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Increasing Storm Tides in New York Harbor, 1844–2013

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Key Points:
- Significant change in storm tide magnitudes have occurred in NY since 1840s
- Interannual variability in storm tides is anticorrelated with NAO index
- Including MSL rise, a 0.72 ± 0.2 m increase in 10 year flood level is estimated

Supporting Information:
- Readme
- Text S1
- Table S1
- Table S2

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Increasing storm tides in New York Harbor, 1844–2013

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Abstract Three of the nine highest recorded water levels in the New York Harbor region have occurred since 2010 (March 2010, August 2011, and October 2012), and eight of the largest twenty have occurred since 1990. To investigate whether this cluster of high waters is a random occurrence or indicative of intensified storm tides, we recover archival tide gauge data back to 1844 and evaluate the trajectory of the annual maximum storm tide. Approximately half of long-term variance is anticorrelated with decadal-scale variations in the North Atlantic Oscillation, while long-term trends explain the remainder. The 10 year storm tide has increased by 0.28 m. Combined with a 0.44 m increase in local sea level since 1856, the 10 year flood level has increased by approximately 0.72 ± 0.25 m, and magnified the annual probability of overtopping the typical Manhattan seawall from less than 1% to about 20–25%.

1. Introduction

The return period of future flooding in New York Harbor (NYH) is a subject of ongoing scientific and practical debate, particularly since portions of the seawall in southern Manhattan are only 1.25–1.75 m above mean sea level (MSL, 1983–2001 epoch) [*Colle et al.*, 2008]. The effect of sea level rise (SLR) on coastal flooding is well established [*Colle et al.*, 2010; *Kemp and Horton*, 2013; *Sweet et al.*, 2013] and helps to explain why eight of the largest 20 extreme water levels since 1927 have occurred since 1990. An additional SLR of 1 m would cause the current 100 year flood event to occur every 20 years [*Lin et al.*, 2012]. However, changes in storm climate and climate variability may also contribute to nonstationary coastal flood heights. *Holland and Webster* [2007] suggest an increase in hurricane frequency since the 1850s, though under-detection of historical events may explain this apparent signal [*Landsea et al.*, 2010]. Along the U.S. Eastern Seaboard and Gulf Coast, *Grinsted et al.* [2012] found that storm surge magnitude is correlated with air temperature anomalies and has increased since 1923. More locally, *Lin et al.* [2012] argued that future coastal storm climatology would alter NYH flood levels, increasing flood risk faster than SLR alone. In addition, variations in the atmospheric pressure gradient between the Azores and Iceland (the North Atlantic Oscillation, or NAO) and other atmospheric processes influence storm tracks and may also affect storm surge heights [*Rogers*, 1990; *Bernhardt and DeGaetano*, 2012].

Local changes in bathymetry and ecosystems may also alter storm tides in the inland tidal waterways surrounding NYH. About 85% of NYH wetlands have been lost [*City of New York*, 2012], human structures have hardened the coastline, and shipping channels have been deepened and widened since the 1850s [*Marmer*, 1935]. In other estuaries, such modifications have sometimes led to increased tidal range due to reduced friction and altered resonance properties [*Amin*, 1983; *Chernetsky et al.*, 2010]. Since storm surges (like tides) are shallow-water waves, altered friction and resonance likely impact storm tides in similar ways, though frequency-dependent effects may also occur.

Previous studies have used monthly summaries of pre-1925 NYH mean sea level (MSL) [e.g., *Kemp and Horton*, 2013], but the original hourly sea level data used to calculate these MSLs have long been unavailable. *Talke and Jay* [2013] rediscovered these and many other nineteenth century records in the U.S. National Archives. Here, we recover and digitize selected NYH archival tide data, thereby doubling the length of the local tidal record. We then assess the long-term trajectory of New York storm tide hazard by (a) assembling and statistically evaluating a data set of peak NYH annual water levels, 1844–2013 and (b) determining return intervals and storm tide trends using a generalized extreme value (GEV) analysis.

2. Methods

Tide gauges have operated nearly continuously in NYH since 1844, with self-registering gauges used since 1853 (Figure 1) [*Talke and Jay*, 2013]. However, most pre-1927 data are only available as paper tabulations at

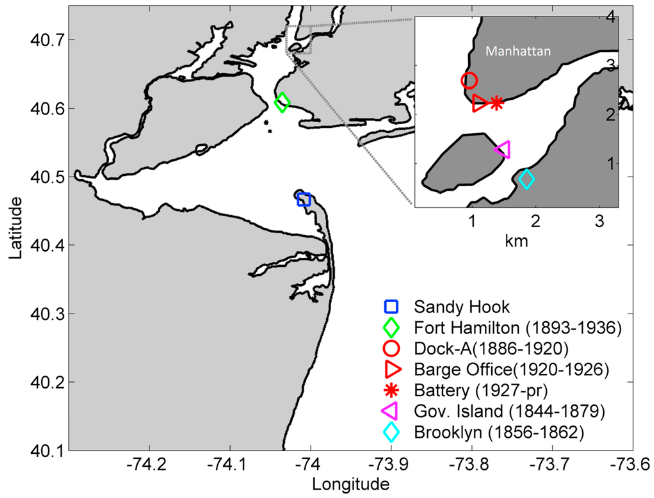

Figure 1. Locations of tide gauges around New York Harbor; the data are described in the methods section and the supplement.

the U.S. National Archives. For this analysis, we have recovered and digitized hourly or high/low data from Governors Island (1844–1872; 1874–1879; 1885), the Hamilton Ferry Dock in Brooklyn (1855–1862), Sandy Hook, NJ (1873; 1876–1885, 1888–1893), and Fort Hamilton, NY (1893–1926). Annual extreme values from Dock-A near Battery Park (Manhattan) (1886–1920) and the "Barge Office" pier at Battery Park (1920–1926) were obtained from *Schureman* [1934]. Hourly data from the Battery (1920–1921 and 1927–2012) and Sandy Hook (1910–1918, 1932–2012) were obtained from the National Oceanographic and Atmospheric Administration (NOAA).

Data were quality assured by inspection, by comparison with other gauges (when possible), by differencing (to remove spurious spikes), and by checking tidal constituents via tidal harmonic analysis (see supporting information for details of the measurements, processing, accuracy, and quality assurance). The 1844–2013 data are ~92% complete; the modern Battery (post-1927) data are 97% complete. To cross check results and identify possibly missed storm events, the *New York Times* archives from 1851 to 1890 were searched monthly using keywords, resulting in the identification of three additional annual maximum storm tide (AMST) values (November 1865, January 1867, and March 1873). Data before 1856 have a larger uncertainty than later observations (Figure 2a; supporting information).

AMST values were obtained by identifying annual peak values in hourly or high/low data and subtracting the annual mean, such that AMSTs are primarily the sum of the astronomical tide and meteorological storm surge. The multiple data sources were compiled into a continuous data set in which 157 out of 170 AMST values were obtained from within a 2 km radius of the Battery tide gauge (Figure 1). The remaining AMST values were obtained from the Sandy Hook gauge after applying a bias correction of −0.052 m, defined from the median difference in AMST values between Sandy Hook and The Battery from 1911 to the present (81 coincident values, $\sigma = 0.058$ m). Other sources of bias were minimized by extensive quality assurance of individual events and comparisons between gauges (see supporting information, sections S2 and S4). For example, the mean difference in AMST between Fort Hamilton and The Battery between 1893 and 1932 was <0.01 m, such that the stations are interchangeable. We therefore average the Fort Hamilton and Battery AMST extremes from 1893 to 1926 (see supporting information). The AMST values from nearby gauges are similar because long-wave attenuation in New York Harbor is small, as also observed in the tides. For example, the nodally corrected M_2 tidal constituent amplitudes are 0.68 and 0.66 m at Sandy Hook and The Battery, respectively. We also define a shorter time series of annual maximum storm surge (AMSS) from available hourly data (1860–1885; 1889–1921; and 1927 to the present), where storm surge is defined as the water level signal which remains after subtracting out MSL and the predicted tide.

Storm tide return periods are modeled by a generalized extreme value (GEV) probability distribution fitted using a maximum likelihood estimation method [*Kotz and Nadarajah*, 2000; *Sweet et al.*, 2013]. To assess possible secular (century-scale) trends in storm tides, we analyze the AMST data in annually incremented, sequential 37 year blocks. This time period was chosen to minimize the effects of the 18.61 year tidal nodal cycle and nonstationarity [*Menéndez and Woodworth*, 2010], yet retain enough data to obtain robust estimates of the once in 5 years and once in 10 years storm tide level. Over this time scale, data sets of storm tides with MSL removed show only residual nonstationary effects [*Menéndez and Woodworth*, 2010]. A similar analysis is performed on AMSS. For annually incremented blocks of 36 years, we also estimate the 25%, 50%, and 75% quartiles by ordering AMST values from smallest to largest and identifying the 9th, 18th, and 27th values. These values are designated the lower quartile threshold (LQT), the median, and the upper quartile

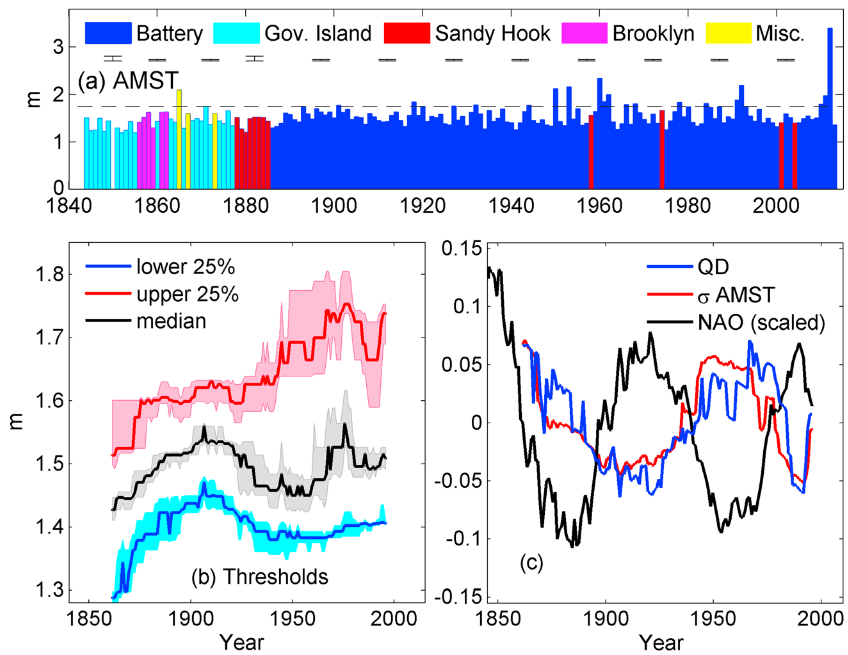

Figure 2. (a) Annual Maximum Storm Tide from gauges around the New York Harbor area; (b) the 25%, 50%, and 75% quartile AMST over a 36 year period and (c) the detrended quartile difference (QD) and detrended standard deviation of AMST versus the annual NAO index, scaled by one fourth for presentation purposes. The shaded areas in Figure 2b denote the bounds of the 20–30%, the 45–55%, and 70–80% thresholds and provide an estimate of statistical variability. The error bars in Figure 2a denote the estimated precision, and the dashed horizontal line depicts the 1.75 m AMST threshold.

threshold (UQT). Results are compared to the standard deviation of AMST and to the annual (NAO) index, compiled using weather station data from 1844 to 1899 and a principal component analysis from 1899 to 2013 [*Jones et al.*, 1997; *Hurrell and Deser*, 2009; *Hurrell and National Center for Atmospheric Research Staff*, 2013; see supporting information]. To enable comparison with the quartile data, the composite NAO index was low-pass filtered with a 36 year moving average. Correlation coefficients and significance values between quartile statistics and the NAO were obtained by a bootstrapping technique which subsampled independent portions of the filtered data sets (see supporting information).

2.1. Long-Term Trends and Decadal Variability in Storm Tides

Our reconstruction suggests that annual maximum storm tides in NYH contain both multidecadal variability and a secular trend in each quartile (Figure 2). The lower quartile threshold (LQT) increased by nearly 0.1 m between the 36 year periods centered at 1862 and 1995 (Figure 2b), while the upper quartile threshold (UQT) outpaced the median and increased from ~1.5 m to ~1.7 m over the same period. The upper and lower quartile trends track each other until the 1920s, after which the UQT rises more rapidly. A periodicity is also apparent in the data: peaks in the UQT and median around 1900 and 1970 are buttressed by minima in the 1920s and 1986–1991 (Figure 2b). A similar decrease in storm surge activity between the 1960s and 1990 has previously been observed [*Colle et al.*, 2010]. The difference (spread) between the LQT and UQT varies from 0.15 to 0.36 m, with an approximately 60–80 year periodicity. Similarly, the standard deviation of each 36 year period varies cyclically from 0.1 m (around 1900) to ~0.23 m from 1947 to 1967 (see supporting information). The observed statistics are not biased by precision errors, which are small (± 0.02 m) relative to secular and decadal variations over most periods (Figure 2a and supporting information). The shaded regions in Figure 2b show the 20%–30%, the 45%–55%, and 70%–80% quantiles and denote the possible variation in statistics that would occur if several AMST data were severely biased.

To investigate decadal variability (and minimize any residual bias), we subtract the LQT from the UQT, after removing the linear trend apparent in both quartiles between 1850 and 2000. The resulting quartile difference (QD; Figure 2c) exhibits a 60–80 year periodicity in which the AMSTs are tightly distributed during some periods (1900–1920 and early 1990s), with other periods exhibiting larger variability and elevated

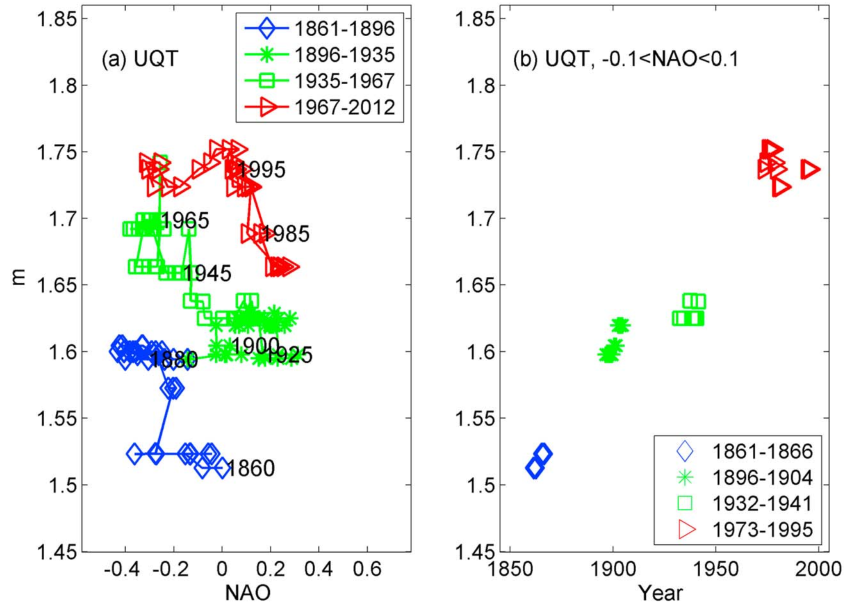

Figure 3. (a) The upper quartile threshold (UQT) versus NAO index and (b) the UQT versus time for conditionally sampled data ($-0.1 < \text{NAO} < 0.1$).

storm risk (e.g., 1950s and 1960s). The detrended standard deviation of AMST (after removing the largest and smallest outlier) closely follows the QD, confirming that the QD is a measure of variability (Figure 2c). Compared to the QD, the standard deviation is likely more biased by outliers.

A portion of decadal AMST variability may be forced by long-term shifts in the NAO index, which is anticorrelated with long-term variability in AMST (Figure 2c). During periods of positive NAO index, the QD is small, whereas negative NAO values produce the largest interannual variability. Using data from the 1856 to 2013 period (when tide data are more reliable), the bootstrapped correlation coefficient between the NAO index and the QD is a mean (median) value of $R = -0.92$ (-0.97), with a mean and median p value 0.076 and 0.032, respectively. Including 1844–1855 data results in a weaker correlation (median $R = -0.81$, p value < 0.2), possibly suggesting issues with early AMST or NAO data. The detrended standard deviation of AMST is also anticorrelated with the NAO (median $R = -0.81$, p value <0.2, 1844–2013). The limited degrees of freedom in the data preclude obtaining statistically significant correlations for the detrended UQT ($R = -0.71$, $p = 0.28$) and LQT ($R = 0.77$, $p = 0.23$). Nonetheless, the QD/NAO correlation suggests that of the 0.2 m long-term variability in QD (Figure 2b), approximately half (0.1 m) is being driven by long-term climatic processes over the Atlantic Ocean (Figure 2c).

The other half of long-term variability in QD appears to be driven by secular trends. Scatterplots of the upper quartile threshold versus the NAO index show that natural variability and long-term shifts in AMST separate into three distinct periods: pre-1896; 1896–1966, and 1967–2013. During each period, the UQT and the NAO index are approximately linearly related with slopes between -0.1 and -0.2 m per NAO index point. These excursions occur simultaneously with a long-term increase in AMST, which is highlighted by conditionally sampling the UQT for neutral NAO conditions of $-0.1 < \text{NAO} < 0.1$ (Figure 3b). The UQT increases approximately linearly by ~0.22 ± 0.02 m, from 1.52 ± 0.01 m for 1861–1866 to 1.74 ± 0.01 m for 1974–1995. This result confirms that a secular trend in large storm tides has occurred since the midnineteenth century, independent of natural variability.

Results of the sequential, overlapping GEV analyses show that the magnitude of the 10 year AMST (event with a return period of 10 years) increased from 1.68 ± 0.07 m in the midnineteenth century to 1.96 m ± 0.14 m at present. Similarly, the magnitude of the 10 year annual maximum storm surge (AMSS) has increased from 1.27 ± 0.05 m to 1.62 ± 0.15 m (see supporting information). Three AMST have exceeded the 1.96 m threshold since 1990, and seven since 1950 (Figure 2a), qualitatively corroborating the AMST return period estimate (Figure 4a). Decadal variability is prominent: a period with an elevated AMST hazard occurred from roughly

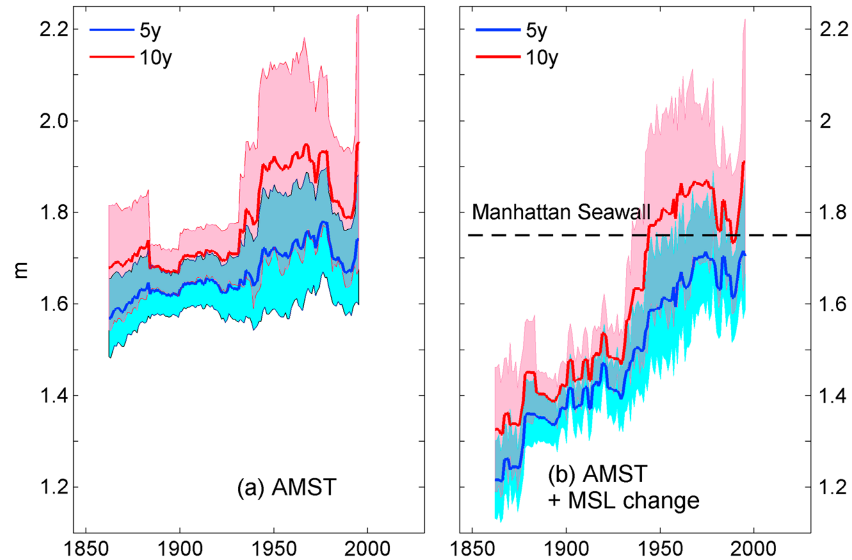

Figure 4. (a) The 5 year and 10 year return period of AMST as a function of time and (b) the 5 and 10 year storm tide elevation, with the effect of sea level rise included. Heights in Figure 4b are referred to the NOAA MSL datum at The Battery, defined using the 1983–2001 tidal epoch. The 95% (2σ) confidence interval is shown by the shaded region for AMST.

1945 to 1975, coinciding with the negative NAO phase, while a minimum in the storm tide hazard occurred in the 37 year period centered around 1990. Comparatively smaller fluctuations in risk are observed pre-1920.

Including the 0.44 ± 0.04 m of relative MSL rise since the 1850s, the flood level for a 10 year return period event has increased by ~0.72 ± 0.25 m (Figure 4b). Similarly, the 5 year flood level has increased by 0.6 ± 0.15 m (Figure 4b). We next assess the probability of overtopping the southern Manhattan seawall, which, following *Colle et al*. [2008], we define to be 1.75 m above the NOAA MSL datum (1983–2001 epoch). The AMST climatology of the midnineteenth century would exceed the Manhattan seawall approximately once every 10 years if it occurred at MSL 2009–2013 (10% annual probability), versus about once every 4–5 years using present-day AMST data (20–25% annual probability). Considering the much lower nineteenth century MSL, the nineteenth century probability of overtopping the modern seawall level (1.75 m) was 0.25 to 1%, annually. Results therefore conservatively suggest that the probability of overtopping the seawall has increased by more than twentyfold.

2.2. Relationship of AMST to Local and Climate Factors

Shifts in storm magnitude, storm track, storm timing (relative to tidal phase), tidal range, and relative sea level can all lead to larger AMST. Previous studies have found that the NAO affects the storm track of both winter and summer storms along the U.S. East Coast [*Rogers*, 1990]. A negative NAO increases North Atlantic blocking [*Shabbar et al*., 2001], which can increase the frequency of coastal storms in the U.S. northeast [*Rogers*, 1990; *Thompson and Wallace*, 2001]. *Elsner* [2003] and *Xie et al*. [2005] found that hurricanes made landfall south of 35°N and 50°N, respectively, during negative NAO conditions, but tracked further north or recurved out to sea during positive NAO conditions. NAO-induced fluctuations in sea level can also affect extremes [*Menéndez and Woodworth*, 2010]. Such observations may help explain our observed NAO/AMST correlation, though analysis of individual events is needed to fully understand the mechanisms. Interestingly, the Arctic Oscillation, which is closely related to NAO [*Ambaum et al*., 2001], is also anticorrelated with our AMST record (see supporting information). Other atmospheric processes may influence storm tides: *Bernhardt and DeGaetano* [2012] found that winter storms moved more slowly during periods in which a negative NAO coincided with an El Niño event, producing higher mean storm surge at the NY/NJ coast. Other studies have previously linked El Niño with greater occurrences of storm surge [*Colle et al*., 2010; *Sweet and Zervas*, 2011], though we find no statistically significant decadal-scale correlation with AMST statistics (see supporting information).

Long-term variability in the NAO may also help explain the relatively small AMSTs measured during the midnineteenth century. Anecdotal evidence supports the idea of a midnineteenth century lull in storm tides.

Ludlam [1963] reports that the 1861 "Expedition Hurricane," a relatively small 1.62 m storm tide, was the largest event since 1833. Similarly, the 21 November 1865 event of ~2.1 m was the largest storm tide since 1821 (*New York Times*, 21 November 1865; 22 March 1871).

Hence, available quantitative and qualitative data confirm that the storm tide produced by Hurricane Sandy was the largest since at least 1821. The Sandy storm tide of nearly 3.4 m above MSL 2012 was more than 1 m larger than the Hurricane Donna storm tide in 1960, the next largest event since 1844, and was ~1.8 m larger than the 1.6 m hurricane storm tide on 24 August 1893 (see supporting information). The 1893 measurement is much less than the 3.0 ± 0.5 m storm tide estimated by *Scileppi and Donnelly* [2007], though a larger storm surge may have occurred further east on Long Island. Nonetheless, careful reevaluation of pre-1844 proxy estimates is warranted, particularly since inclusion of the large storm tides in 1821 (2.6–3.6 m) and 1788 (2.4–3.4 m) [*Kussman*, 1957; *Scileppi and Donnelly*, 2007] would greatly decrease return-period estimates of a Sandy-magnitude return interval [*Sweet et al*., 2013]. Due to the uncertainty in the pre-1844 extreme events, we refrain from estimating a Sandy return period. The century-scale trends evident in AMST (Figures 2 and 3) also suggest that nonstationary statistical analysis is required for analysis of long (>50 years) data sets, to avoid underestimating present-day risk. In particular, given the relatively small AMSTs in the midnineteenth century, the 1821 and 1788 events appear to have been larger outliers than modern conditions would suggest.

Multiple factors may have contributed to the secular shift in storm tides over the past two centuries. Climate change and increasing global temperatures may have contributed to changing storm tides, particularly since the 1970s and 1980s [*Grinsted et al*., 2012]. A local, anthropogenic contribution to altered storm surge dynamics is also plausible, since tidal dynamics have also shifted: tidal constituents in NYH exhibit small but noticeable nonastronomic variability over time [*Marmer*, 1935; *Woodworth*, 2010, supporting information], possibly due to changed frictional properties and channel depth.

3. Summary

In summary, a 170 year record of AMST has allowed us to separate secular shifts in storm risk from the 60 to 80 year NAO cycle. During periods with negative NAO conditions, interannual variability in the AMST record is larger, leading to an enhanced probability of extreme events. Since the midnineteenth century, interannual variability has increased, and the upper quartile of storm tides has become larger. Together with MSL rise, these factors have led to a 0.72 m ± 0.25 m increase in the 10 year flood level. Our analysis therefore suggests that Hurricane Sandy occurred against a backdrop of increasing storm tides. Determining the relative contributions of climate and local changes, and obtaining a better understanding of the 1821 and 1788 events, is required to improve our understanding of the evolving NYH storm risk.

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