https://doi.org/10.5194/nhess-2021-251
Preprint. Discussion started: 7 September 2021

Natural Hazards and Earth System Sciences
Discussions

Tropical cyclone storm surge probabilities for the east coast of the United States: A cyclone-based perspective

Katherine L. Towey[1], James F. Booth[1,2], Alejandra Rodriguez Enriquez[3], Thomas Wahl[3]

[1]Earth and Environmental Science, The Graduate Center, City University of New York, New York, NY, 10016, USA
[2]Earth and Atmospheric Science, The City College of New York, City University of New York, New York, NY, 10031, USA
[3]Civil, Environmental, and Construction Engineering and National Center for Integrated Coastal Research, University of Central Florida, Orlando, FL, 32816, USA

Correspondence to: Katherine L. Towey (ktowey@gradcenter.cuny.edu)

Abstract. To improve our understanding of the influence of tropical cyclones (TCs) on coastal flooding, the relationships between storm surge and TC characteristics are analyzed for the east coast of the United States. Using observational data, the statistical dependencies of storm surge on TCs are examined for these characteristics: distance from TC center, TC intensity, track path angle, and propagation speed. Statistically significant but weak linear correlations are found for nearly all sites. At each location, storm surge is influenced differently by these characteristics, with some locations more strongly influenced by TC intensity and others by the distance from the TC center. The correlation for individual and combined TC characteristics increases when conditional sorting is applied to isolate strong TCs close to a location, though the fraction of surge variance explained is never greater than 60 %. The probabilities of TCs generating surge exceeding specific return levels (RLs) are then analyzed for TCs that pass within 500 km of a location, where between 7 % and 26 % of TCs were found to cause surge exceeding the 0.5-yr RL. If only the closest and strongest TCs are considered, the percentage of TCs that generate surge exceeding the 0.5-yr RL is between 30 % and 50 % at sites north of Sewell's Point, VA, and over 70% at almost all sites south of Charleston, SC. Overall, this analysis demonstrates that no single TC characteristic dictates how much surge will be generated and offers a unique perspective on surge probabilities that is based on all TCs rather than focusing only on those that cause extreme surge.

1 Introduction

Regions such as the east coast of the United States (US) have become more vulnerable to coastal flooding due to the expansion of densely populated communities in low-lying areas (e.g., Strauss et al., 2012; Hallegatte et al., 2013). In these same regions, conditions that generate storm surges, which drive the largest flooding events, are likely to become worse in the future. This can be attributed to rising sea levels (e.g., Tebaldi et al., 2012; Sweet and Park, 2014; Moftakhari et al., 2015), geomorphic changes in the coastal regions (e.g., Familkhalili et al., 2020), and increasing storm intensities with anthropogenic climate change (e.g., Sobel et al., 2016). The magnitude of the changes to these factors will influence how much destruction storm surge may cause in low-lying communities in the future (e.g., Rahmstorf, 2017). However, the response of storm surge to changes in the atmosphere and coastal ocean might not be monotonic. Thus, we need to expand on our current understanding of storm surge behavior, in terms of the drivers of its variability.

For the US east coast, both tropical cyclones (TCs) and extratropical cyclones (ETCs) can create storm surge that generate major hazards to coastal areas (e.g., Zhang et al., 2000; Colle et al., 2010; Booth et al., 2016). For ETCs, different circulation scenarios can produce large surge (Catalano and Broccoli, 2018), and the most-common track paths of ETCs causing storm surge differ for the Mid-Atlantic and the Northeast US (Booth et al., 2016). Additionally, cities that are farther north tend to have less TC-related storm surge extremes (Needham et al., 2015). However, even as far north as Boston, MA, four of the top 10 surge events since 1979 were caused by TCs (Booth et al. 2016). We know that the atmospheric dynamics of TCs and ETCs differ (e.g., Jones et al., 2003; Yanase and Niino, 2015). Because of these differences in storm dynamics, flood exceedance curves for TCs and ETCs can have different characteristics when one considers long timescales (e.g., 100-year events; Orton et al., 2016). Thus, even though TCs occur much less frequently than ETCs along the US east coast, individual TCs can cause more damage. Therefore, it is important to understand how differences in TC characteristics relate to storm surge.

Several studies have utilized numerical models to assess the relationship between storm surge and TC characteristics. Lin et al. (2010) showed an exponential relationship between increasing wind speed and increasing surge at New York City. The result was based on thousands of synthetic storms for a specific track path, and the relationship was still quite noisy (Fig. 5 in Lin et al., 2010). Garner et al. (2017) illustrated the uncertainty associated with shifts in TC tracks near the Battery in New York City. Camelo et al. (2020) simulated 21 storms in the Gulf of Mexico and along the east coast of the US and found no individual TC characteristic correlates well with storm surge. In the Gulf of Mexico, Irish et al. (2008) found a noisy, but statistically significant relationship between storm surge amplitude and the size of TCs. Needham and Keim (2014) empirically found that storm surge correlates better with TC winds pre-landfall as opposed to winds at landfall; Roberts et al. (2015) found a similar result for all storm types. Modelling work also suggests that with anthropogenic climate change, TCs will become stronger, and peak intensity will occur at higher latitudes, and thus, changes to the intensity, frequency, and tracks of TCs are predicted to impact storm surge (Knutson et al., 2020). While many studies have focused on utilizing models to better understand the relationship between storm surge and TCs, to our knowledge, no previous assessment has examined historical surge observations outside of a regional area, with a focus on surge variability relative to TC characteristics. Therefore, we have designed an analysis to utilize past observations to determine the correlation between TC characteristics and storm surge at various locations along the eastern US.

We note that storm surge magnitude is also impacted by coastal characteristics over a particular location, such as its bathymetry (Weaver and Slinn, 2010) and depth of near-shore waters combined with the astronomical tide cycle (Rego and Li, 2010; Talke et al., 2014). However, our focus herein will be TC characteristics. TC information, such as the track path, storm strength, and track direction, can be ascertained from historical cyclone track information. These TC characteristics can then be related to storm surge itself. By utilizing this method of storm attribution, the analysis herein examines surge events and TCs in the observed record to understand empirically how TC characteristics can influence storm surge.

In this paper, we present a two-part analysis that examines how the magnitude and frequency of storm surge events associated with TCs vary based on the characteristics of the TCs themselves. Section 2 describes the data and methods used in calculating storm surge and associating storm surge events with TCs. Section 3 is divided into two parts, with part one first analyzing how TC characteristics both individually and in conjunction with one another correlate with the magnitude of storm surge. We further explore if examining TC characteristics individually or combined with one another improves the predictability of storm surge. Part two computes the return levels of storm surge and examines the likelihood of storm surge being exceeded by TCs that meet certain criteria at various locations along the east coast of the US. The paper concludes with a discussion of the results in section 4.

2 Data and Methodology

Section 2.1 describes how storm surge data is calculated from the original water level data. Section 2.2 details how storm surge events are associated with TCs as well as the TC characteristics that are examined in determining the relationship between storm surge and TC characteristics.

2.1 Storm Surge Data

The water level data utilized in this analysis is obtained from the National Oceanic and Atmospheric Administration (NOAA) Tides and Currents website (NOAA, 2021). Twelve tide gauges, which record the water levels, that span along the east coast of the US were selected for this analysis (Table 1). Our analysis begins in 1946 for most sites, unless the station has data available beginning in a year later than 1946, as shown in Table 1. It is important to note that the water level data is not continuous for all locations and thus, some sites may contain gaps in the data. The year 1946 is selected as the starting date in our analysis because in 1945, the NOAA predicted tide and/or sea level data appeared to have a timing issue at some locations where the data are offset which causes the difference between the sea level and the tide to have a tidal pattern.

The water level data is initially provided in hourly time intervals. Each water level time series results from a combination of mean sea level, astronomical tides, and non-tidal residual, which mainly contains the surge component. We are aware that the wave setup can influence the water level, but we neglect this component. To obtain surge levels, we first remove the astronomical tide, which is provided on the NOAA Tides and Currents website (NOAA, 2021), from the water level data and then remove low-frequency trends by subtracting a 365-day running mean of the water level for each site's water level time series. We refer to the resulting value as surge. Using hourly surge, we find the maximum surge per day and refer to this value as the maximum daily storm surge.

95 **Table 1. Locations of tide gauges used in analysis with their latitude, longitude and length of data record. The number of TCs within 500 km before and after the removal of missing mean sea-level pressure values are included here. The average SLP of TCs through the time averaging technique within 500 km, 250 km, and 100 km, which are referenced throughout the manuscript, are included here.**

Location	**Latitude**	**Longitude**	**Record Length**	**Number of TCs within 500 km**	**Number of TCs within 500 km with SLP available**	**Average SLP of TCs within 500 km (hPa)**	**Average SLP of TCs within 250 km (hPa)**	**Average SLP of TCs within 100 km (hPa)**
Portland, ME	43.66° N	70.25° W	1945-2019	96	83	987.2078	989.7761	995.1048
Boston, MA	42.36° N	71.05° W	1945-2019	118	102	987.9074	990.6463	988.3217
Newport, RI	41.51° N	71.33° W	1946-2019	126	108	987.4477	990.0447	993.0641
New York, NY	40.7° N	74.02° W	1946-2019	129	115	988.9265	989.6776	988.5800
Sandy Hook, NJ	40.47° N	74.01° W	1946-2019	132	117	988.6768	990.5679	989.6271
Cape May, NJ	38.97° N	74.96° W	1966-2019	85	85	990.5786	990.9775	980.9500
Sewell's Point, VA	36.95° N	76.33° W	1946-2019	161	145	988.9418	989.2514	994.7525
Duck, NC	36.18° N	75.75° W	1979-2019	87	87	989.3469	990.2318	991.0889
Charleston, SC	32.78° N	79.92° W	1946-2019	159	135	988.1105	988.9286	990.5564
Fort Pulaski, GA	32.04° N	80.90° W	1950-2019	137	119	987.9745	989.8003	992.8212
Fernandina Beach, FL	30.67° N	81.47°W	1946-2019	154	133	990.0043	989.1333	991.5492
Key West, FL	24.55° N	81.81° W	1950-2019	117	104	990.2946	985.9717	981.9602

https://doi.org/10.5194/nhess-2021-251
Preprint. Discussion started: 7 September 2021

2.2 Methods

Using our dataset of maximum daily storm surge for each site, we associate the surge events with TCs. The National Hurricane Center's Atlantic hurricane database (HURDAT2; Landsea and Franklin, 2013) is used to identify TCs. The HURDAT2 database provides at least 6-hourly observations of each TC, therefore we use only the 6-hourly data for all TCs. The TC variables we utilize are its location, central mean sea-level pressure minimum (SLP) and maximum surface wind intensity. All TCs that pass within a specified distance centered on each tide gauge site are retained for this analysis, with results for multiple distance thresholds reported in Section 3. Distance from the TC centers to sites are calculated using great circles. We then find all time steps along the TC track when the TC was within the specified distance and examine what the maximum daily storm surge was at each of those time steps. We consider all TCs in the HURDAT2 database that are categorized as a tropical storm, hurricane, or having undergone extratropical transition during at least one time instance when the storm is within the search distance. Thus, if a cyclone in the database only reaches tropical depression strength during the time that it is within the search distance for a specific site, it is not included in our analysis. Hereafter, we simply refer to these storms that we are analyzing as TCs.

The 6-hourly time steps when the TCs are within a specified distance of a site are associated with the maximum daily storm surge that occurred on that day. The highest maximum daily storm surge that occurred when the TC is within a specified distance of a site is the one storm surge value that we associate with the TC. Thus, the storm surge value at a given location attributed to a TC is the highest maximum daily storm surge value of all values when the TC is within a specified distance of a site. We note that the maximum daily storm surge we find in this manner is not necessarily the storm surge that occurs at the time when the TC was closest to site, instead, the maximum surge is the largest surge that can be realistically attributable to the TC that is in the vicinity of the site.

The first part of our analysis utilizes variables provided in the HURDAT2 dataset to examine how the maximum daily storm surge varies with distance, intensity, track path angle, and propagation speed. In our analysis of the relationships between TC characteristics and storm surge, linear regression is used to generate linear best fits. Correlation coefficients are calculated using the Pearson method. Single and multiple linear regression analyses are presented to determine the predictability of these TC characteristics on storm surge. To test for statistical significance, we use the p-value method, where we select a significance level of 5 %. The null hypothesis is that the correlation coefficient of our data sample is not significantly different from zero. If the p-value is less than the significance level, we reject the null hypothesis and thus conclude that there is a statistically significant relationship among our data.

For TC intensity, our primary analysis uses SLP. Since SLP data is missing for some instances, we use the average of SLP values that are recorded over the time period from 18 hours prior to the surge maximum to 6 hours post surge maximum. This choice of timing is motivated by the results of Needham and Keim (2014) and Roberts et al. (2015). We tested different time windows, shifting it forward or backward in time relative to the time of the surge maximum, and found that changes in results were negligible (not shown). This time-averaging technique will be referenced throughout the analysis and applied to other variables. If there are no recorded SLP values during this time-averaging period, we remove the TC from our analysis. Table 1 indicates the number of TCs within 500 km for each site before and after we remove those TCs from our analysis. We also analyzed the maximum surface wind intensity as a measure of TC intensity but found that wind speed and SLP are highly correlated (not shown), and thus, we just consider SLP for this analysis.

For the calculation of track path angle, we quantify the change in latitude and longitude between subsequent time steps along the track of the TC and use the vectors averaged over the 24 h time interval described for our analysis of SLP to get one value of the track path angle representative of that time frame. The track path angles range from 0° or 360° (eastward) to 90° (northward) to 180° (westward) to 270° (southward). Examples of TC tracks and their respective track path angles for New York, NY and Charleston, SC are shown in Fig. 1. For both New York and Charleston, the majority of TCs propagate toward the northeast relative to each site, though there are many TCs that also move toward the northwest relative to Charleston.

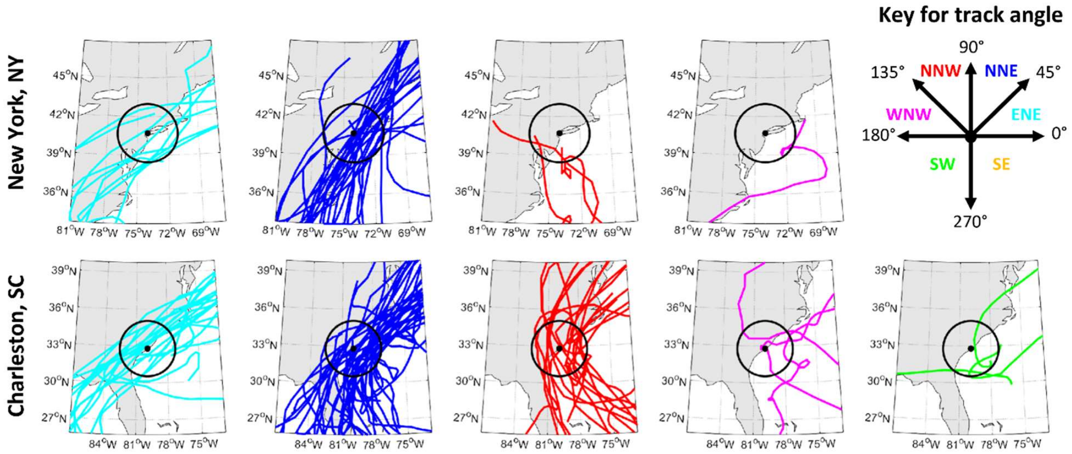


Figure 2. Tracks of TCs within 250 km for New York, NY (top row) and Charleston, SC (bottom row) separated by track path angle around the time of the surge maximum. Colors of tracks indicate the track path angle as portrayed in the key and include toward the ENE (column 1), NNE (column 2), NNW (column 3), WNW (column 4), and SW (column 5). No tracks moved toward the SE. The tide gauge location is indicated by a black dot and the search radius of 250 km around the location is indicated by the black circle.

Propagation speed is calculated using distance traveled per 6-hourly time step based on great circles. We then apply the same time-averaging technique described for SLP to the calculations of propagation speed. For the data that we analyzed, however, the relationship between the surge maximum and TC propagation speed is negligible and is not included in this analysis. This does not mean that propagation speed does not have some physical impact on the surge generated by a TC; it

https://doi.org/10.5194/nhess-2021-251
Preprint. Discussion started: 7 September 2021

means that the signal of that forcing is too small compared to the noise associated with all of the other variability in the mechanisms that influence surge.

The second part of this analysis examines the likelihood of the rate of occurrence of a storm surge event through calculating the storm surge levels for various return periods at each site. Surge return levels are calculated using a peaks-over-threshold method (Coles, 2001) by fitting a Generalized Pareto Distribution (GPD) to the top 1 % of hourly storm surge events at each location. Before performing the fitting to the GPD, the events over the threshold are de-clustered using a 3 d window, so we satisfy the assumption of independence (Wahl et al., 2017). Return levels at 0.5 yr, 1 yr, 2 yr, 5 yr, 10 yr, and 25 yr intervals are determined from the GPD and are included in Table 2. Focusing on the 0.5 yr return levels, which provides us with a large enough sample size, we then do a probabilistic analysis in which we determine how many TCs produce a surge maximum that exceeds the 0.5 yr return level threshold and have TC characteristics that meet certain criteria.

Table 2. Return levels (m) for each location for return periods of 0.5-yr, 1-yr, 2-yr, 5-yr, 10-yr, and 25-yr intervals.

Location	**0.5-yr**	**1-yr**	**2-yr**	**5-yr**	**10-yr**	**25-yr**
Portland, ME	0.6391 m	0.7429 m	0.8500 m	0.9972 m	1.1129 m	1.2718 m
Boston, MA	0.7471 m	0.8758 m	1.0040 m	1.1730 m	1.3003 m	1.4680 m
Newport, RI	0.6147 m	0.7260 m	0.8456 m	1.0172 m	1.1583 m	1.3608 m
New York, NY	0.7950 m	0.9471 m	1.1128 m	1.3548 m	1.5569 m	1.8523 m
Sandy Hook, NJ	0.8034 m	0.9607 m	1.1345 m	1.3924 m	1.6113 m	1.9362 m
Cape May, NJ	0.7084 m	0.8257 m	0.9450 m	1.1061 m	1.2305 m	1.3985 m
Sewells Point, VA	0.6752 m	0.8096 m	0.9551 m	1.1659 m	1.3406 m	1.5939 m
Duck, NC	0.6107 m	0.7036 m	0.7962 m	0.9179 m	1.0096 m	1.1302 m
Charleston, SC	0.5751 m	0.6694 m	0.7731 m	0.9261 m	1.0551 m	1.2454 m
Fort Pulaski, GA	0.6790 m	0.7862 m	0.9020 m	1.0695 m	1.2081 m	1.4086 m
Fernandina Beach, FL	0.7910 m	0.9184 m	1.0491 m	1.2272 m	1.3662 m	1.5556 m
Key West, FL	0.2223 m	0.2567 m	0.2967 m	0.3595 m	0.4159 m	0.5046 m

3 Results

Section 3.1 examines the correlation between storm surge and TC characteristics individually, combined, and through conditionally sorting. Section 3.2 assesses the probabilities associated with TCs producing storm surge exceeding the 0.5-yr return level given certain TC characteristics.

3.1 Storm surge correlation with TC characteristics

For our correlation analysis, the first characteristic we analyze is the distance between the TC center and the tide gauge site, hereafter referred to simply as distance. When considering TCs that pass within 500 km of a location, the magnitude of storm surge generally increases for TCs that are closer to a given site (Fig. 2). Each site exhibits a negative correlation between storm surge and distance and the relationship is statistically significant at all sites based on the method described in Section 2.2. Many of the largest storm surge events do tend to be at distances less than 200 km for most locations. However, as seen in Fig. 2, there are also instances where TCs close to a location generate relatively small storm surge. Conversely, there are also instances where TCs are further away from a location, but result in high storm surge (e.g., Boston, MA in Fig. 2). While the correlation is low for most sites, there is a moderate relationship at New York, NY, Sandy Hook, NJ, Fernandina Beach, FL, and Key West, FL, suggesting that distance alone is not a strong predictor of storm surge.

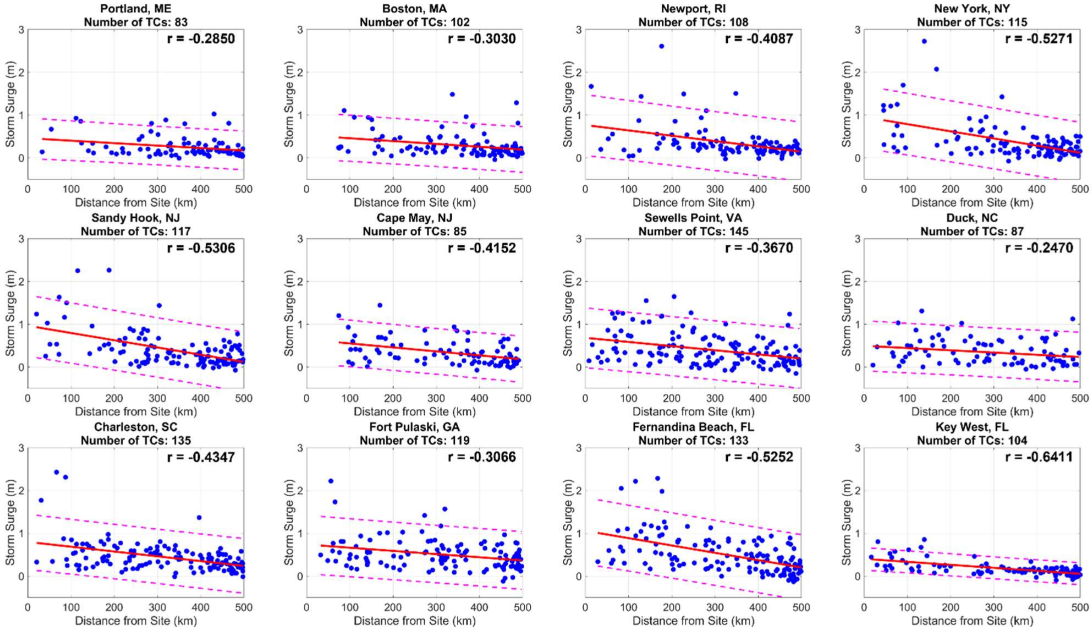


Figure 2. Linear fit (red line) between storm surge (m) and distance of TC from site (km) with 95 % confidence intervals (dashed magenta line) for all TCs within 500 km. Correlation coefficient, r, is provided at each site and is bold if it is statistically significant.

https://doi.org/10.5194/nhess-2021-251
Preprint. Discussion started: 7 September 2021

The second characteristic we consider is TC intensity, based on the SLP of the TC, as discussed in Section 2.2. All locations display a similar relationship in which the magnitude of storm surge is larger for TCs with lower SLP, which generally signifies a more intense TC (Fig. 3). All locations, however, exhibit low to moderate correlation coefficients, though the relationship is statistically significant. These results also indicate that SLP alone is not a good enough predictor of storm surge. However, the larger the correlation, as compared to the distance analysis, for most locations would indicate that there is value added by examining the intensity of TCs in addition to distance. We also examined the time rate of change in the SLP of TCs and found that it was not a better predictor of surge as compared to the full SLP (not shown).

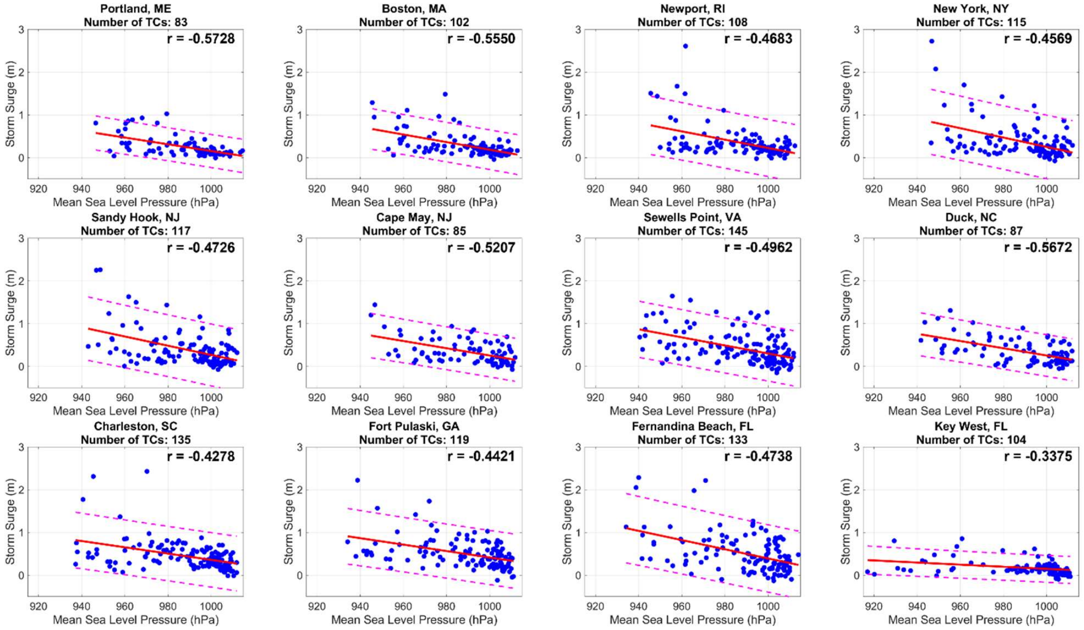


Figure 3. Linear fit (red line) between storm surge (m) and mean sea-level pressure (hPa) with 95 % confidence intervals (dashed magenta line) for all TCs within 500 km. Correlation coefficient, r, is provided at each site and is bold if it is statistically significant.

The path that a TC takes relative to each location is also likely to influence the magnitude of the resulting storm surge. This would be due to the direction of the winds toward the coastline around the TC that can greatly influence storm surge. Figure 4 shows how the magnitude of storm surge varies based on the angle of the track relative to each location around the time of storm surge event for all TCs within 500 km of a site. The TCs near the most northern sites along the New England coastline (e.g., Portland, ME and Boston, MA) almost exclusively move toward the northeast. As latitude decreases, the range of track paths grows, with more TCs moving toward the northwest and southwest, especially for locations south of Sewell's Point, VA. For locations north of Cape May, NJ, the largest storm surge events tend to be associated with TCs that move toward the northeast, with the exception being during Hurricane Sandy, a TC which was known for its unique track (Hall and Sobel, 2013). For most locations, however, there is not a significant difference in the average storm surge between different track paths. The starkest difference in storm surge based on track path is seen in Fernandina Beach, FL, where TCs moving toward the east-northeast have a median storm surge of 0.17 m, whereas TCs moving toward the west-northwest have a median storm surge of 0.74 m.

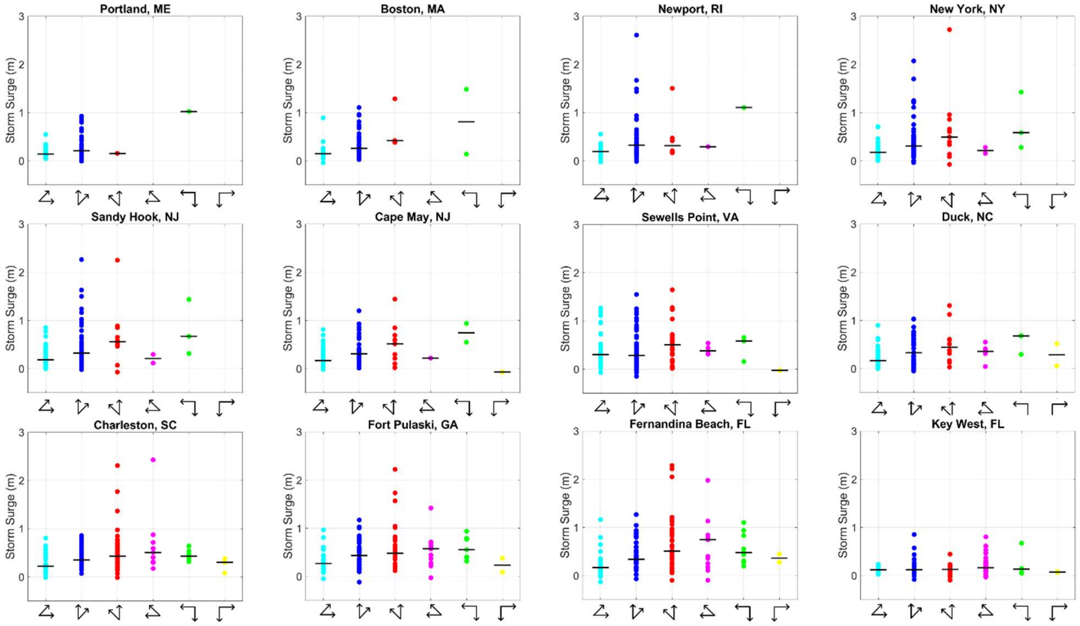


Figure 4. Storm surge (m) separated by track path angle. Arrows along x-axis indicate range of TC track movement and is similar to track path angle key in Fig. 1. From left to right, arrows correspond to ENE (light blue), NNE (dark blue), NNW (red), WNW (magenta), SW (green) and SE (yellow). Horizontal black line indicates the median value of storm surge for each group of track path angles.

Individually, we have shown how the magnitude of storm surge varies based on TC distance, intensity, and track path. We also examined the influence of propagation speed (not shown) and found a negligible correlation between it and storm surge. Next, we use conditional sorting to explore if a stronger relationship exists among these TC characteristics with storm surge.

To see how the combination of these variables can influence the predictability of storm surge, we examine how the magnitude of storm surge correlates against distance for only TCs that have a SLP less than or equal to the average SLP of all TCs within 500 km of a site which, hereafter are referred to as strong TCs (Fig. 5). The average SLP is calculated for each location and is provided in Table 1. The strongest relationship is seen in Key West, FL, whereas a nearly negligible relationship is seen at Duck, NC. Figure 5 also shows the average track path angle for each storm surge event. For strong TCs, most locations show no discernible relationship with track path angle for storm surge and distance. For both New York, NY and Sandy Hook, NJ, which are closely located to one another, TCs that move toward the east-northeast are often associated with lower storm surge and are further away, whereas TCs that move toward the north-northeast occur at all distances and subsequently result in storm surge of low and high magnitudes. We also used conditional sorting to examine how the magnitude of storm surge correlates with SLP for only TCs within 250 km (not shown) and saw a similar improvement in the correlation as shown in this analysis. Conditional sorting based on track path and, separately, track propagation speed, did not lead to improved correlations between TC distance and surge (not shown).

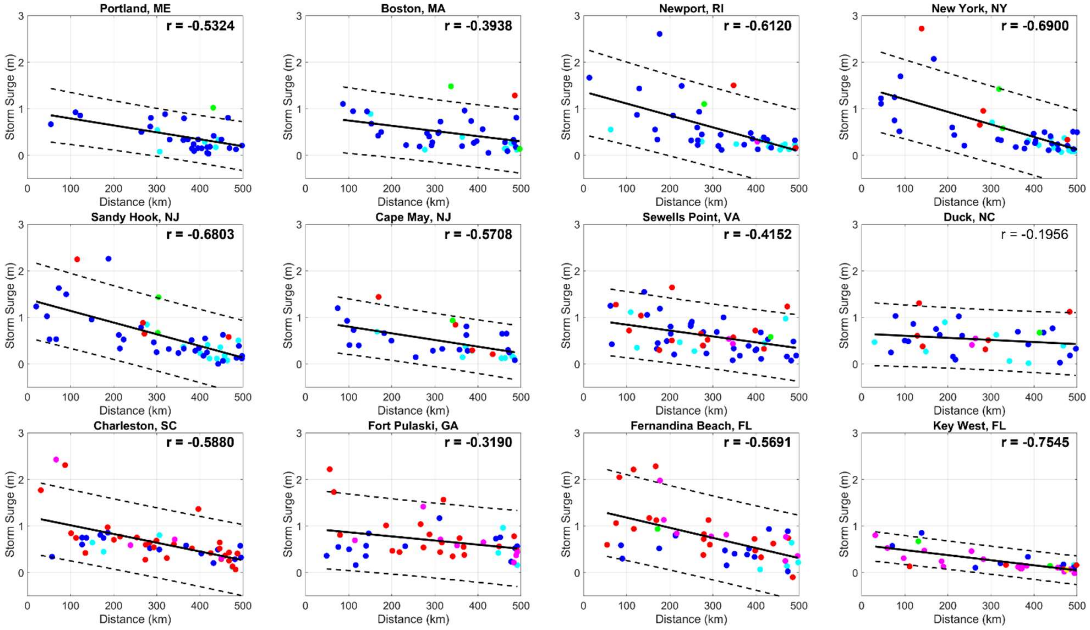


Figure 5. Linear fit (black line) between storm surge (m) and distance of TC from site (km) for only TCs whose mean sea-level pressure was less than or equal to the average mean sea-level pressure of all TCs within 500 km with 95 % confidence intervals (dashed black line) for all TCs within 500 km. Points are color coded based on average track path angle as outlined in Fig. 4. Correlation coefficient, r, is provided at each site and is bold if it is statistically significant.

A comparison of the correlations between surge and distance (Fig. 2) and those for surge and distance after conditionally sorting to isolate for stronger TCs (Fig. 5) indicates that many locations have an increase in their correlation coefficient. Table 3 contains the correlation coefficients for individual, combined, and conditionally sorted variables in their ability to predict storm surge at each location. While the relationships are statistically significant, distance and SLP, individually, do not have a strong relationship with storm surge for TCs within 500 km of a location. Some locations, such as New York, NY, Sandy Hook, NJ, Charleston, SC, Fernandina Beach, FL, and Key West, FL, exhibit a higher correlation with distance than SLP. When distance and SLP are combined, the correlation increases compared to the correlation for the variables individually and are statistically significant for all locations. If we isolate only TCs that are considered strong (i.e., SLP is less than or equal to the average SLP of all TCs within 500 km of a site) and then examine the predictability of storm surge based on distance, we see that the correlation increases and is statistically significant for all locations except Duck, NC (Table 3, Column 5).

Table 3. Correlation coefficients from linear analysis of storm surge with distance, mean sea-level pressure, combination of distance and mean sea-level pressure, and distance for only TCs whose mean sea-level pressure was less than or equal to the average mean sea-level pressure of all TCs within 500 km. Bold coefficients indicate the relationship is statistically significant.

Location	Distance	SLP	SLP+Distance	Distance using strong SLP only
Portland, ME	**-0.2850**	**-0.5728**	**-0.6340**	**-0.5324**
Boston, MA	**-0.3030**	**-0.5550**	**-0.6017**	**-0.3938**
Newport, RI	**-0.4087**	**-0.4683**	**-0.5950**	**-0.6120**
New York, NY	**-0.5271**	**-0.4569**	**-0.6633**	**-0.6900**
Sandy Hook, NJ	**-0.5306**	**-0.4726**	**-0.6648**	**-0.6803**
Cape May, NJ	**-0.4152**	**-0.5207**	**-0.6340**	**-0.5708**
Sewell's Point, VA	**-0.3670**	**-0.4962**	**-0.6000**	**-0.4152**
Duck, NC	**-0.2470**	**-0.5672**	**-0.5891**	-0.1956
Charleston, SC	**-0.4347**	**-0.4278**	**-0.6091**	**-0.5880**
Fort Pulaski, GA	**-0.3066**	**-0.4421**	**-0.5329**	**-0.3190**
Fernandina Beach, FL	**-0.5252**	**-0.4738**	**-0.6708**	**-0.5691**
Key West, FL	**-0.6411**	**-0.3375**	**-0.6943**	**-0.7545**

3.2 Storm surge exceedance probabilities

In considering impacts and coastal disaster planning, hazards are often ranked using return periods. These metrics provide timescales that help in conceptualizing the potential magnitudes of the hazards, and therefore we have analyzed the return periods for the storm surge events at our study locations. Herein we report on the relationship between the return periods and the TC characteristics, using conditional sorting that builds on the lessons learned from our regression analysis in the previous section.

We calculated return levels for various return periods for each location (Table 2) using the peaks-over-threshold method as previously defined in Section 2.2. Return levels are calculated using hourly storm surge values for each location for all times during the year. In our analysis, we focus on the 0.5-year return level, which would mean on average, a location could expect to experience two storm surge events of this magnitude each year (or each hurricane season).

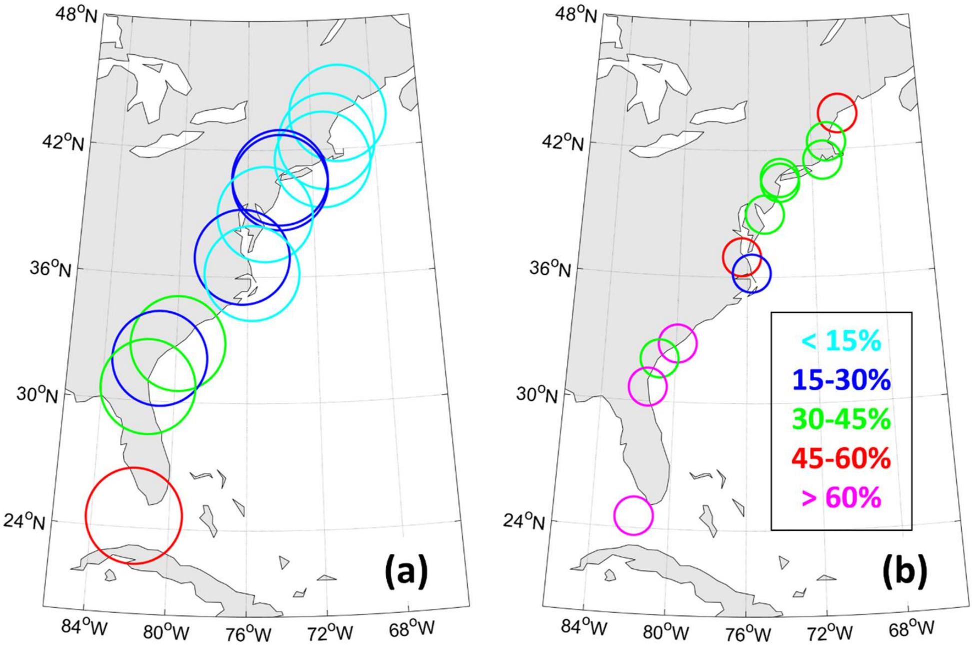
Using the 0.5-year return levels, we seek to determine the probability of storm surge exceeding this threshold conditional on TC characteristics (Table 4). First, we examine the probability of TCs within a specific distance resulting in storm surge exceeding the 0.5-year return level. As the distance decreases from 500 km to 100 km, the percentage of TCs creating storm surge exceeding the 0.5-year return level increases. At a distance of 250 km, less than 10 % of TCs have resulted in storm surge that exceeds at least the 0.5-year return level at the two most northern sites, Portland, ME and Boston, MA (Fig. 6a). Three of the four most southern sites, including Charleston, SC, Fernandina Beach, FL, and Key West, FL, have experienced more than 30 % of TCs within 250 km resulting in storm surge exceeding the 0.5-year return level, with almost 50 % at Key West, FL.

Table 4. Percentages for each location of TCs within 500 km, 250 km, and 100 km under two criteria: 1) within a specified distance that exceeded 0.5-yr return level and b) within a specified distance and whose mean sea-level pressure is less than or equal to the average mean sea-level pressure of all TCs within a specified distance that exceeded 0.5-yr return level. The number of individual TCs that met all criteria is given by "N" and the total number of TCs that met the distance and/or intensity criteria but did not exceed the return level is given by the bracketed number. The "N" number divided by the bracketed number will give the percentage in the same box.

Location	**If a storm is within X distance, how many result in 0.5-yr return level?**			**If a storm is within X distance and the TC has SLP less than or equal to the mean SLP, how many result in 0.5-yr return level?**		
	500 km	**250 km**	**100 km**	**500 km**	**250 km**	**100 km**
Portland, ME	9.64 % N = 8 [83]	10 % N = 3 [30]	14.29 % N = 1 [7]	23.53 % N = 8 [34]	30 % N = 3 [10]	50 % N = 1 [2]
Boston, MA	7.84 % N = 8 [102]	5.56 % N = 2 [36]	10 % N = 1 [10]	20.51 % N = 8 [39]	16.67 % N = 2 [12]	33.33 % N = 1 [3]
Newport, RI	9.26 % N = 10 [108]	11.36 % N = 5 [44]	15.38 % N = 2 [13]	21.43 % N = 9 [42]	31.25 % N = 5 [16]	40 % N = 2 [5]
New York, NY	9.57 % N = 11 [115]	18.42 % N = 7 [38]	20 % N = 3 [15]	17.78 % N = 8 [45]	38.46 % N = 5 [13]	40 % N = 2 [5]
Sandy Hook, NJ	11.11 % N = 13 [117]	20 % N = 8 [40]	18.75 % N = 3 [16]	21.28 % N = 10 [47]	38.46 % N = 5 [13]	33.33 % N = 2 [6]
Cape May, NJ	10.59 %	13.51 %	14.29 %	21.88 %	26.67 %	33.33 %

https://doi.org/10.5194/nhess-2021-251
Preprint. Discussion started: 7 September 2021

	N = 9 [85]	N = 5 [37]	N = 1 [7]	N = 7 [32]	N = 4 [15]	N = 1 [3]
Sewells Point, VA	21.38 % N = 31 [145]	23.17 % N = 19 [82]	25.93 % N = 7 [27]	37.04 % N = 20 [54]	37.93 % N = 11 [29]	45.45 % N = 5 [11]
Duck, NC	17.24 % N = 15 [87]	10.91 % N = 6 [55]	11.11 % N = 2 [18]	38.24 % N = 13 [34]	20 % N = 4 [20]	16.67 % N = 1 [6]
Charleston, SC	25.93 % N = 35 [135]	31.08 % N = 23 [74]	30.77 % N = 8 [26]	51.92 % N = 27 [52]	61.29 % N = 19 [31]	75 % N = 6 [8]
Fort Pulaski, GA	24.37 % N = 29 [119]	26.56 % N = 17 [64]	27.27 % N = 6 [22]	38.64 % N = 17 [44]	43.48 % N = 10 [23]	42.86 % N = 3 [7]
Fernandina Beach, FL	23.31 % N = 31 [133]	37.88 % N = 25 [66]	38.1 % N = 8 [21]	39.13 % N = 18 [46]	69.23 % N = 18 [26]	71.43 % N = 5 [7]
Key West, FL	24.04 % N = 25 [104]	48.84 % N = 21 [43]	50 % N = 9 [18]	33.33 % N = 11 [33]	61.54 % N = 8 [13]	71.43 % N = 5 [7]



270

Figure 6: Visual depiction of data from table 4 for percentage of TCs a) within 250 km that exceed 0.5-yr return level and b) within 100 km and whose mean sea-level pressure is less than or equal to the average mean sea-level pressure of all TCs within 100 km. Size of circles indicates the search radius around each location and is color coded based on the percentage value with <15 % (light blue), 15-30 % (dark blue), 30-45 % (green), 45-60 % (red), and >60 % (magenta).

From our analysis in Section 3.1, we found that distance is not sufficient when considering its effect on the magnitude of storm surge. Therefore, we next report on the probability of TCs within a specific distance and with a specific intensity. Because the average TC SLP varies across our study location, instead of using a fixed SLP threshold to sort the TCs, we use the average SLP of all TCs within a specified distance per site. Herein we focus on the TCs with SLP lower than the site averages. At 100 km, all locations with the exception of Duck, NC have at least a third of all TCs resulting in storm surge exceeding the 0.5-year return level. Similar to before, three of the four most southern sites, including Charleston, SC, Fernandina Beach, FL, and Key West, FL have experienced more than 70 % of all TCs resulting in storm surge exceeding the 0.5-year return level (Fig. 6b). Since Duck, NC is the only location that sees a decrease in the probability of strong TCs exceeding the 0.5-year return level as distance decreases, we examined the tracks of these TCs within each distance of 500 km and 250 km (not shown). From this, we can conclude that this decrease in TC probability at Duck, NC cannot be explained by the TC track paths themselves as TCs within 250 km take similar paths as those within 500 km. Additionally, most of the TCs that move near Duck, NC do not pass over land and instead move parallel to the coastline or remain further out to sea.

While distance and the intensity of the TCs are important factors in predicting storm surge, we cannot ignore the role of the angle of the TC track relative to each location. While we have shown that some locations experience TCs from a specific range of angles (Fig. 4), that track can end up passing by a location in a different quadrant where, for example, a TC could pass to either the northwest or southeast of Charleston but have similar track path angles. In this scenario, one TC would track over land while the other TC would track over the open water. This difference could impact the structure of the TC, including its intensity and the direction that the winds are blowing, all of which might impact the magnitude of the storm surge. We consider this and examined TC locations and the intensity of the TC at the time of the surge maximum (not shown). However, there was no clear relationships among these variables but they do warrant further examination in future analysis of storm surge and TC characteristics.

4 Conclusion

This study used observations to examine the predictability of storm surge based on the following TC characteristics: the distance of the TC center from a site as well as its intensity, track path angle, and propagation speed. At each location along the east coast of the US, storm surge is influenced differently by these TC characteristics, with some locations more strongly influenced by TC intensity (e.g., New York, NY, Charleston, SC, and Key West, FL) and others more strongly influenced by the distance of the TC center to each site (e.g., Boston, MA, Cape May, NJ, and Sewell's Point, VA). All locations except Duck, NC see an increase in the correlation of the distance from the TC with storm surge once only strong TCs are considered.

When correlating TC characteristics with storm surge, all individual variables display a statistically significant low to moderate correlation, which indicates the complicated (i.e., statistically noisy) nature of relationships between the TCs and the surges they drive. This result reinforces the natural variability of TCs, such that each TC is unique in its shape, size, speed, and location. Thus, it is challenging to find a strong correlation between storm surge and TC characteristics. For most sites, the highest storm surge occurs when a TC is within 200 km of a site and the TC intensity is strong. This, at least, affirms the natural assumption that a TC that is both close to a site and strong has the greatest chance of resulting in strong storm surge. Related to this point: when comparing all TCs within 500 km to those TCs considered strong within 500 km, the correlation increased for all locations except Duck, NC. The site at Duck, NC is unique from the other locations because it is not near or in a bay or harbor. The track path angle and propagation speed contribute very little to the overall correlation among all variables for all sites.

When we consider all TCs that pass within 500 km of a site, the percentage of TCs that cause surge exceeding the 0.5-yr return level is between 7 % and 26 %, with the higher percentages at the more southern sites. For a 100 km search radius, the percentage of TCs generating storm surge exceeding the 0.5-yr return level are larger at nearly all sites. For sites in Florida, the percent increase is greatest, from 14 % to 26 %. For all other locations, the increase is between 2 % and 10 %. Interestingly, for Duck, NC, the percent of TCs creating surge exceeding the 0.5-yr return level is lower for the smaller search radius. We examined if this change was due to the smaller search radius leading to a larger fraction of the associated TCs being over land, and that is not the case. Nor is it the case that the distribution of track path angles for the smaller radius differ significantly from that for the larger radius. Thus, the difference is likely related to coastal orientation or chance.

If we consider only the strongest TCs, most sites see an increase in the probability of a 0.5-yr surge exceedance for a search radius of 500 km compared to 100 km. Duck, NC is again an exception, signifying that other variables must play a more important role in storm surge generation. For sites that are farther south, there is a greater likelihood that TCs that pass within a fixed distance of a site will generate storm surge that exceeds the 0.5-yr return level, which is consistent with the fact that TCs reach their maximum strength at lower latitudes.

Before starting this study, we hypothesized that (based on basic physics): TC intensity would have a strong relationship with storm surge, if we were able to isolate TC cases in which other cyclone characteristics were similar. Ultimately, we found that isolating “the same type” of TC is not simple. For the southernmost sites, the relationships are more obvious, and that is possibly due to the larger sample size. For the more northern sites, one might consider testing the hypothesis using numerical modelling, which to our knowledge, has not been done yet. For instance, one could model a single TC and synthetically change details of the storm. However, we want to emphasize that such an approach is very different from our work herein, because in the observations it is not possible to ensure that only one characteristic of a TC varies while all others remain constant.

While many studies have focused on the utilization of numerical models to understand the relationship between TC characteristics and storm surge, this study takes historical observations for 12 sites along the east coast of the US to assess the relationship between TC characteristics and storm surge. This type of analysis allows us to understand the current relationship between TC characteristics and storm surge so that this information can be applied to the understanding of how storm surge and subsequently, the characteristics of TCs, may change under a warming climate. While no single TC characteristic determines how much surge will be generated, this analysis does offer a unique perspective on the probabilities of surge events associated with all TCs rather than only those that cause extreme surge. This analysis, while limited to the east coast of the US, can easily be applied to any location with a record of surge observations.

Data Availability. Water level data that is used for the calculation of storm surge is publicly available and can be accessed at https://tidesandcurrents.noaa.gov/. Dataset of tropical cyclones is also publicly available and can be accessed at https://www.nhc.noaa.gov/data/.

Author contribution. KT wrote the manuscript with input from JB, ARE, and TW. JB downloaded data and calculated surge. KT completed data analysis and analyzed results with JB, ARE, and TW. JB provided code framework for cyclone association code. ARE provided code framework for calculation of return levels.

Competing interests. The authors declare that they have no conflict of interest.

Acknowledgements. This work was partially funded through NSF PREEVENTS award numbers 1854773 and 1854896.

References

Booth, J. F., Rieder, H. E., and Kushnir, Y.: Comparing hurricane extratropical storm surge for the Mid-Atlantic and Northeast coast of the United States from 1979-2013, Environ. Res. Lett., 11, 094004, doi:10.1088/1748-9326/11/9/094004, 2016.

Camelo, J., Mayo, T. L., and Gutmann, E. D.: Projected climate change impacts on hurricane storm surge inundation in the coastal United States, Front. Built Environ., 6, 588049, doi:10.3389/fbuil.2020.588049, 2020.

Catalano, A. J. and Broccoli, A. J.: Synoptic characteristics of surge-producing extratropical cyclones along the northeast coast of the United States, J. Appl. Meteorol. Clim., 57, 171–184, doi:10.1175/JAMC-D-17-0123.1, 2018.

Coles, S.: An introduction to statistical modelling of extreme values, Springer-Verlag London, 209 pp., doi:10.1007/978-1-4471-3675-0, 2001.

Colle, B. A., Rojowsky, K., and Buonaito, F.: New York City storm surges: Climatology and an analysis of the wind and cyclone evolution, J. Appl. Meteorol. Clim., 49, 85–100, 2010.

Familkhalili, R., Talke, S. A., and Jay, D. A.: Tide-storm surges interactions in highly altered estuaries: How channel deepening increases surge vulnerability, J. Geophys. Res-Oceans, 125, e2019JC015286, doi:10.1029/019JC015286, 2020.

Garner, A. J., Mann, M. E., Emanuel, K. A., Kopp, R. E., Lin, N., Alley, R. B., Horton, B. P., DeConto, R. M., Donnelly, J. P., and Pollard, D.: Impact of climate change on New York City's coastal flood hazard: Increasing flood heights from the preindustrial to 2300 CE, P. Natl. A. Sci. USA, 114, 11861–11866, doi:10.1073/pnas.1703568114, 2017.

Hall, T. M. and Sobel, A. H.: On the impact angle of Hurricane Sandy's New Jersey landfall, Geophys. Res. Lett., 40, 2312–2315, doi:10.1002/grl.50395, 2013.

Hallegatte, S., Green, C., Nicholls, R. J., and Corfee-Morlot, J.: Future flood losses in major coastal cities, Nat. Clim. Change, 3, 802–806, 2013.

Irish, J. L., Resio, D. T., and Ratcliff, J. J.: The influence of storm size on hurricane surge, J. Phys. Oceanogr., 38, 2003–2013, doi:10.1175/2008JPO3727.1, 2008.

Jones, S. C., Harr, P. A., Abraham, J., Bosart, L. F., Bowyer, P. J., Evans, J. L., Hanley, D. E., Hanstrum, B. N., Hart, R. E., Lalaurette, F., Sinclair, M. R., Smith, R. K., and Thorncroft, C.: The extratropical transition of tropical cyclones: Forecast challenges, current understanding, and future directions, Weather Forecast., 18, 1052–1092, 2003.

Knutson, T., Camargo, S. J., Chan, J. C. L., Emanuel, K., Ho, C-H., Kossin, J., Mohapatra, M., Satoh, M., Sugi, M., Walsh, K., Wu, L.: Tropical cyclones and climate change assessment: Part II: Projected response to anthropogenic warming, B. Am. Meteorol. Soc., 101, E303–E322, doi:10.1175/BAMS-D-18-0194.1, 2020.

Landsea, C. W. and Franklin, J. L.: Atlantic hurricane database uncertainty and presentation of a new database format, Mon. Weather Rev., 141, 3576–3592, doi:10.1175/MWR-D-12-00254.1, 2013.

Lin, N., Emanuel, K. A., Smith, J. A., and Vanmarcke, E.: Risk assessment of hurricane storm surge for New York City, J. Geophys. Res-Atmos, 115, D18121, doi:10.1029/2009JD013630, 2010.

Moftakhari, H. R., AghaKouchak A., Sanders, B. F., Feldman, D. L., Sweet, W., Matthew, R. A., and Luke, A.: Increased nuisance flooding along the coasts of the United States due to sea level rise: Past and future, Geophys. Res. Lett., 42, 9846 – 9852, 2015.

Needham, H. F. and Keim, B. D.: Correlating storm surge heights with tropical cyclone winds at and before landfall, Earth Interact., 18, 7, doi:10.1175/2013EI000527.1, 2014.

Needham, H. F., Keim, B. D., and Sathiaraj, D.: A review of tropical cyclone-generated storm surges: Global data sources, observations, and impacts, Rev. Geophys., 53, 545–591, doi:10.1002/2014RG000477, 2015.

NOAA: https://tidesandcurrents.noaa.gov/, last access: 31 May 2021.

Orton, P. M., Hall, T. M., Talke, S. A., Blumberg, A. F., Georgas, N., and Vinogradov, S.: A validated tropical-extratropical flood hazard assessment for New York Harbor, J. Geophys. Res-Oceans, 121, 8904 – 8929, doi: 10.1002/2016JC011679, 2016.

Rahmstorf, S.: Rising hazard of storm-surge flooding, P. Natl. A. Sci. USA, 114, 11806–11808, doi:10.1073/pnas.1715895114, 2017.

Rego, J. L. and Li, C.: Nonlinear terms in storm surge prediction: Effect of tide and shelf geometry with case study from Hurricane Rita, J. Geophys. Res., 115, C06020, doi:10.1029/2009JC005285, 2010.

Roberts, K. J., Colle, B. A., Georgas, N., and Munch, S. B.: A regression-based approach for cool-season storm surge predictions along the New York-New Jersey coast, J. Appl. Meteorol. Clim., 54, 1773–1791, doi:10.1175/JAMC-D-14-0314.1, 2015.

Sobel, A. H., Camargo, S. J., Hall, T. M., Lee, C-Y., Tippett, M. K., and Wing, A. A.: Human influence on tropical cyclone intensity, Science, 353, 242–246, doi:10.1126/science.aaf6574, 2016.

Strauss, B. H., Ziemlinski R., Weiss, J. L., and Overpeck, J. T.: Tidally adjusted estimates of topographic vulnerability to sea level rise and flooding for the contiguous United States, Environ. Res. Lett., 7, 014033, doi:10.1088/1748-9326/7/1/014033, 2012.

Sweet, W. V. and Park, J.: From the extreme to the mean: Acceleration and tipping points of coastal inundation from sea level rise, Earth's Future, 2, 579–600, doi:10.1002/2014EF000272, 2014.

Talke, S. A., Orton, P. M., and Jay, D. A.: Increasing storm tides in New York Harbor, 1844-2013, Geophys. Res. Lett., 41, doi:10.1002/2014GL059574, 2014.

Tebaldi, C., Strauss, B. H., and Zervas, C. E.: Modelling sea level rise impacts on storm surges along US coasts, Environ. Res. Lett., 7, 014032, doi:10.1088/1748-9326/7/1/014032, 2012.

Wahl, T., Haigh, I. D., Nicholls, R. J., Arns, A., Dangendorf, S., Hinkel, J., and Slangen, A. B. A.: Understanding extreme sea levels for broad-scale coastal impact and adaptation analysis, Nat. Commun., 8, 16075, doi:10.1038/ncomms16075, 2017.

Weaver, R. and Slinn, D. N.: Influence of bathymetric fluctuations on coastal storm surge, Coast. Eng., 57, 62–70, doi:10.1016/j.coastaleng.2009.09.012, 2010.

Yanase, W. and Niino, H., Idealized numerical experiments on cyclone development in the tropical, subtropical, and extratropical environments, J. Atmos. Sci., 72, 3699–3714, 2015.

Zhang, K., Douglas, B. C., and Leatherman, S. P.: Twentieth-century storm activity along the U.S. east coast, J. Climate, 13, 1748–1761, 2000.