) data between 1993 and 2019, were compared with self-organizing map (SOM)-based atmospheric circulation and surface wind field categorizations to reveal spatiotemporal patterns and their interrelationships with high-water-level conditions at tide gauges. Regional elevated sea level patterns and variability were strongly associated with synergistic patterns of atmospheric circulation and wind. Recurring atmospheric patterns associated with high-tide flooding events and flood risk were identified, as were specific regional oceanographic variability patterns of SLA response. The incorporation of combined metrics of wind and circulation patterns further isolate atmospheric drivers of high-tide flood events and may have particular significance for predicting future flood events over multiple spatial and temporal scales.

SIGNIFICANCE STATEMENT: Mean sea level and minor to moderate coastal flood events, also called blue-sky or high-tide floods, are increasing along many U.S. coastlines. While the drivers of such events are numerous, here we identified key contributing weather patterns and environmental factors linked to increased risk of regional and local high-water conditions along the Atlantic coast. Our results indicate that the predictability of elevated sea levels and high-tide floods is highly dependent upon atmospheric drivers including wind and circulation patterns and, if applied in a tested modeling framework, may prove useful for predicting future floods at various time scales.

KEYWORDS: Atmosphere; Ocean; Coastlines; Continental shelf/slope; North America; Anticyclones; Atmosphere–ocean interaction; Atmospheric circulation; Forcing; Pressure; Sea level; Tides; Wind; Climatology; Intraseasonal variability; Oceanic variability; Seasonal variability; Flood events; Regional effects; Resilience; Risk assessment; Societal impacts; Wind effects

1. Introduction

Coastal flooding along many U.S. coastlines is becoming increasingly frequent, causing a myriad of impacts to property and public infrastructure, economies, coastal communities, and ecosystems (Fleming et al. 2018). While mean sea levels and instances of minor coastal flooding (also known as high-tide flooding) are increasing, rates of change and cumulative effects are not temporally or spatially uniform along all U.S. coastlines, with variability and trends driven by several interrelated factors (Woodworth et al. 2019; Sweet et al. 2020). Since areas with the highest incidences of minor floods, and consequently most problematic in terms of societal impact, are disproportionately along the Atlantic coast, this region was chosen as the study area and focus of this research (Sweet et al. 2018).

Since tidal influences on sea levels and climate change induced rise in mean sea levels are well studied (e.g., Widlansky et al. 2020; Kopp et al. 2015; Lorbacher et al. 2012; Landr er et al. 2007; Wöppelmann and Marcos 2016), this research pays particular interest in the forcing mechanisms that drive sea level change over shorter scales, from daily to weekly. Such variability can be thought of as “superimposed” on existing tidal influences and background sea level rise and thereby related to more episodic and extreme sea level changes and flood events.

For areas along the U.S. Atlantic coast, multiple studies have addressed the importance of regional atmosphere and ocean processes to explain anomalous sea levels and the higher incidence of coastal floods. Sea level variations along the entire Atlantic coast are influenced by factors related to Gulf Stream dynamics and entrainment, water export/import, and Ekman processes (Andres et al. 2013; Ezer et al. 2013; Churchill and Gawarkiewicz 2012). In particular, Andres et al. (2013) and Woodworth et al. (2014) used satellite altimeter-derived sea surface height (SSH) estimates, in situ observations, and hydrodynamic models to show the significant impact of negative wind stress on Ekman flow characteristics and mean sea level variability over multiple
time scales. In terms of shelf-scale processes influencing coastal mean sea level, Churchill and Gawarkiewicz (2012) showed that equatorward transport and advection of water along the Mid-Atlantic Bight shelf and slope can eventually flow “downcoast” near a Cape Hatteras, North Carolina, export region, where waters can either move southward into the South Atlantic Bight or be transported offshore to the Gulf Stream. Piecuch and Ponte (2015) and Piecuch et al. (2016) summarized direct contributions of atmospheric forcing on sea level variability, attributing wind forcing and the inverse barometer (IB) effect to anomalous sea level peaks along the North Atlantic coast.

In addition to these factors, numerous weather-related phenomena including extreme events contribute to significant deviations in coastal sea levels on shorter time scales, including the effects of tropical and midlatitude cyclones on waves and surge. Beyond extremes, there are many coastal minor floods in which atmospheric conditions “synergize” to produce anomalously high sea levels and floods (Sheridan et al. 2017, 2019; Neal et al. 2018). To better understand this relationship, Sheridan et al. (2017) summarized the variability of anomalous sea levels as partly a function of “ambiguous” and transitional weather situations between persistent high pressure patterns to the north and developing low pressure to the south. Sheridan et al. (2019) further assessed these remote driver–response relationships, and successfully reconstructed the time series of anomalous sea levels through nonlinear autoregressive models with exogenous input (NARX models) for over 90 tidal stations across three domains representing the major continental U.S. coastal zones.

Although these and other studies have addressed the relative importance of atmospheric forcing to help explain anomalous coastal sea level variability and increased flood frequency, ultimately, questions still remain about 1) the importance of the timing and recurrent nature of weather pattern forcing in the context of atmosphere–ocean interactions at work, 2) the combined influence of circulation and wind forcing on high-water events and regional elevated sea level response, and 3) the associations between recurring atmospheric patterns and increased high-tide flood risk along the coast.

In this research, we extend our previous work in applied synoptic methods to assess regional and local-scale anomalous sea levels from satellite and in situ tide gauge data, and examine the occurrence, co-occurrence and recurring behavior of atmospheric patterns in relation to specific episodes of high-water conditions and minor floods. The specific objectives of the research are to 1) identify and map mean spatial patterns of elevated sea level anomaly (SLA) and variability along shelf areas of the mid-Atlantic coast from gridded altimetry fields; 2) evaluate the relationship between individual patterns and combinations of “synergistic” atmospheric patterns, and associations with tide gauge response and regional SLA response; and 3) identify and define flood risk associated with weather pattern occurrence, their co-occurrence and relation to sea level response, through risk analysis and image compositing of SLA during meteorological high-water events.

2. Materials and methods

a. Self-organizing maps, methods, and applications

The use of synoptic climatology to assess atmosphere–ocean ecosystem interactions and predictability of mechanisms in coastal systems is summarized in Capotondi et al. (2019) and Jacox et al. (2020). As in our previous applications, we utilized self-organizing maps (SOMs; Sheridan and Lee 2011), which renders the spatial variability in atmospheric patterns of a particular variable in a two-dimensional matrix, as a continuum of patterns. This partitioning of atmospheric states was then used to assess the relationship between atmospheric forcing, nontidal residuals and ocean pattern behavior, and to better understand the mechanisms related to minor flood event frequency. Following Sheridan et al. (2017), we evaluated specific atmospheric pattern relationships and coastal mechanisms to further illuminate key contributing factors to the combined ocean–atmospheric effects related to the frequency and timing of elevated sea levels and minor floods.

Climate data for the classification of atmospheric circulation patterns were obtained from the North American Regional Reanalysis project (NARR; Mesinger et al. 2006; Table 1). Daily values of mean sea level pressure (SLP), and 10-m winds were obtained for the domain spanning 23.5°–54°N and 95°–55°W, from 1979 to 2016. For each of the two datasets (SLP and 10-m winds) prior to classification, all data were standardized column-wise (i.e., by grid cell) and then subjected to s-mode principal components analysis (with days as rows and grid cells as columns). This process reduces data dimensionality and eliminates spatial autocorrelation from influencing the clustering results. All principal component scores (PCs) with eigenvalues greater than 1 were retained as input into the SOM clustering algorithm.

The SOM is a clustering technique that uses artificial neural networks. The network itself can be conceptualized as a net/grid of connected neurons on a two-dimensional plane that spans the two leading modes of variability (the first two PCs). Through thousands of iterations, batches of data (e.g., retained PCs representing daily fields of SLP) are introduced to this network and the neurons shift their positions in Euclidean space to fit the dataset. Since the network is initialized using an ordered rectangular structure, once finished, the final positions of each of the neurons has maintained this order and the final network has morphed around and through the data, spanning much of the PC dataspace, and each observation (row/day of data) can be assigned to the neuron it is closest to. In our application of SOMs, each neuron represents a single atmospheric pattern, resulting in each day of the dataset becoming categorized into a discrete pattern based upon its similarity to patterns nearby in this SOM space.

For each set of data (SLP and Wind), multiple SOMs were constructed and trained in an effort to determine the optimal SOM size (i.e., number of clusters, size of each dimension). Each possible SOM size from 3 × 3 to 9 × 9 was evaluated, with these limits defining either the minimal number of patterns necessary to resolve nearly 14000 days of atmospheric data (3 × 3), or at the other end, the maximum SOM size that could be reasonably examined without becoming unwieldy.
(9 × 9). Each SOM size was evaluated using multiple cluster validation criteria—the silhouette index (Rousseeuw 1987), the Davies–Bouldin index (Davies and Bouldin 1979), and the distributed variability skill score (Lee 2016)—for both internal (using the retained PCs for evaluation) and external (using tidal gauge station data along the U.S. East Coast) data. No SOM size performed best using all metrics and datasets, and thus, this cluster validation was used mainly to discard poor performing SOM sizes from being selected. Ultimately, the final SOM size for each of the five datasets was selected from the better-performing SOMs from the validation, and a final SOM was trained (which is discussed below). All SOMs were trained using MatLab’s Neural Network Toolbox 2017b, version 11.0 (which has since been renamed the Deep Learning Toolbox).

b. Reference tidal observations and residuals

To test local sea level variability and relationships with synoptic forcing, quality-controlled tide gauge data from the National Oceanic and Atmospheric Administration (NOAA) National Ocean Service Center for Operational Oceanographic Products and Services (CO-OPS), consisting of daily maximum observed tide and nontidal residuals, were used for seven tide stations along the Atlantic coast (Fig. 1): 1) Cape May, New Jersey; 2) Lewes, Delaware; 4) Chesapeake Bridge, Virginia; 4) Sewells Point, Virginia; 5) Beaufort, North Carolina; 6) Charleston, South Carolina; and 7) Fort Pulasky (Savannah), Georgia. The nontidal residual values provided by CO-OPS were calculated by subtracting the harmonic tidal predictions from the observed sea level on hourly scales. The residuals are considered to be the meteorologically induced component of sea level incorporating effects such as winds, atmospheric pressure, and river discharge as well as any nonastronomical tidal oscillations not among the harmonic constituents used to create the residual (Horsburgh and Wilson 2007; Pugh 1987). We used the daily maximum nontidal residual for all stations in the analyses. Following Sheridan et al. (2019), data were further standardized to account for nonstationarities in the data as secular trends and seasonal influences. This was achieved using a best-fit, third- to fourth-degree polynomial, to detrend the full time series and subtracting out the long-term monthly mean anomaly to remove seasonality. These two processes yielded the final anomalous sea level values used in this research.

c. Satellite altimeter data processing and SLA climatology

Observations from satellite altimetry have been used extensively to study sea level variations in both coastal and open ocean environments through SSH estimates, considering the orbital altitude and range of the instrument to the sea surface, and the geophysical parameter corrections, including tidal effects, to yield a precise measurement of sea level (Cipollini et al. 2017). Both the use and limitations of altimeter data along the coast have been summarized in Risien and Strub (2016) and Strub et al. (2015), among others. The intent of this study was to evaluate sea level patterns and variability along expansive Atlantic coastal regions where the altimeter products are well suited to provide a consistent, stable sampling framework and coverage for this analysis.

For ocean satellite observational data processing, we utilized the Archivage, Validation, Interprétation des données des Satellite Océanographiques (AVISO) global, daily scale, blended satellite gridded SLA altimeter dataset. The 0.25° latitude × 0.25° longitude gridded SLA fields were produced by Data Unification and Altimeter Combination System/Segment Sol Multimissions d’Altimetrie, d’Orbitographie et de Localisation Précise (DUACS/SSALTO) and distributed as part of the Copernicus Marine Environment Monitoring Service (CMEMS). Here we used the global-scale two-satellite altimetry product known as the delayed-time “twosat” product and time series for each day from 1993 to 2019. The SLA product refers to a vertical deviation from a temporal mean sea surface (i.e., the mean sea surface profile over a 20-yr period from 1993 to 2012) removed at every grid cell.

AVISO altimetry SLA products are made available as IB-corrected files, thereby removing IB effects and winds through a barotropic model (Mog2D-G; Carrere and Lyard 2003). To account for the dynamic ocean response to pressure and wind forcing at higher frequencies, we reprocessed SLA daily fields to create a new SLA (IB uncorrected) product using dynamic atmospheric correction (DAC) auxiliary files from AVISO. Following Long et al. (2021), we regenerated SLA (IB uncorrected) for the full time series by adding the AVISO DAC to the SLA (SLA+DAC).

Initially, to focus on daily scale water level fluctuations along the coast, all SLA+DAC images were retained for analysis for the domain shown in Fig. 1. From these images, we created an SLA+DAC climatology to assess spatial variability in the SLA patterns over a typical annual cycle. During specific high-water periods from tidal gauge analyses, spatial patterns of elevated sea levels can be detected from SLA+DAC (herein SLA) data (Fig. 1b). SLA grids and maps were analyzed individually and along a shelf-slope transect line spanning areas of increased (decreased) variability depicting known ocean “features” of variability, specifically across shelf and slope waters and along the mean axis of the Gulf Stream (Fig. 1c from Andres 2016).
Next, to isolate higher frequency SLA variability for direct comparisons with daily fields of SLP and wind patterns, we detrended and deseasonalized the SLA time series over 7-yr moving intervals, fit using least squares, following iterative procedures from Verbesselt et al. (2010). A 7-yr window was chosen to retain an adequate number of observations for averaging, for removal of the trend and seasonal components, and for characterizing the short-term deviations in SLA beyond the moving baseline. A 7-yr moving mean of SLA for each month \( (t) \) was calculated as

\[
\text{SLA(month}_t\text{)} = \frac{1}{2n + 1} \sum_{j=-n}^{n} \sum_{j=1}^{31} \text{SLA(yr, month}_t\text{, day)}
\]

(1)

where SLA\((\text{yr, month}_t\text{, day)}\) is the daily-scale sea level anomaly in month \( t \), with \( n = 3 \) years prior and after month \( t \), and \( j \) includes the number of observations in month \( t \).

SLA values were then used to create a moving index of SLA departure from climatological normal, or SLA deviation.
(Fig. 1b), using the daily scale time series of moving values standardized to account for seasonal cycles using the formula

\[ \text{SLA Deviation}(t) = \text{SLA}(t) - \overline{\text{SLA}} \text{ month}_t, \]  

(2)

where \( \text{SLA Deviation}(t) \) represents the climatological temporal deviation for each grid cell, considering the sign changes of the \( \text{SLA}(t) \) term, to reveal how instantaneous SLA values deviate from the expected value within each month.

d. Estimating SLA pattern response from SOM nodes

To gain insights on the relationship between SLP [circulation patterns (CPs)] and wind patterns (WPs) with SLA spatial patterns along the coast, normalization procedures adapted from Pirhalla et al. (2016) were applied to develop climatological SLA monthly mean ratio map composites for all 52 SOM nodes analyzed. That is, for each SOM node in each calendar month, the ratio of SLA monthly mean for only those dates when the node of interest occurred over the moving 7-yr mean was calculated as

\[ \text{SLA Ratio}_{CP, WP} = \frac{\text{mSLA Deviation}_{CP_x, WP_y}}{\text{SLA month}_t}, \]  

(3)

where \( \text{mSLA Deviation}_{CP_x, WP_y} \) is the mean climatological temporal deviation associated with a given CPx or WPy. Spatial clusters of elevated (or diminished) SLA patterns for each node were mapped in SOM space by month, then aggregated for all months. To further examine the atmospheric patterns leading to high-water events, specific dates having a high-water event at each tidal station were identified and the SLA, SLP, and wind fields for these days were composited.

e. Associations of reference tidal data, altimetry SLA, and SOM nodes

Initially, we tested the associations of individual tidal station observations, calculated nontidal residuals and gridded altimetry SLA using Pearson product correlations. Next, to assess the nonlinear association of each SOM classification as a whole (rather than by individual SLP/wind patterns) with sea level anomalies, we computed eta correlations \( \eta \). Based upon common outputs in an ANOVA table, the eta correlation is simply the positive square root of the sum of squared errors between each SLP (or wind) pattern, divided by the total sum of squares. Eta correlations range from 0 to 1, with greater values indicating that the SOM is more highly associated with water levels (i.e., that the variability in water levels is better partitioned by SOM patterns).

f. SOM patterns and relative risk

To help identify and define high-tide flood risk pattern aggregates, we further examined the influence of individual and combinations of CPs and WPs on extreme high-water events (i.e., those in the top 5th percentile at each tidal gauge station), through relative risk. Based upon 2 \( \times \) 2 contingency tables, relative risk (RR) is the ratio of the probability of a high-water event (HWE) occurring on the same day as a particular CP (or WP, or CP–WP combination/aggregate), divided by the probability of a HWE occurring when that CP (or WP, or CP–WP combination/aggregate) does not occur. For example, if a HWE occurs 20% of the time that a certain CP occurs, but HWEs only occur 5% of the time when that CP does not occur, then the RR = 4.0 (20%/5%). RRs can be interpreted as the \( x \)-fold increase/decrease in the likelihood of HWEs associated with the occurrence of a specific pattern. Statistical significance is achieved when the 95% confidence intervals of the RR do not span 1.0. We examined the RRs of every combination of CP and WP co-occurrence that happened at least 30 times; those with substantial RRs were then selected as CP–WP “combinations” of interest for further analyses.

3. Results

a. SLA patterns of variability

The climatological cycle of SLA across the transect line (Fig. 2a) is depicted. The annual SLA cycle from January through December (Figs. 2b,c) reveals the moving daily scale SLA mean and standard deviation, respectively. Mean SLA range represents the seasonal signal with trends removed. SLA are higher in summer to autumn due in part to heating and thermal expansion effects, with spatially neutral SLA along the transect from early winter through late spring. Temporal patterns of SLA (Fig. 2c) reveal greater standard deviations along nearshore areas and for areas near the Gulf Stream (red arrows). Lower standard deviations are evident along the shelf break and slope region (blue arrows). Increased standard deviations in northern coastal areas (Fig. 2c; A–B) occur from autumn through early spring, and generally all year in southern coastal areas (Fig. 2c; D–E).

Daily tidal station observations, calculated residuals, and gridded altimetry SLA were correlated using Pearson product correlations, and maps for the association between seven tide stations daily and altimetry-derived values are shown (Fig. 3). Correlations increase in a northward trajectory along the coast, with correlations ranging from ~0.5 to 0.83. Patterns of spatiotemporal correlations in areas north and south of Cape Hatteras are seen as two semidistinct subregions, similar to findings in Xu et al. (2019). Correlations are stronger when using the daily nontidal residual dataset when compared with the nonadj usted tidal observations.

b. SOM results

The sea level pressure SOM depicts the range of patterns that affect eastern North America, with high pressure patterns generally aligned toward the top of the array, and low pressure patterns along the bottom (Fig. 4). Along each row, patterns tend to be organized in terms of their seasonality; the two leftmost columns are warm-season dominant, and all include manifestations of the Bermuda high; the center columns contain the most intense pressure centers and are thus winter dominant, including coastal cyclones in patterns 3–5, and broad continental high in patterns 18 and 25. The rightmost columns generally show weaker pressure centers and are transition season centered.
In comparison with SLP, the 10-m wind SOM shows less clear seasonal distinction, with nearly all patterns possible at all times of year (Fig. 5). The array is arranged with stronger Gulf Coastal winds along the left side of the array, which tend to occur throughout the year except in summer, at which time the Bermuda high weakens overall circulation. Patterns with lighter winds tend to dominate the central part of the array, and these tend to occur on the shoulders of the warm season. Several patterns (3, 9, 10, 16, and 17) tend to dominate the core of the summer, where the dominant feature is the return flow around the Bermuda high, affecting the coastal waters of the U.S. East Coast. Winter and spring patterns, reflecting the very large thermal gradient at this time of year, tend to dominate the right side of the array, with several patterns showing mean wind speeds in excess of 10 m s$^{-1}$ across the open Atlantic.

c. Correlations of SOM patterns and sea levels

Categorical (eta, $\eta$) correlations between altimetry SLA and the SLP SOM as a whole (Fig. 6a) are generally better than those with the wind SOM (Fig. 6b), with the strongest correlations ($\eta > 0.68$) along the midshelf region. The SLP SOM has more consistent associations with sea level height along all coasts in the domain, with slightly higher correlations ($\eta > 0.5$) from Long Island southward to the Virginia/North Carolina border.

Categorical correlations between the SOMs and tidal-gauge station data (Table 2) show similar results to those noted with the altimetry data along the coasts in Fig. 6, with the notable difference being that the wind SOM is consistently more highly correlated with tidal levels than the SLP SOM. Generally, the highest correlations are for the four northernmost stations (Cape May; Lewes; Chesapeake Bridge; and Duck, North Carolina), with markedly lower correlations farther south. Table 2 also demonstrates the substantial improvement of the association between atmospheric patterns and sea levels when examining nontidal residuals relative to observed water levels.

d. SOM-based relationships with SLA spatial patterns

Postprocessing of monthly mean SLA and ratio maps for each circulation and wind pattern are shown in SOM space (Fig. 7), and yielded a general relationship between active, transitional, and weaker CPs centered along the right side of the SOM matrix, and elevated SLA patterns (Fig. 7a; red), along the bottom-left and top-right axes of the WPs SOM matrix (Fig. 7b). SLA pattern associations and responses occur across all months and seasons, with the strongest relationships evident for CPs 5–7, 12–14, 19–21, and 26–28; and WPs 1–3, 12, 18, and 22–24.

e. Atmospheric patterns and relative risk of high-water events

The RRs of high-water events associated with wind patterns and circulation patterns are shown in Table 3a. Individual wind patterns showing the highest RR across the seven
tidal stations shown were WPs 1–3, 18, and 22–24 with WPs 1–3 RR values slightly higher for lower mid-Atlantic stations (Chesapeake and Duck) and highest RR for Southeast stations (Charleston and Savannah). In addition, WPs 22–24 showed a twofold to sixfold increased risk of high water, mainly in the mid-Atlantic stations. Sea level pressure CPs overall show slightly weaker RR values (Table 3b), with CPs 5–7, 12–14, 19–21, and 26–28 showing significant increased risk of high water at many locations when they occur. The highest RRs are seen with CPs 5–7 in areas north of Cape Hatteras, with much lower RR (∼1) in the Southeast. Conversely, CPs 26–28 reveal higher RR for Southeast stations with approximately a twofold to threefold increase in RR in Charleston and Savannah stations versus stations north of Cape Hatteras. Relative risks of a flooding event for all combinations of CP and WP co-occurrence, shown for the mid-Atlantic and Southeast subregions, reveal a discernable set of patterns with elevated RR ≥ 2 (Tables 4 and 5; boldface and italicized values). For space considerations, RR values were averaged across tide gauges, representing areas above Cape Hatteras (Table 4) and below it (Table 5). RR values for all tidal gauge stations can be found as Table S1 in the online supplemental material).

f. Weather pattern aggregate selection

From the evaluation of SLA ratios and relative risk for all 52 SOM nodes, specific groupings of circulation and wind patterns showing strong association with elevated sea levels were evident, both in the position and orientation of individual SOM nodes in the SOM arrays (Fig. 7), as well as in the co-occurrence of individual circulation and wind patterns during elevated high-water events (Tables 3–5, as well as Table S1 in the online supplemental material). From this evaluation, relative risk values ≥2 were used to group multiple CP/WP pairs

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Fig. 3. Pearson product correlation maps between daily tide gauge (left, right center) residuals or (left center, right) observations and daily scale altimetry-derived SLA values for each grid cell calculated, January 1993–December 2017.
together to form the combined weather aggregates. We isolated seven CP and WP synchronous pattern aggregates that showed strong associations with elevated monthly SLA. Individual CP (4 patterns) and WP (4 patterns) groupings and co-occurring pattern aggregates (7 patterns), relative risk values, and a brief description of pattern characteristics are shown in Table 6.

g. Aggregates and SLA spatial patterns

SLA monthly mean ratio maps were calculated to show elevated, neutral, or diminished SLA spatial distribution patterns, separately for stations north and south of Cape Hatteras for the seven aggregates (Fig. 8). From this evaluation, we identified four synchronous patterns of synoptic-scale meteorological forcing contributing to greater frequencies of sea level variability and high-tide flooding:

1) Active cyclones/onshore flow. Active cyclone passage, onshore flow and surge combined with likely IB effects were apparent mainly north of Cape Hatteras (Fig. 8, column 1, rows 2 and 3).

2) Weak low pressure/longshore flow. Weak or generalized low pressure areas and alongshore flow represent more regional forcing along broad sections of the Atlantic coast (Fig. 8; column 2, rows 1 and 4).

3) Transitional. Transitional situations consisting of building ridges and troughs show less pronounced effects on heightened residuals (Fig. 8; column 3, rows 1 and 4).

4) Building anticyclones/northerly flow. Building anticyclones with increased along-shelf pressure gradients, and negative wind stress, may interact with Ekman flow processes and result in elevated sea level residuals and increased high-tide flood risk (Fig. 8; column 4; rows 1 and 4).

The first two synchronous patterns are associated with active weather patterns, such as midlatitude cyclones most evident in winter and spring (Fig. 8, column 1, row 1). Summarized as deepening cyclones in Sheridan et al. (2017), these aggregate patterns reveal intense low pressure areas affecting sea levels mainly north of Cape Hatteras; or with CPs (12, 13, and 14) as generalized areas of low pressure to the south, affecting sea levels along the entire Atlantic coast (Fig. 8; column 2, row 1). This distinction can be seen in the sea level response patterns, or “bulge” effect along the Atlantic coast. Because of a more pronounced decrease in sea level pressure with CPs 5–7, and coincidence with WPs 18, 22–24, an inverse barometer effect and direct onshore flow, indicative of significant wave heights, and surge, are likely with this scenario.

FIG. 4. SOM of mean SLP data for the study region. SOM CP numbers/node positions are indicated. Monthly frequency of each node is indicated by the bars above each map (from left to right: December–November, color coded by meteorological season); the dotted line near the top of each histogram indicates 10% relative frequency.
A third synchronous pattern represents a transitional situation, or reinforcing coastal ridge pattern to the west, and high pressure centered near the Saint Lawrence River valley, coupled with a coastal frontal boundary and lower maritime pressure, typical of CPs 19–21 (Fig. 8; column 3), with northeasterly and alongshore flow. The fall- and winter-dominant WPs (1–3), likely result in cycling or reinforcement of Ekman-induced flow elevating sea levels along the coast. There is no distinct coastal low associated with this aggregate, and effects on sea level tend to be less dramatic overall, though the general low over the subtropical Atlantic does reinforce elevated sea levels south of Cape Hatteras.

A fourth situation represents an elongated high pressure that builds over Maine, as shown in CPs 26–28. The functional aspect of this aggregate is that this orientation and positioning of the high pressure forces an equatorward northeast-to-southwest funneling of wind and water parallel to the shore (Fig. 8; column 4), typical of WPs 1–3. The most pronounced effects are in areas south of Cape Hatteras (Fig. 8; column 4). Specific CPs (26–28) likely create onshore Ekman convergence to the south, indicative of a subregional effect.

4. Discussion

Sea level conditions and variability along the Atlantic coast reflect the dynamic nature of the shelf, slope, and Gulf Stream environment. Dramatic spatial variability in sea level is evident especially along the main axis of the Gulf Stream with a lesser effect along shelf and slope areas.

Weather patterns showing significant association with elevated sea levels from tide gauge and altimetry-derived SLA data along the Atlantic coast were evident. SLA patterns usually showed their highest correlations with weather patterns at zero lag time, with generally decreasing eta correlation with increased lag time (not shown). Although persistence was not addressed directly in this study, cross correlations examining lag effects revealed correlations between tide gauge height and SOM occurrence on day 0, day 1, or day 2.
(varying by location and SOM pattern), with the largest absolute correlations most often occurring on day 0.

The evaluation of circulation pattern co-occurrence with wind patterns and relative flood risk provided additional insights on pattern aggregates and development of coastal flood risk patterns. Among the multiple aggregates and CP–WP combinations that were examined (and shown in Fig. 8 and Tables 3–5), the most prominent atmospheric drivers found (i.e., those showing highest relative risk and regional effects on sea levels) are discussed below.

a. Coastal or deepening cyclones

This flood risk pattern aggregate is most easily recognized by intense or developing cyclones along the Atlantic coast, indicative of an inverse-barometer effect, elongated fetch, surge, and onshore flow (Sheridan et al. 2017) especially in the northern tidal stations (Fig. 9, rows 1 and 2). The lack of co-occurrence with elongated equatorward wind patterns may explain why the patterns did not exhibit the highest relative risk of high-water events, when compared with other risk patterns. This aggregate shows its strongest impact on sea levels in areas north of Cape Hatteras.

b. Offshore frontal boundary and ridge

This flood risk pattern emerges during atmospheric transitions as described in Sheridan et al. (2017), but with subtle differences in the offshore contribution to sea level response (Fig. 9, row 3). Results show that a weak area of low pressure associated with a frontal boundary off the Atlantic coast, combined with a weak high pressure ridge to the north over the Saint Lawrence Valley, forms a pressure gradient along the coast, resulting in northeasterly winds and equatorward flow that can rapidly influence Ekman flow processes in areas both north and south of Cape Hatteras, elevating SLA. It is speculated that this scenario is contributing most to the pronounced equatorward flow and advection of waters from north to south beyond the Cape Hatteras export region, thereby aiding elevated relative sea levels along the East Coast.

c. Building northern anticyclones

This pattern aggregate is similar to the previous offshore frontal boundary/ridge pattern, but with a strong high pressure over the extreme northeastern United States, coupled with a stationary offshore frontal boundary (Fig. 9, row 4). This high pressure results in a more pronounced effect in the southern part of the study region with onshore and alongshore flow. This pattern and effect on sea level likely depends on whether the offshore frontal boundary and the reinforcing high to the north remains in place.
FIG. 7. Climatological SOM-space maps of SLA associations with circulation and wind patterns for all months, calculated as the ratio of SLA on dates when each (a) CP and (b) WP occurred to the 7-yr moving monthly mean for the 25-yr period. The figure enables visualization of higher (red; boxed) and lower (blue) mean SLA conditions associated with each CP and WP.
TABLE 3. Relative risks or risk ratios defined as the ratio of the incidence rate of a flood event happening at each location when a certain CP/WP/aggregate happens over the incidence rate of a flood event happening when that CP/WP does NOT occur. RRs are calculated using daily maximum residual tides at each selected tidal gauge station. Flooding events are defined as days on which the maximum residual tide exceeds the 95th percentile. Boldface values are statistically significant, achieved when the 95% confidence intervals do not span 1.00.

<table>
<thead>
<tr>
<th>Location</th>
<th>Wind patterns</th>
<th>Circulation patterns</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cape May</td>
<td>1.37</td>
<td>2.48</td>
</tr>
<tr>
<td>Lewes</td>
<td>1.53</td>
<td>2.99</td>
</tr>
<tr>
<td>Chesapeake</td>
<td>1.95</td>
<td>5.23</td>
</tr>
<tr>
<td>Duck</td>
<td>1.59</td>
<td>5.10</td>
</tr>
<tr>
<td>Beaufort</td>
<td>1.88</td>
<td>2.93</td>
</tr>
<tr>
<td>Charleston</td>
<td>3.98</td>
<td>6.92</td>
</tr>
<tr>
<td>Savannah</td>
<td>5.33</td>
<td>6.55</td>
</tr>
<tr>
<td>Avg</td>
<td>2.52</td>
<td>4.60</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cape May</td>
<td>1.07</td>
<td>0.37</td>
</tr>
<tr>
<td>Lewes</td>
<td>0.76</td>
<td>0.30</td>
</tr>
<tr>
<td>Chesapeake</td>
<td>0.24</td>
<td>0.10</td>
</tr>
<tr>
<td>Duck</td>
<td>0.25</td>
<td>0.10</td>
</tr>
<tr>
<td>Beaufort</td>
<td>1.12</td>
<td>0.57</td>
</tr>
<tr>
<td>Charleston</td>
<td>0.59</td>
<td>0.20</td>
</tr>
<tr>
<td>Savannah</td>
<td>0.43</td>
<td>0.13</td>
</tr>
<tr>
<td>Avg</td>
<td>0.64</td>
<td>0.25</td>
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</tbody>
</table>
As our hypothesis in this study is that nontidal effects are largely meteorological, we do not explicitly address Gulf Stream dynamics and adjacent shelf and slope variability; however, their influence on sea levels and trends deserves further investigation. In particular, for this study region, potential drivers of variability include the northeastward flowing Gulf Stream, interacting with the southward shelf/slope current, and deep western boundary current. One area of particular interest is the persistent low SLA variability “feature” described in Andres et al. (2013), Gawarkiewicz et al. (2008), and earlier work including Csanady and Hamilton (1988). Located near the shelf break, the area has been characterized as having “fixed” sea levels of low variance, separating areas of high sea level variance from the variance on the shelf and could influence alongshore transport mechanisms further influencing sea level variability in shelf waters.

On the role of atmospheric–ocean interacting processes influencing sea levels, we speculate ocean water “containment” along the shelf is potentially reinforced through specific weather pattern cycling and Ekman flow and convergence as contributors to regional elevated sea level patterns. Although more research is needed, findings do support the effects of negative wind stress on Ekman convergence, and regional sea level effect along the coast (Andres et al. 2013), and that specific circulation and wind patterns may act to reinforce elevated coastal sea level response.

5. Summary and conclusions

This research relates the combined effects of atmospheric and ocean-related process on anomalous sea levels and high-water events using two sets of predefined SOM-based weather patterns, in situ observational tidal residuals and altimetry-derived SLA data. Findings further substantiate previous research that highlights the role of atmospheric forcing in the form of larger-scale circulation and wind patterns on conditions in the ocean environment that can enhance both regional and local tidal anomalies and incidences of high-water events.

Overall, the univariate SOM approach provided a clear spatial continuum for evaluating individual and combinations of atmospheric patterns and pattern associations with extreme water level residuals and for determining high-tide flood risk patterns and aggregates. The approach provided a reliable means to
analyze highly resolved details of individual weather-related mechanisms likely influencing large-scale water mass movements near the coast, especially over regional to subregional domains.

For this study, our goals were specific to understanding processes related to daily scale variations in sea level, or positive deviations, represented by nontidal residuals. With a few caveats, nontidal residuals provided a useful analytic for understanding meteorological effects and forcing factors linked to daily scale anomalous sea level and increased high-tide flood risk along coast. However, the use of maximum nontidal residual does not always coincide with actual (and impactful) high water levels (e.g., Horbury and Wilson 2007), which can limit its use for estimating specific high-water events and flooding impacts. We use residuals here as the

**Table 5.** As in Table 4, but for selected Southeast tide gauges: Beaufort, Charleston, Fort Pulasky (Savannah).

<table>
<thead>
<tr>
<th>No.</th>
<th>Type</th>
<th>Patterns</th>
<th>RR (Avg)</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>CP</td>
<td>5, 6, 7</td>
<td>2.93</td>
<td>Active cyclones</td>
</tr>
<tr>
<td>2</td>
<td>CP</td>
<td>12, 13, 14</td>
<td>2.33</td>
<td>Weak low pressure</td>
</tr>
<tr>
<td>3</td>
<td>CP</td>
<td>19, 20, 21</td>
<td>1.74</td>
<td>Transitional</td>
</tr>
<tr>
<td>4</td>
<td>CP</td>
<td>26, 27, 28</td>
<td>1.80</td>
<td>Building anticyclones</td>
</tr>
<tr>
<td>5</td>
<td>WP</td>
<td>12, 18, 24</td>
<td>2.45</td>
<td>Cyclonic flow</td>
</tr>
<tr>
<td>6</td>
<td>WP</td>
<td>22, 23, 24</td>
<td>3.08</td>
<td>Transitional southerly flow</td>
</tr>
<tr>
<td>7</td>
<td>WP</td>
<td>1, 2, 3</td>
<td>3.85</td>
<td>Northerly longshore flow</td>
</tr>
<tr>
<td>8</td>
<td>WP</td>
<td>22, 23, 24, 1, 2, 3</td>
<td>4.93</td>
<td>Meridional flow</td>
</tr>
<tr>
<td>9</td>
<td>AGG</td>
<td>5, 6, 7 with 12, 18, 24</td>
<td>3.27</td>
<td>Active cyclones</td>
</tr>
<tr>
<td>10</td>
<td>AGG</td>
<td>5, 6, 7 with 22, 23, 24</td>
<td>3.97</td>
<td>Transitioning cyclones</td>
</tr>
<tr>
<td>11</td>
<td>AGG</td>
<td>12, 13, 14 with 1, 2, 3</td>
<td>4.26</td>
<td>Longshore low pressure</td>
</tr>
<tr>
<td>12</td>
<td>AGG</td>
<td>12, 13, 14 with 22, 23, 24</td>
<td>4.55</td>
<td>Longshore transitional</td>
</tr>
<tr>
<td>13</td>
<td>AGG</td>
<td>12, 13, 14 with 1, 2, 3, 22, 23, 24</td>
<td>4.57</td>
<td>Longshore meridional</td>
</tr>
<tr>
<td>14</td>
<td>AGG</td>
<td>19, 20, 21 with 1, 2, 3</td>
<td>3.12</td>
<td>Transitional</td>
</tr>
<tr>
<td>15</td>
<td>AGG</td>
<td>26, 27, 28 with 1, 2, 3</td>
<td>2.96</td>
<td>Building ridge</td>
</tr>
</tbody>
</table>
genuine meteorological contribution to sea level, although other factors including tide and surge interactions and, harmonic prediction errors and timing may be significant as well.

In conclusion, understanding atmosphere and ocean processes in relation to both regional and local sea level variability superimposed on trends of sea level rise is fundamental to the

<table>
<thead>
<tr>
<th>CP Aggregate</th>
<th>Cyclonic</th>
<th>Transitional</th>
<th>Anticyclonic</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 6 7</td>
<td>12 13 14</td>
<td>19 20 21</td>
<td>26 27 28</td>
</tr>
</tbody>
</table>

Fig. 8. Climatological SLA index ratios for co-occurring circulation (columns) and wind (rows) pattern aggregates for all months, calculated using the upper 75th percentile of tidal station residuals, as the ratio of the SLA monthly mean of observations, to the 7-yr moving monthly SLA mean for the 25-yr period only for when individual CPs and WPs co-occurred. Numbers of matching CP and WP daily co-occurrences are noted in the upper left corner of each map. The figure enables visualization of positive (red) SLA conditions associated with each CP/WP aggregate. Tidal stations: Cape May, Chesapeake, Beaufort, and Charleston (Fig. 1).
development of reliable flood indicators and for predicting flood hazard risk in the future. Further pursuit of this research will be on the testing and use of circulation and wind model outputs to render coastal risk weather patterns, and in combination with continuous water level observations, the development of multi-scale outlooks of minor to moderate flood probability.

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REFERENCES

