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Rapid Communication

Contribution of relative sea-level rise to historical hurricane flooding in New York City

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ABSTRACT: Flooding during hurricanes is a hazard for New York City. Flood height is determined by storm surge characteristics, timing (high or low tide) and relative sea-level (RSL) change. The contribution from these factors is estimated for seven historical hurricanes (1788–2012) that caused flooding in New York City. Measurements from The Battery tide gauge and historical accounts are supplemented with a RSL reconstruction from Barnegat Bay, New Jersey. RSL was reconstructed from foraminifera preserved in salt-marsh sediment that was dated using marker horizons of lead and copper pollution and ^{137}Cs activity. Between the 1788 hurricane and Hurricane Sandy in 2012, RSL rose by 56 cm, including 15 cm from glacio-isostatic adjustment. Storm surge characteristics and timing with respect to astronomical tides remain the dominant factors in determining flood height. However, RSL rise will raise the base level for flood heights in New York City and exacerbate flooding caused by future hurricanes.

KEYWORDS: Hurricane Sandy; New Jersey; salt marsh; storm surge; tide gauge.

Introduction

Flooding during hurricanes is a hazard and economic burden to New York City (Coch, 1994; Gornitz *et al.*, 2001; Colle *et al.*, 2008). In October 2012, Hurricane Sandy caused an estimated $50 billion of damage, making it the second-costliest hurricane (after Katrina in 2005) to hit the United States (Blake *et al.*, 2013). In New York City, coastal New Jersey, and elsewhere along the US north-east Atlantic coast, this damage was caused predominantly by flooding. Notable historical flooding from hurricanes in New York City also occurred in 1985 (Hurricane Gloria), 1960 (Hurricane Donna), 1938, 1893, 1821, and 1788 (unnamed; Coch, 1994; Scileppi and Donnelly, 2007).

The height of flooding attained during a hurricane is the product of storm-surge height, timing in the astronomical tidal cycle and relative sea-level (RSL) change. Storm-surge height is unique to each hurricane, being governed by meteorological conditions and coastal geomorphology (Irish *et al.*, 2008; Lin *et al.*, 2010). Worse flooding occurs when a hurricane's impact is coincident with higher tides. Conversely, lower tides provide vertical space to accommodate a storm surge and to lessen, or prevent, flooding. RSL changes through time and is ultimately the base level on which astronomical tides and storm surges are superimposed. Consequently, the flood height reached at a particular location in New York City (e.g. a building or landmark) during one hurricane compared with another is partly attributed to RSL change. In the 21st century, RSL rise will impact New York City by augmenting the height of storm surges and tides (Bindoff *et al.*, 2007; Yin *et al.*, 2009).

The contribution of RSL change to flooding in New York City during Hurricane Sandy compared with earlier historical events is unknown. We reconstruct RSL for the past $\sim$230 years from salt-marsh sediment in northern New Jersey and show that RSL rose by 56 ± 4 cm between the 1788 hurricane and Hurricane Sandy in 2012. Ongoing glacio-isostatic adjustment accounted for an estimated 15 cm of this change. These results demonstrate that future RSL rise will add to flood heights attained during hurricanes, but that variability among storm surges and timing remain the dominant controls on flooding in New York City.

Historical hurricane flooding in New York City

The National Hurricane Center defines a storm tide as the water level reached from the combined effects of astronomical tides and storm surge and expressed relative to a contemporary tidal datum. Storm-surge height at a tide gauge is the difference between the observed water level and the predicted astronomical tide for that time. Tide level reflects the daily rising and falling of the tides and also position in the astronomical cycle of spring and neap tides. Great diurnal tidal range at The Battery tide gauge in New York City is currently 1.54 m. Wave heights are excluded from these definitions because they are filtered out by tide-gauge measurements. RSL is the height of the ocean surface relative to the land at a given location, where zero commonly refers to present (Shennan *et al.*, 2012). It is what an observer on a coast would experience and the net effect of many processes acting simultaneously, including glacio-isostatic adjustment. RSL rise between hurricanes raises the base level on which tides and storm surges are superimposed.

The digitized instrumental record of individual hurricane flooding events in New York City is available from the National Ocean Survey since 1920, although archival data from as early as 1835 exist (Talke and Jay, 2013). Tide-gauge data from The Battery on the southern tip of Manhattan (Fig. 1) show that Hurricane Sandy (October 2012) generated a 2.81-m storm surge that occurred with a high astronomical tide (0.67 m above mean tide level; MTL) resulting in a storm tide of 3.48 m MTL (Fig. 2). The King's Point tide gauge in

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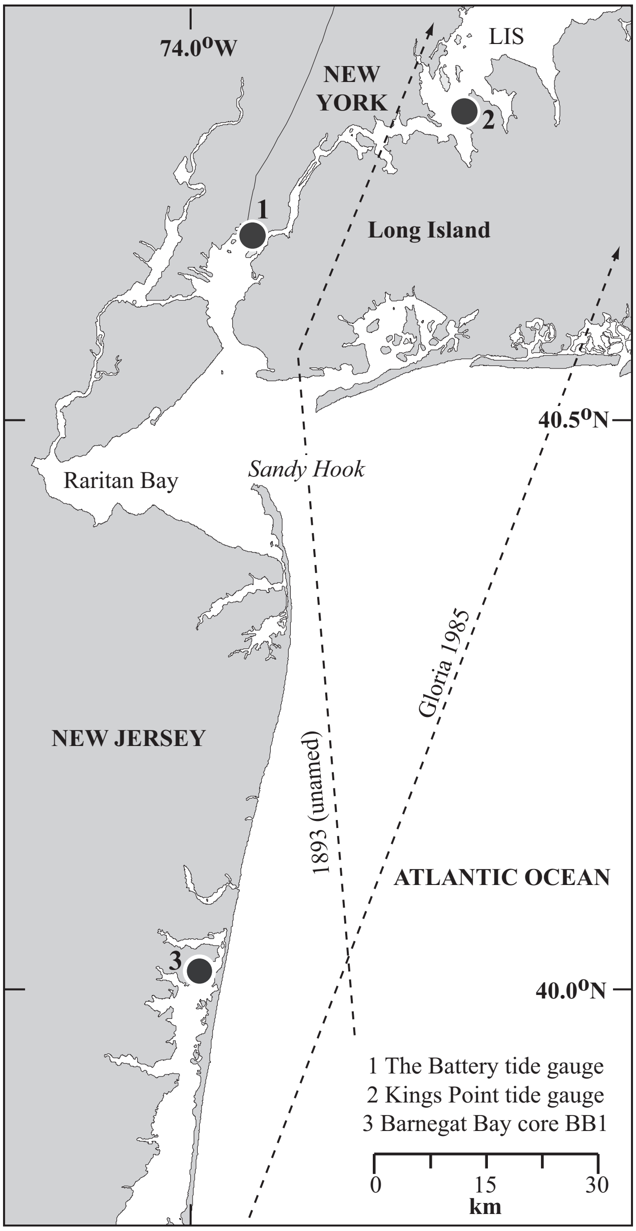

Figure 1. Location of The Battery tide gauge (1) and the Barnegat Bay core (BB1) used to reconstruct relative sea level (3). The two locations are ~75 km apart. The Kings Point tide gauge is located in Queens (2) and measures water level in Long Island Sound (LIS). Tracks of study hurricanes that passed within 75 km of New York City are shown.

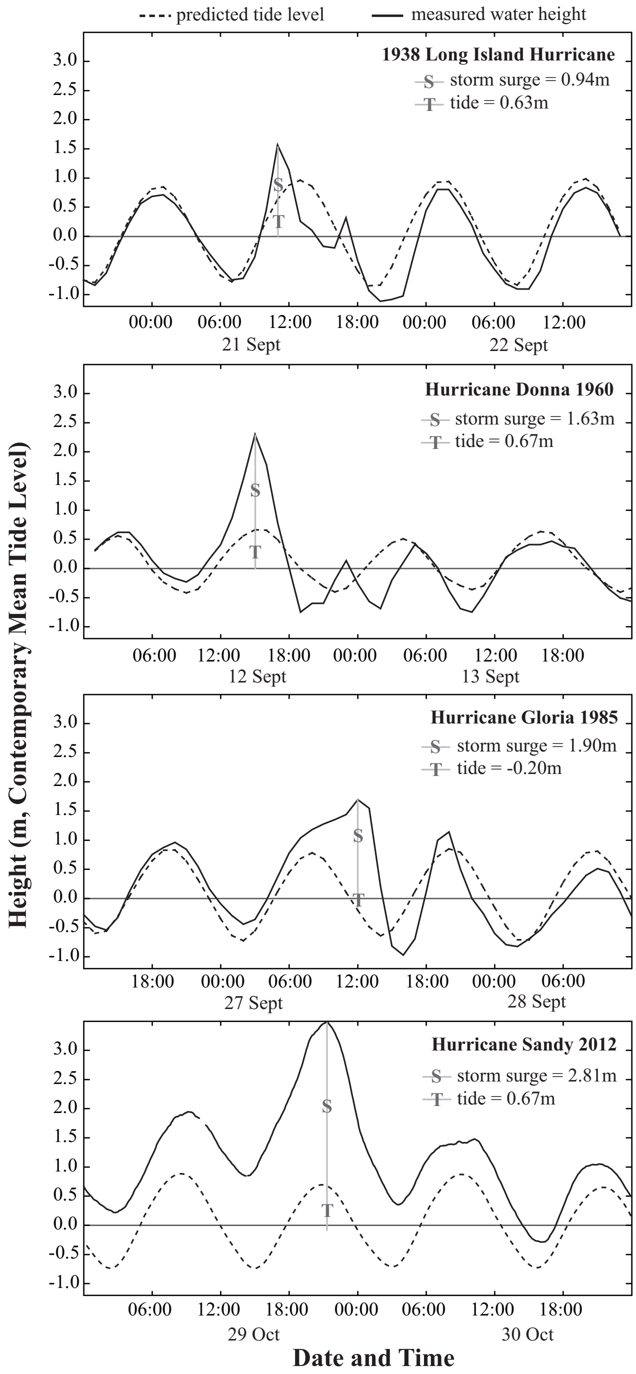

Figure 2. Measured water levels (solid lines) during historical hurricanes at The Battery tide gauge in New York City and expressed relative to contemporary mean tide level (MTL). Storm tide is the peak water level measured during each hurricane. Verified water-level measurements are at hourly intervals for the 1938, 1960 and 1985 hurricanes and at 6-min intervals for Sandy in 2012. True maximum storm tide may have occurred between measurements. Predicted tides are assumed to represent actual astronomical tides (dashed line) and water levels in excess of this are treated as the estimate of storm-surge height. Tides below MTL are treated as making a negative contribution to the storm tide. Data from NOAA Tides and Currents.

Queens (Fig. 1) recorded a 2.61-m storm surge and an astronomical tide of 0.58 m MTL to produce a storm tide of 3.19 m MTL in Long Island Sound. In September 1985, Hurricane Gloria generated a storm tide of 1.70 m MTL that comprised a 1.90-m storm surge and an astronomical tide of −0.20 m MTL (Fig. 2). In September 1960, Hurricane Donna's storm tide was 2.30 m MTL, including a 1.63-m storm surge and an astronomical tide of 0.67 m MTL. During the 1938 New England Hurricane, the storm tide at The Battery was 1.57 m MTL, comprising a 0.94-m storm surge and an astronomical tide of 0.63 m MTL.

In the historical but pre-instrumental period, hurricanes caused significant flooding in New York City in 1893, 1821 and 1788 (Coch, 1994; Scileppi and Donnelly, 2007). The absence of available tidal data for this period prevents distinguishing between the contributions of the storm surge and astronomical tides. *The New York Times* reported that half a mile of '"the Boulevard"' was submerged in Astoria, Queens, during the 1893 hurricane. Scileppi and Donnelly (2007) interpret that the 1893 storm tide was ~3.0 m MTL based on the lowest elevation along Vernon Boulevard. The 1821 hurricane had a storm tide estimated to be ~3.2 m MTL in lower Manhattan (Ludlum, 1963; Scileppi and Donnelly, 2007). William C. Redfield noted that the hurricane struck at low tide and water levels in New York City rose 3.96 m in 1 h (Ludlum, 1963). Redfield's 'Compilation of Storms (1494–1859)' and daily 'Meterological Journal (1831–1861)' held in the Yale University Meteorological Archive do not list the source of these flood-height data. Historical accounts of the 1788 hurricane state that the cellars on Front and Water Streets in Manhattan were flooded (Ludlum, 1963). Scileppi and Donnelly (2007) estimate that the 1788 storm tide was ~3.0 m MTL.

RSL history of New York City

Annual RSL estimates at The Battery tide gauge are available from the National Oceanic and Atmospheric Administration (NOAA) since 1853 with only 15 years missing (Fig. 3C). To estimate the contribution of RSL rise to hurricane flooding during the missing years and before 1853 we reconstructed RSL using a core (BB1) of salt-marsh sediment from Barnegat Bay in northern New Jersey (Fig. 3C). The site is ~75 km from The Battery (Fig. 1) and is assumed to record the same RSL history. A site closer to New York City with suitable tidal and sedimentary conditions for reconstructing RSL with sufficient resolution to make meaningful comparisons with the instrumental record was not available. Under a regime of gradually rising sea level salt marshes accumulate sediment to maintain a position in the tidal frame (Morris *et al.*, 2002). The resulting accumulations of salt-marsh sediment are archives of RSL change. Foraminifera preserved in the core were employed as sea-level indicators as the modern distribution of assemblages in New Jersey is closely linked to tidal elevation allowing accurate and precise RSL reconstruction (Kemp *et al.*, 2013). We developed a transfer function from modern samples collected at 12 sites in New Jersey that was applied to assemblages of foraminifera preserved in 1-cm-thick samples from BB1 to reconstruct the elevation at which each sample formed (palaeomarsh elevation; PME). RSL was reconstructed by subtracting transfer-function-derived estimates of PME from measured sample altitudes, meaning zero RSL occurred in 2010. For conveniently comparing historical storms we later specify zero RSL to be 1788. The transfer function estimated an uncertainty ($\sim 1\sigma$) for each reconstruction that was approximately ± 14% of tidal range, equating to ± 2.5 cm assuming a constant microtidal regime at Barnegat Bay (17 cm great diurnal range; Horton *et al.*, 2013). Details of the transfer function and its application to core BB1 to reconstruct PME are presented in Kemp *et al.* (2013).

The core was dated using chronological markers. Downcore changes in lead concentration and the ratio of stable lead isotopes (^{206}Pb:^{207}Pb) were related to historical patterns of lead production in the US and Upper Mississippi Valley, respectively (Kemp *et al.*, 2012, 2013). Maximum ^{137}Cs activity marks the peak of above-ground testing of nuclear weapons in 1963. We added an additional marker to the existing Kemp *et al.* (2012) chronology by recognizing the onset of copper pollution at 25 cm and corresponding to 1890–1910 (Fig. 3A). A new age–depth model was developed for BB1 using Bchron (Parnell *et al.*, 2008) incorporating all

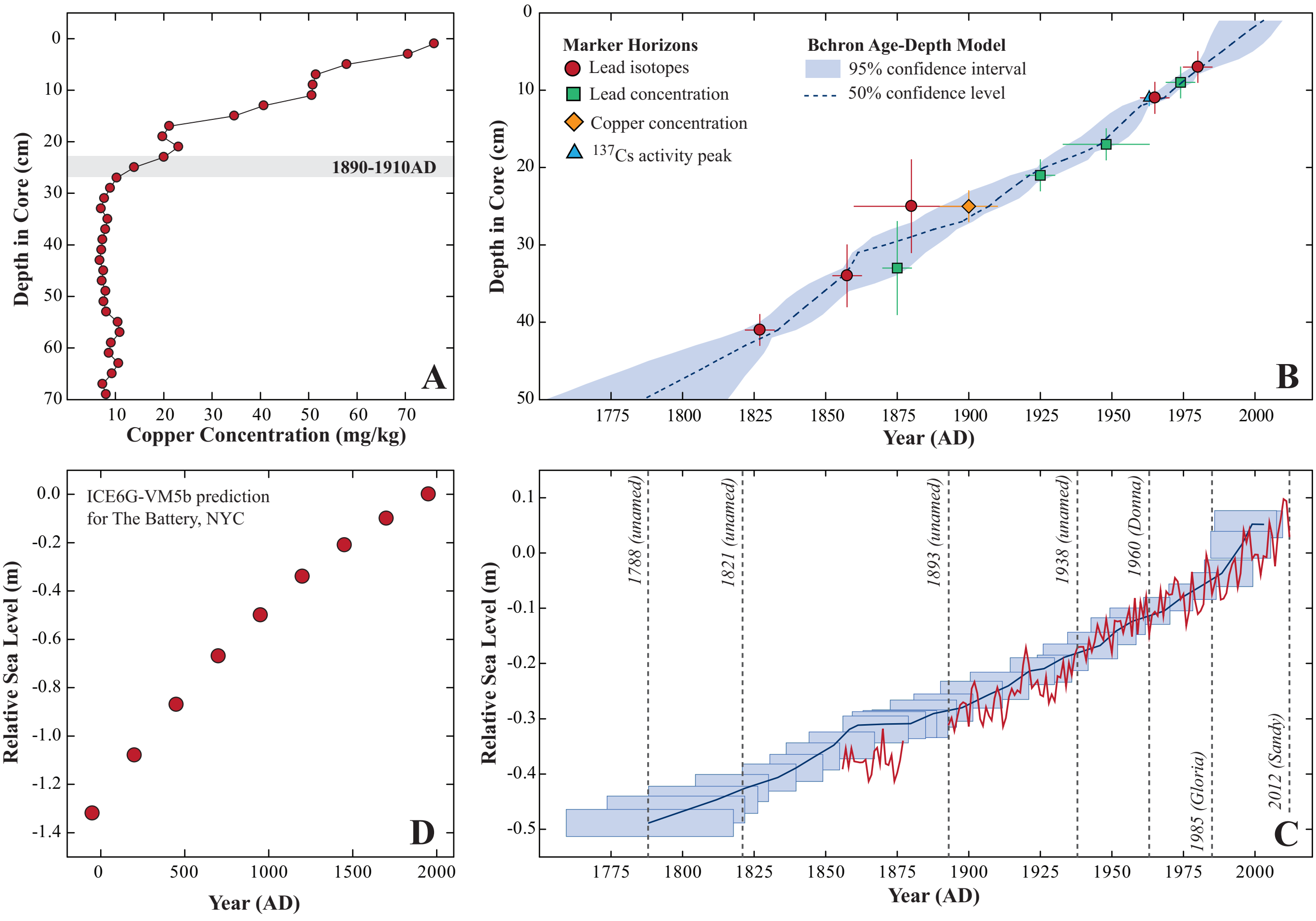

Figure 3. Relative sea level (RSL) history of New York City. (A) Copper concentration in core BB1; the onset of pollution at ~29 cm marks the start of national production in 1890–1910. (B) Chronology and age–depth model developed for the Barnegat Bay core. Modified from Kemp *et al.* (2012). (C) Annual average of RSL measured at The Battery tide gauge in lower Manhattan since 1853 (red line) and RSL reconstructed using the core of salt-marsh sediment from Barnegat Bay (blue). Boxes represent age and sea-level errors. The solid blue line connects mid-points of the reconstruction. (D) RSL predictions for the location of The Battery tide gauge from ICE6G-VM5b. The average linear rate for the past 2000 years is 0.66 mm a^{-1}, and is attributed solely to glacio-isostatic adjustment. This figure is available in colour online at wileyonlinelibrary.com.

dating results to provide downcore age estimates at 1-cm intervals with uncertainties (95% confidence interval) of ±4 to ±29 years. The lowest age marker in BB1 is 1827 at 41 cm. To include the 1788 hurricane, sample age was modelled an additional 8 cm beyond the lowest dated horizon (Fig. 3B, C).

The Barnegat Bay RSL reconstruction shows a 56 ± 4 cm RSL rise since 1788 and agrees with the tide-gauge record from The Battery as evidenced by the measurements lying within the margins of the reconstruction (Fig. 3C). This agreement suggests that there was minimal difference in the rate of glacio-isostatic adjustment (GIA) between the two sites and that local-scale factors were not dominant drivers of RSL change. The contribution of GIA was estimated for The Battery by the ICE6G-VM5b model, which shows an improved fit to Holocene RSL reconstructions for the New Jersey and New York regions compared with alternative models (Engelhart *et al.*, 2011). For the period under consideration, a linear rate of GIA (0.66 mm a^{-1}) was assumed from model predictions (Fig. 3D). Therefore, the estimated contribution from GIA to RSL change between the 1788 hurricane and Hurricane Sandy in 2012 is 15 cm (Fig. 4). Alternatively, Holocene RSL reconstructions in the New York City region estimate that GIA and other processes causing land-level change contributed 1.2 ± 0.1 mm a^{-1} equating to 25–29 cm of RSL rise (Engelhart *et al.*, 2009).

RSL rise since 1788 made a relatively small contribution to flood heights attained during subsequent hurricanes (Fig. 4). The RSL rise of 56 cm between the 1788 hurricane and Hurricane Sandy in 2012 equates to approximately one-third of modern great diurnal tidal range at The Battery. The timing of a hurricane's arrival in the cycle of astronomical tides remains a more important factor in the flooding hazard faced by New York City. The role of future climate change in governing storm-surge height is widely debated (Knutson *et al.*, 2010), but modelling predicts that storm-surge heights will increase during the 21st century in New York City (Lin *et al.*, 2012). There is high confidence that sea-level rise will continue in the 21st century (Bindoff *et al.*, 2007; Rahmstorf, 2007) and that GIA will continue at its current rate. Consequently, RSL rise will reduce the return interval of flooding in New York City and the water level associated with any given frequency will grow (Tebaldi *et al.*, 2012). For example, Lin *et al.* (2012) estimated that 1 m of sea-level rise by 2100 would cause current 100-year flood events to occur every 20 years. As damage is governed by water levels (including waves) that exceed physical thresholds (e.g. sea walls), the relationship between flood height and damage is non-linear. Therefore, incremental RSL rise will increase the likelihood of extensive damage during future hurricanes in New York City, independent of whether hurricanes produce larger or more frequent storm surges (Lin *et al.*, 2012; Tebaldi *et al.*, 2012).

Concluding remarks

The changing height of flooding attained during historical hurricanes is the product of storm-surge height, timing in the astronomical tidal cycle and RSL change. The contribution of these factors was estimated for seven historical hurricanes

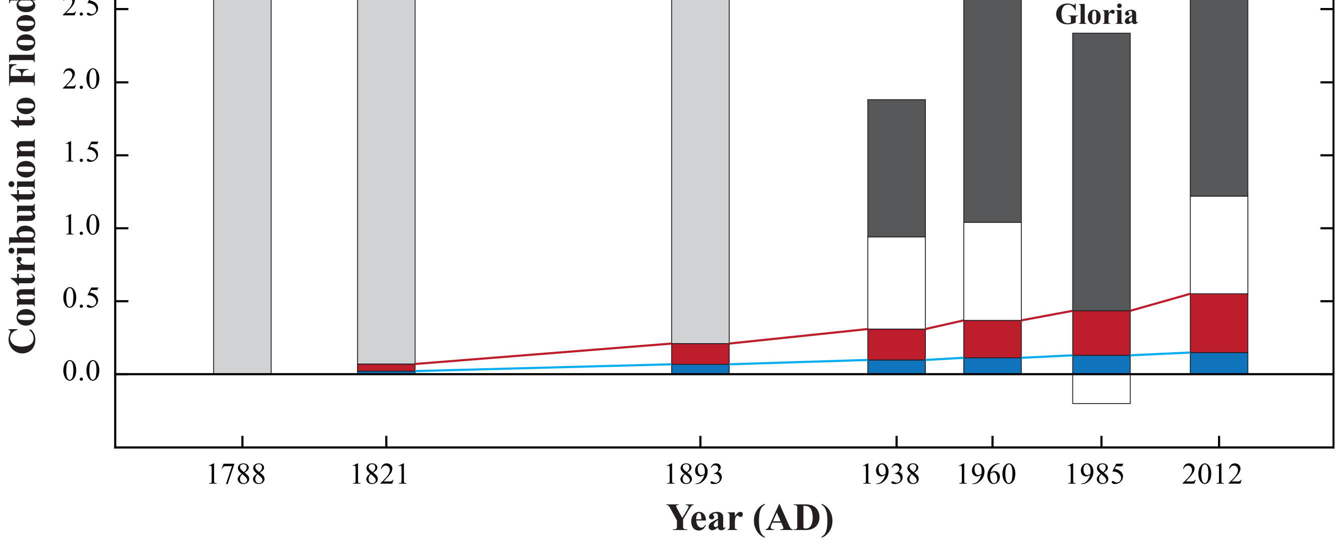

Figure 4. Estimated contributions to flood heights in New York City for notable historical hurricanes. For 1938, 1960, 1985 and 2012 hurricanes storm surge and tide heights were measured at The Battery tide gauge. The negative tidal contribution for Hurricane Gloria in 1985 reflects a maximum measured storm tide that occurred on an astronomical tide below contemporary mean tide level (MTL). Storm tides for earlier, pre-instrumental hurricanes are the estimates of Scileppi and Donnelly (2007) and represent the net effect of storm-surge height and astronomical tides. The 1788 hurricane is used as an arbitrary zero point for relative sea level. The cumulative contribution from glacio-isostatic adjustment was estimated using the ICE6G-VM5b model and subtracted from RSL reconstructed at Barnegat Bay to provide the sea-level rise contribution. This figure is available in colour online at wileyonlinelibrary.com.

that caused notable flooding in New York City, including Hurricane Sandy in 2012. Based on tide-gauge measurements from The Battery and descriptions of pre-instrumental hurricanes, storm-tide heights varied from 1.57 m (1938 hurricane) to 3.48 m (Hurricane Sandy). Between the 1788 hurricane and Hurricane Sandy, RSL in New York City rose by 56 cm, of which 15 cm is attributed to GIA. Therefore, the magnitude of RSL rise is small (one-third of modern great diurnal tidal range) in comparison with the amplification of the storm surge when it occurs at highest astronomical tide, as it did during Hurricane Sandy. RSL rise in the 21st century will effectively raise the base level on hurricane storm surges and tides and consequently reduce the return interval for flooding of any given height. Flooding in New York City from future hurricanes will be exacerbated by RSL rise (including ongoing GIA) irrespective of any increase in the magnitude of storm surges.

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Abbreviations. GIA, glacio-isostatic adjustment; MTL, mean tide level; NOAA, National Oceanic and Atmospheric Administration; PME, palaeomarsh elevation; RSL, relative sea level

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