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Water level response in back-barrier bays unchanged following Hurricane Sandy

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Key Points:
- Water level response in back-barrier bays was not altered by Hurricane Sandy
- Water level in the bays reflected offshore sea level with tides being attenuated
- High water levels in the bays after Sandy were caused by intense winter storms

Supporting Information:
- Readme
- Table S1
- Table S2
- Table S3
- Figure S1
- Figure S2

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Abstract On 28–30 October 2012, Hurricane Sandy caused severe flooding along portions of the northeast coast of the United States and cut new inlets across barrier islands in New Jersey and New York. About 30% of the 20 highest daily maximum water levels observed between 2007 and 2013 in Barnegat and Great South Bay occurred in 5 months following Hurricane Sandy. Hurricane Sandy provided a rare opportunity to determine whether extreme events alter systems protected by barrier islands, leaving the mainland more vulnerable to flooding. Comparisons between water levels before and after Hurricane Sandy at bay stations and an offshore station show no significant differences in the transfer of sea level fluctuations from offshore to either bay following Sandy. The post-Hurricane Sandy bay high water levels reflected offshore sea levels caused by winter storms, not by barrier island breaching or geomorphic changes within the bays.

1. Introduction

Hurricane Sandy, an extreme storm with a long return interval (700 years for the path [*Hall and Sobel*, 2013] and around 100 years for the magnitude of the flooding [*Scileppi and Donnelly*, 2007]), caused record flooding along portions of the northeast coast of the United States in the Middle Atlantic Bight (MAB) (Figure 1) on 28–30 October 2012. Overwash and subsequent breaching of the barrier islands during Sandy resulted in geomorphic change and new inlets at Mantoloking, New Jersey (closed by 4 November 2012), and across Fire Island, New York, at Cupsoque County Park (closed November 2012), at Smith Point County Park (closed November 2012), and at Old Inlet south of Bellport, New York (open as of March 2014) (Figure 1). In 5 months following Hurricane Sandy, anomalously high water levels occurred several times during winter storms, raising the concern that Sandy may have altered the coastal system and left the mainland more vulnerable to flooding [for example *Foderaro*, 2013; *Miller*, 2013; *James*, 2013]. U.S. Army Corps of Engineers' breach management strategy indicates that barrier-island breaches can cause "unwanted increases in water level" [*Kraus and Wamsley*, 2003]. In the Fire Island system, the *U.S. Army Corps of Engineers* [2001] suggested that breaching of the barrier island could increase tidal range as much as 0.3 m along the mainland. Hurricane Sandy, with its potential to modify the barrier island and estuarine geomorphology at an unprecedented scale, offered an opportunity to explore the water level response of these back-barrier bays following an extreme event.

Barnegat Bay (BB) is connected to the offshore through Barnegat and Little Egg Inlets, and Great South Bay (GSB) is connected through Fire Island Inlet and several smaller inlets (Figure 1). The major inlets are about 500 m wide; the new inlet in Fire Island is about 150 m wide. Water level in semienclosed back-barrier bays is primarily driven by the offshore sea level. In general, larger inlets allow a greater fraction of offshore fluctuations into bays, and long-period fluctuations are more effectively transferred than short-period fluctuations. Water level in the bays would match the offshore level if maintained long enough to allow a sufficient volume of water to overcome frictional effects and flow through the constricted inlets [*Chuang and Swenson*, 1981]. In BB and GSB, the tidal range is about 20% of the range offshore, because enough water cannot flow through the inlets in the ~6 h interval between low and high water to equalize with the offshore level. However, offshore high (or low) water levels associated with storms can last for several days, providing more time for the water level in the bay to match the offshore [*Wong and Wilson*, 1984].

Several processes control offshore sea level [*Pugh*, 1996]. The main processes include tides; wind setup, primarily associated with storms; the inverted barometer effect [*Wunsch and Stammer*, 1997]; seasonal steric changes [*Tsimplis and Woodworth*, 1994; *Antonov et al*., 2002]; long-term sea level rise [*Douglas*, 1991; *Church and White*, 2006; *Holgate*, 2007; *Ezer*, 2013]; and regional and basin-wide response to wind, currents, and pressure systems [*Wunsch*, 1991; *Ezer et al*., 2013; *Kopp*, 2013] that

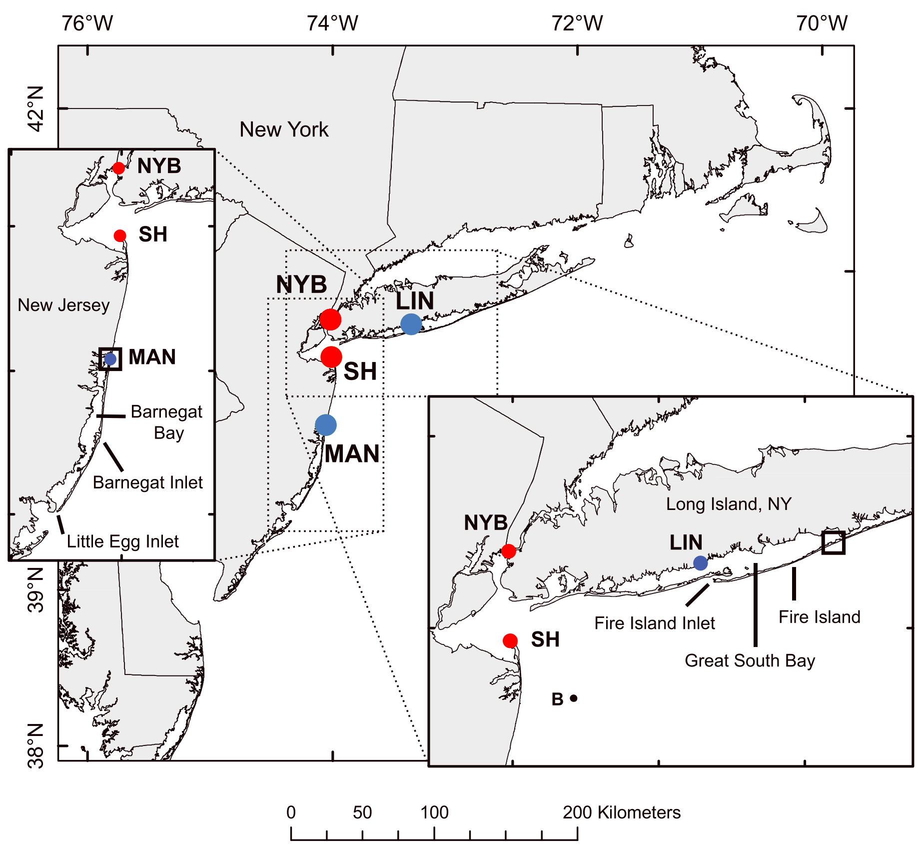


Figure 1. Map of Middle Atlantic Bight showing locations of water level stations at Mantoloking, New Jersey (MAN), and Lindenhurst, New York (LIN), in blue (in estuaries behind barrier islands) and at Sandy Hook, New Jersey (SH), in red (used as proxy for offshore water level). The Battery in New York (NYB) is also shown in red. Inset maps show (left) Barnegat Bay and (right) Great South Bay, and open squares show the location of breaches at Mantoloking, New Jersey, and Old Inlet, New York, that occurred during Hurricane Sandy. The letter B represents the location of pressure measurements on the inner shelf (1999–2000).

produce interannual fluctuations such as the North Atlantic Oscillation (NAO) [*Hurrell*, 1995] and the Atlantic Multidecadal Oscillation (AMO) [*Schlesinger and Ramankutty*, 1994; *Trenberth and Shea*, 2006].

In this paper, we examine whether the new inlets or other geomorphic changes that may have occurred during Hurricane Sandy influenced the maximum water levels in the bays following Sandy. We compare the water level response at locations (Figure 1) in BB and GSB to offshore forcing before (October 2007 to September 2012) and after (December 2012 to September 2013) Hurricane Sandy and find that it was not notably different. The high water levels that occurred in the months following Sandy were a result of offshore high sea level associated with a series of winter storms.

2. Observations and Data Processing

Water level data were obtained at two coastal sites (offshore proxies: Sandy Hook, New Jersey (SH), and The Battery, New York (NYB), in New York Harbor) and at two sites in back-barrier bays (Mantoloking, New Jersey (MAN), in BB and Lindenhurst, New York (LIN), in GSB) for the period 1 October 2007 to 31 December 2013 (Figure 1 and Table S1 in the supporting information). Water levels were recorded at 6 min intervals at all stations. The SH and NYB data were referenced to local mean sea level, and the MAN and LIN data were referenced to NAVD88. The datum referenced does not affect the comparisons presented here, because they are consistent from year to year for a given pair of coastal and bay sites. The water level gauge at SH failed at 23:30 UTC, 29 October 2012 during Hurricane Sandy and resumed operation on 7 December 2012. In this paper, we use sea level at SH as a proxy for sea level offshore of the inlets to BB and GSB. The entrance to Raritan Bay, where the SH gauge is located, is 8 km wide and over 10 m deep, and therefore, water exchange with the

Table 1. Rank of Daily Maximum Water Levels at SH and Bay Sites MAN and LIN for the Period 2007–2013[a]

Rank	SH			MAN			LIN		
	Date	6 min	DMS	Date	6 min	DMS	Date	6 min	DMS
1	[b]**30-Oct-12**	3.50	1.98	**30-Oct-12**	2.11	1.86	**30-Oct-12**	1.99	1.57
2	[b]**29-Oct-12**	3.24	1.98	***21-Dec-12***	1.03	0.75	**29-Oct-12**	1.83	1.54
3	28-Aug-11	2.19	0.98	**31-Oct-12**	0.93	1.09	28-Aug-11	1.24	0.76
4	[c]13-Mar-10	1.99	1.08	***27-Dec-12***	0.88	0.70	14-Nov-09	0.96	0.61
5	18-Oct-09	1.72	0.65	17-Apr-11	0.81	0.59	14-Mar-10	0.93	0.61
6	[c]17-Apr-11	1.66	0.58	14-Mar-10	0.80	0.70	***8-Nov-12***	0.89	0.71
7	5-Jun-12	1.65	0.55	9-Dec-09	0.77	0.64	***9-Mar-13***	0.87	0.63
8	14-Nov-09	1.62	0.79	***8-Nov-12***	0.77	0.44	***10-Mar-13***	0.84	0.62
9	31-Mar-10	1.61	0.50	10-Dec-09	0.77	0.65	***27-Dec-12***	0.83	0.64
10	13-Nov-09	1.61	0.79	***10-Mar-13***	0.75	0.59	28-Oct-08	0.82	0.32
11	17-Oct-09	1.60	0.66	1-Dec-10	0.74	0.49	***7-Mar-13***	0.82	0.54
12	***27-Dec-12***	1.60	1.06	11-Mar-11	0.70	0.46	***21-Dec-12***	0.81	0.65
13	12-May-08	1.59	0.86	19-Sep-12	0.69	0.55	17-Oct-09	0.80	0.55
14	12-Dec-08	1.59	0.41	27-Dec-09	0.68	0.58	6-Nov-11	0.80	0.59
15	**28-Oct-12**	1.59	0.85	11-Nov-10	0.67	0.53	**31-Oct-12**	0.80	0.70
16	16-Oct-09	1.58	0.72	***31-Jan-13***	0.67	0.48	13-Nov-09	0.78	0.57
17	***27-Feb-13***	1.55	0.64	18-Sep-12	0.66	0.57	18-Oct-09	0.77	0.49
18	***7-Mar-13***	1.55	0.86	12-Nov-10	0.65	0.55	13-Mar-10	0.77	0.61
19	18-May-11	1.55	0.45	26-Oct-08	0.65	0.43	31-Mar-10	0.77	0.46
20	26-Apr-10	1.54	0.50	14-Oct-11	0.65	0.51	12-May-08	0.76	0.53

[a]For each station, the table includes the daily maximum 6 min observation and the daily maximum subtidal water level (DMS) for the day, in which the maximum 6 min event occurred. Emphasis identifies Hurricane Sandy (in bold) and the storms following Sandy (in bold italic). MAN was not operational during Hurricane Irene (28 August 2011), and SH was not operational from 30 October to 7 December 2013.
[b]Water level for 29 and 30 October 12 at SH was set as the level observed at NYB.
[c]Indicates a high-water event that spanned midnight and is entered as one event.

adjacent shelf can be considered unrestricted. The coherence and transfer coefficient between the water level at SH and the pressure observations at a station on the inner shelf (Figure 1) from December 1999 to April 2000 [*Butman et al.*, 2003] were close to unity, further evidence that SH is an appropriate proxy for offshore water level.

We evaluated the data with the objective of determining whether water level fluctuations had changed after Hurricane Sandy. Specifically, we compared the before and after Hurricane Sandy values for tidal amplitudes, spectra of water level fluctuations, and spectral coherence and transfer functions between offshore and bay water levels. We also evaluated the 6 year trend in water levels at offshore and bay stations.

The maximum water level for each calendar day since 2007 was identified at each site based on the 6 min data and the 20 highest daily events in the record ranked (Table 1). A high-water event that spanned midnight and resulted in two daily maximum events separated by less than 1.5 h was designated as a single event on the day of the highest level. The maximum subtidal water level for each day (daily maximum subtidal water level; DMS hereafter) was determined from the 30 h low-pass filtered data (Table 1). Data from the NYB were similar to SH and were used as a proxy in periods where the SH gauge was not operational. The robust linear regression between DMS water levels at offshore and bay stations was calculated using the Theil–Sen estimator [*Gilbert*, 1987] (also known as the repeated median regression method [*Helsel and Hirsch*, 1992]).

Tidal constituents for water levels were computed using T_Tide [*Pawlowicz et al.*, 2002] for yearly intervals (1 November to 31 October) to provide estimates of tidal amplitude before and after Hurricane Sandy (Table S2 in the supporting information). Subtidal water levels were calculated by applying a low-pass filter with a 1/30 h cutoff frequency to identify storm events and a 1/60 day cutoff to identify seasonal variations. Water level trends over the period 2007–2013 were determined by linear regression. The spectral coherence and transfer function between water levels at SH (input) and MAN (output) and between SH and LIN were computed to determine the water level response in the bays to offshore forcing before and after Hurricane Sandy (uncertainty envelopes were estimated using the formulation by *Bendat and Piersol* [1986]). The spectra were computed using a Hanning 512 h window with overlapping (50%) data segments, providing estimates at periods between 12 min and 21 days. Uncertainty estimates were determined based on the number of degrees of freedom estimated as record length divided by filter window length.

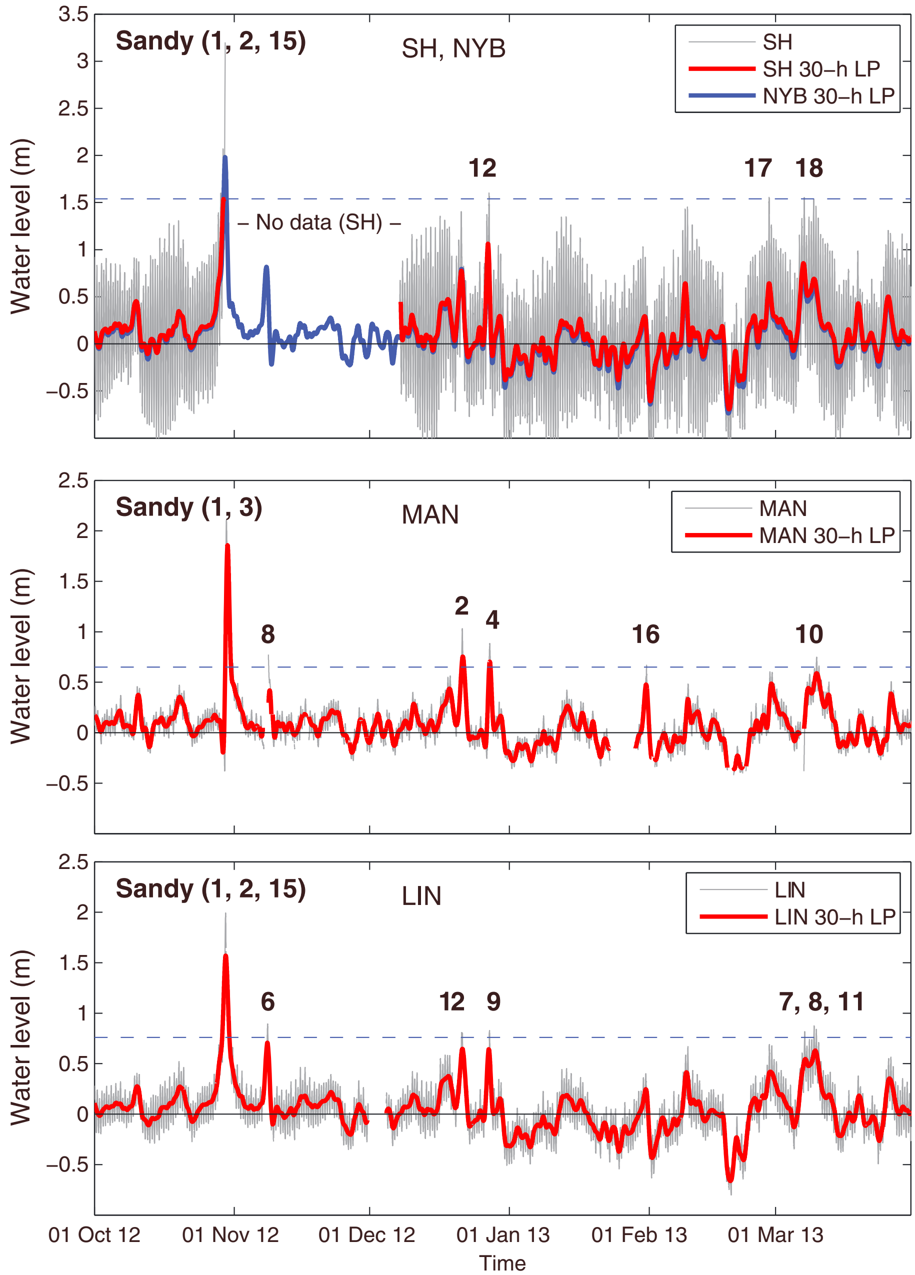
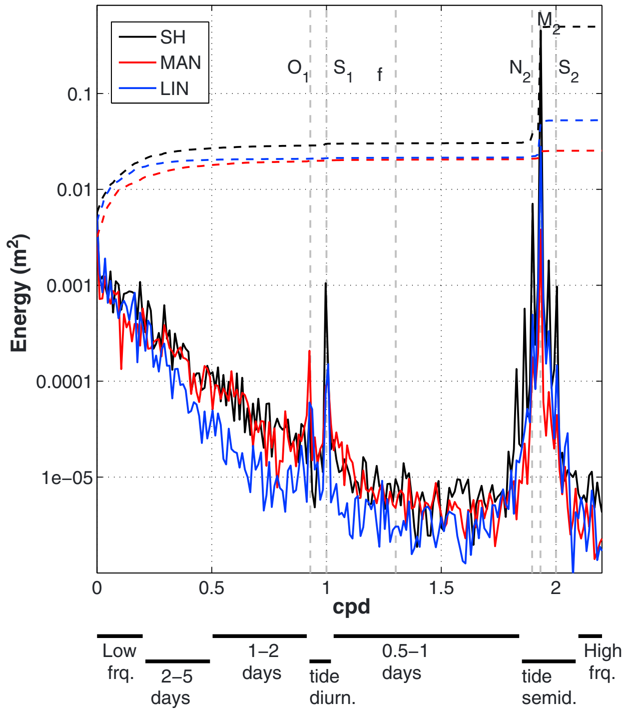


Figure 2. Time series of 6 min (gray) and 30 h low-pass filtered (red) sea level at SH, MAN, and LIN for October 2012 to April 2013. Low-pass filtered sea level at NYB (blue) included on SH plot. Numbers are the event rank for the top 20 daily high-water events since 2007 (Table 1), and the blue dashed lines are the event thresholds at each station. High-water events following Hurricane Sandy occurred on 8 November, 21 December, and 27 December 2012 and 31 January and 7 March 2013 (weather maps for these events are in Figure S2 in the supporting information). Events labeled with multiple numbers indicate a record water level occurring on successive days.

3. Results

Maximum water levels in the period 2007–2013 (Figure 2, Figure S1 in the supporting information, and Table 1) occurred during Hurricane Sandy, reaching 3.25 m (before the gauge failed) at SH, 3.5 m at NYB, 2.11 m at MAN, and 2.00 m at LIN in GSB. Of the 20 highest daily water levels observed between 1 October 2007 and 31 March 2013, about 30% of the non-Hurricane Sandy events occurred in 5 months following Sandy (5 of 18 events at MAN and 6 of 17 events at LIN) (Table 1). Each of these high water levels was



	Low frq.	2–5 days	1–2 days	tide diurn.	0.5–1 days	tide semid.	High frq.
SH	0.022	0.007	0.002	0.008	0.001	0.247	0.002
MAN	0.015	0.005	0.001	0.001	0.000	0.004	0.000
LIN	0.020	0.004	0.001	0.001	0.000	0.016	0.001

Figure 3. Energy spectra at SH, MAN, and LIN (solid lines) and cumulative energy (dashed lines). O_1, S_1, N_2, M_2, and S_2 label the principal tidal frequencies and "f" the inertial frequency. Values at the bottom is the sum of energy (m^2) at SH, MAN, and LIN in low frequency, 2–5 days, 1–2 days, diurnal tide, 0.5–1 day, semidiurnal tide, and high-frequency bands. (cpd: cycles per day).

associated with a low-frequency rise in water level (Figure 2, Figure S1 in the supporting information, and Table 1) caused by low-pressure weather systems that influenced the U.S. East Coast (Figure S2 and Table S3 in the supporting information). The five storms that occurred in winter 2012–2013 were more than the number that occurred in the previous cold seasons that ranged from zero (2007–2008) to four (2009–2010), and four of the five high water levels following Hurricane Sandy at MAN and four of the six at LIN were in the top 10 events (Table 1 and Figure 2). The strength and frequency of the top 20 high water levels compared to the previous 5 years could have resulted in the perception that Hurricane Sandy somehow altered the coastal system and was responsible for these high water levels.

Water level energy (variance) was concentrated in periods longer than 2 days and at tidal frequencies (Figure 3). The total energy at SH was 5 times larger than at LIN and an order of magnitude larger than at MAN. At SH, fluctuations in the 30 h low-pass filtered data were about 0.2 m and about 0.1 m in the 60 day low-pass data. The largest fluctuations were at tidal frequencies associated with the M_2 constituent with amplitude of 0.68 m at SH, 0.08 m at MAN, and 0.17 m at LIN (Table S2 in the supporting information). The M_2 tidal amplitude at SH and LIN after Hurricane Sandy was not different from the mean over the 6 years of observations. At MAN, the M_2 amplitude after Sandy was higher than previous years by around 0.01 m, continuing a linear increase over the last 6 years (0.0025 m yr^{-1}, $R = 0.9$, $P = 0.015$) and unrelated to the occurrence of Sandy. Changes in the other main tidal constituents (N_2, S_2, K_1, and O_1) were less than 0.005 m. The 18.6 year nodal modulation was about 3% higher than average during 2013, adding about 0.02 m to the M_2 fluctuations at SH.

Sea level at MAN and LIN was highly coherent with SH at semidiurnal and diurnal tidal periods (Figure 4). The coherence at periods longer than 10 days was about 0.6 at MAN and greater than 0.9 at LIN and decreased almost linearly to about 0.2 at MAN and 0.5 at LIN at diurnal frequencies. Similar coherence was reported in GSB in 1979 with shorter records from other stations [*Wong and Wilson*, 1984]. The inlets limit transfer of the offshore fluctuations to about 80% at periods between 2 and 10 days, about 40% at diurnal periods, and about 20% at semidiurnal periods (Figures 4c and 4d). Coherence and transfer coefficient values after Hurricane Sandy were comparable to the 6 year average values in these energetic bands. The transfer coefficient and coherence between water levels at SH and NYB, a station pair with no intervening barrier island to dampen the offshore water level fluctuations, were close to unity.

There was an enhanced coherence between SH and LIN at periods between 26 and 40 h after Hurricane Sandy (Figure 4b), but less than 3% change in the energy transferred at those frequencies (Figure 4d). The differences in both coherence and transfer coefficient after Hurricane Sandy at periods between 26 and 40 h and between 16 and 22 h had large uncertainties, and in most instances, the confidence envelope included the long-term estimates, suggesting that they could be associated with interannual changes rather than

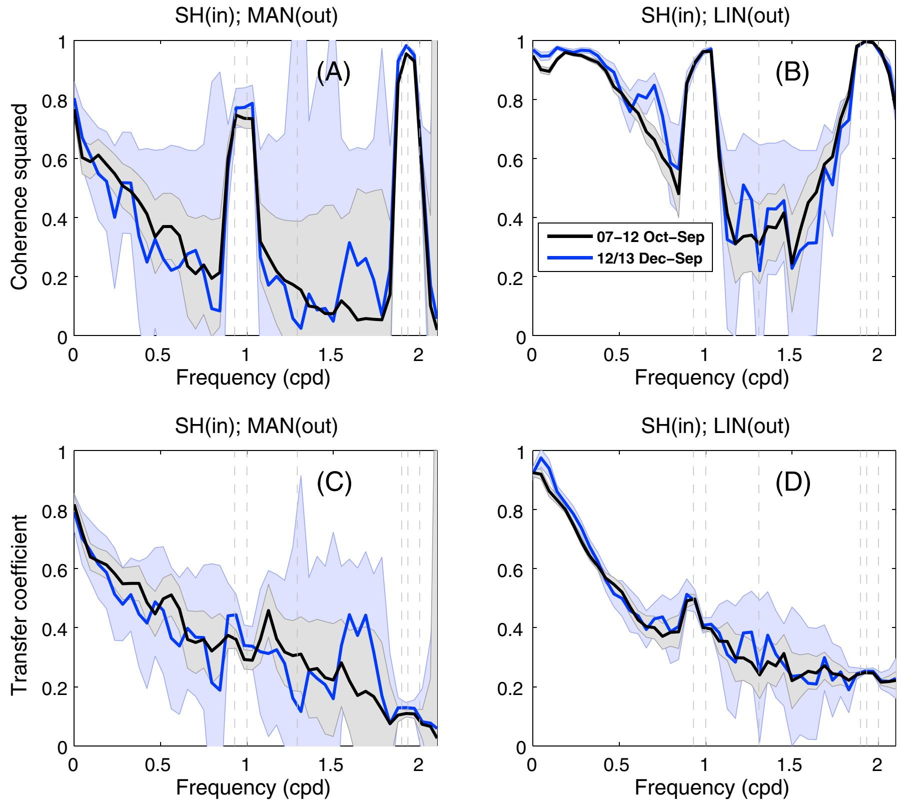


Figure 4. (a and b) Water level coherence and (c and d) transfer function between SH and MAN and between SH and LIN for the October to September period for 2007–2012 (pre-Hurricane Sandy) and December to September 2012–2013 (post-Sandy). The shaded areas denote uncertainty envelopes for coherence and transfer function [*Bendat and Piersol*, 1986]. SH data are the input spectrum, and MAN and LIN are output spectra.

Sandy-related changes. Moreover, fluctuations at these frequencies do not contribute much to water levels; the fraction of the observed water level fluctuation at these frequencies was less than 0.02 m (Figure 3) and thus contributed little to the increased levels observed after Hurricane Sandy.

The daily maximum subtidal water level (DMS) at MAN and LIN was linearly related to the DMS at SH, but reduced to 77 and 87% of the offshore values, respectively (Figure 5). The regression between SH and MAN was lower than the regression between SH and LIN, likely reflecting local processes (e.g., local wind setup) affecting MAN water level. The daily averaged regression values were consistent with the coherence at periods longer than 1 day (Figures 4a and 4b). There is no indication that the relationship between offshore and bay DMS after Hurricane Sandy deviated significantly from either the regression or other years.

Contributions from large-scale processes that increase sea level in the MAB include the NAO [*Hurrell*, 1995] and the AMO [*Schlesinger and Ramankutty*, 1994; *Trenberth and Shea*, 2006]. During the negative phase of the NAO, higher water elevations are expected along the northwestern Atlantic. Higher water levels are also expected during positive AMO associated with higher average detrended sea surface temperature anomalies in the Atlantic. The 60 day low-pass filtered water level data at Sandy Hook was significantly correlated with the monthly NAO index ($R = -0.36$, $P < 0.001$) and the monthly AMO index ($R = 0.45$, $P < 0.001$). The correlation with NAO is comparable to the values encountered in the North Atlantic [*Woolf et al.*, 2003] and the eastern U.S. [*Kopp*, 2013]. The correlation with AMO is slightly higher than the values from nearby stations in the eastern U.S. [*Kopp*, 2013]. These correlations suggest that 0.05–0.10 m of water level at intra-annual and longer time scales could be associated with the changing phase and intensity of interannual fluctuations such as NAO and AMO. Hurricane Sandy occurred during negative NAO and positive AMO, resulting in slightly higher water levels as a result of these basin-scale effects.

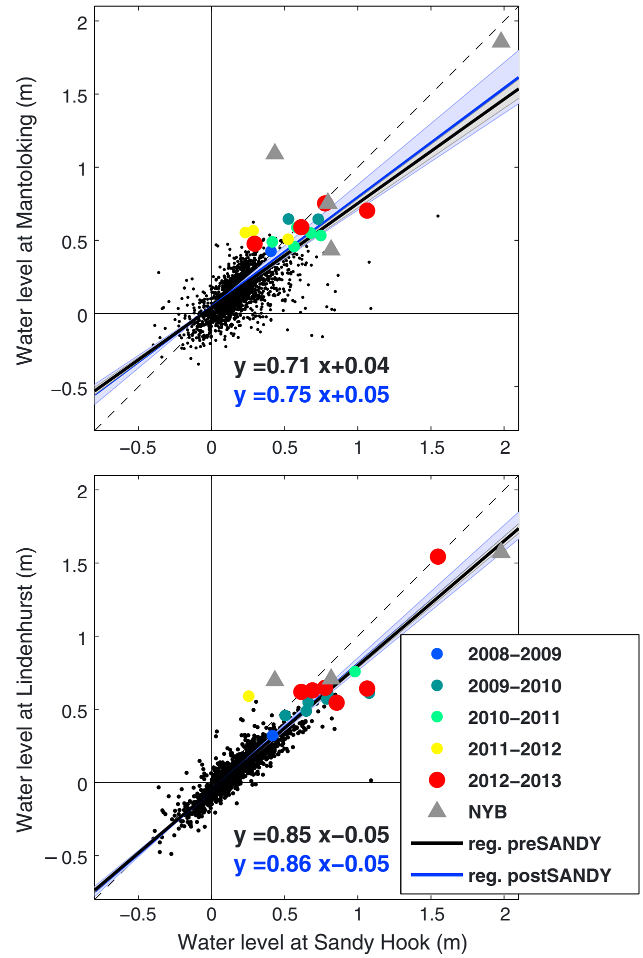


Figure 5. Scatterplot of daily maximum subtidal (DMS) water level in back-barrier bays at MAN and LIN versus coastal sea level at SH (NYB data (triangle markers) was used when SH was down). The DMS water levels associated with the 20 highest daily high-water events at LIN and MAN (Table 1) are shown as larger dots and colored by year with the post-Hurricane Sandy events marked with larger red dots. Dashed line is 1:1, and the pre-Sandy (black) and post-Sandy (blue) robust regressions are indicated with solid lines (formula shown), and shading is the 95% confidence bounds.

4. Discussion

The timing of storms with respect to high tide, spring-neap cycle, seasonal sea level variations, and longer-term fluctuations (NAO, AMO, and sea level rise) affect the resulting maximum water level in the bay. For example, all of the highest water levels were caused by tidal peaks that occurred near the maximum storm-associated water level (Figure 2). At SH (and NYB as proxy), storms occurring during neap tide (e.g., 8 November 2012 and 21 December 2012) were not in the top 20 list, but the low-frequency increase in water level associated with these events was responsible for the top 20 high water levels observed at both MAN and LIN. The seasonal cycle in offshore sea level of about 0.1 m (Figure S1 in the supporting information) would reduce water levels associated with winter storms and increase water level associated with tropical storms that typically occur in summer.

The sea level trend for the period 2007–2013 was 10.6 mm yr^{-1} for SH, 12.3 mm yr^{-1} for MAN, and 13.5 mm yr^{-1} for LIN. These rates are consistent with recent sea level trend estimates in the MAB [*Church and White*, 2006; *Ezer*, 2013] and are accelerated above the global rate of sea level rise [*Sallenger et al.*, 2012; *Ezer*, 2013; *Ezer et al.*, 2013]. The Federal Emergency Management Agency's 10% flood level estimates (a flood occurring once in 10 years) are 0.98 m at Mantoloking and 1.13 m at Lindenhurst [*Federal Emergency Management Agency*, 1998, 2006]; these values are 0.33 m and 0.36 m, respectively, higher than the water level that defined the top 20 daily maximum levels and was exceeded 2–3 times in the period 2007–2013. The estimated rate of sea level rise continued for 10 years would add about 0.1 m to mean sea level and would approximately double the number of storms exceeding the threshold of 1.55 m at SH (Table 1) in a 5 year period, assuming storm characteristics and frequency remain unchanged. If continued for about 30 years, the top 20 events observed in 5 years would nearly meet the Federal Emergency Management Agency once in 10 year level.

The relatively small remaining inlet into GSB and other geomorphic changes caused by the extreme conditions associated with Hurricane Sandy did not change the transfer of energy from the offshore to the back-barrier bays at subtidal and tidal frequencies at the stations examined here. The size, number, and distribution of inlets and the geomorphic characteristics of the back-barrier bay ultimately determine the magnitude of transfer from the offshore. For example, larger connections could increase the water level transfer; this could be particularly important if changes increased the transfer of the semidiurnal tides (about 1 m offshore amplitude during spring tides), where only about 20% of the amplitude is currently transferred. In contrast, about 80% of the fluctuations at storm periods are currently transferred. Similar transfer coefficient relationships have been reported for other coupled embayment—ocean systems (Lake Pontchartrain [*Chuang and Swenson*, 1981] and Delaware Estuary and Chesapeake Bay [*Wong*, 1991]), suggesting that other barrier island systems (e.g., Outer Banks, North Carolina; Sanibel and Captiva islands, Florida; and Padre Island, Texas) also protect the mainland from high water levels by filtering the offshore signal.

5. Summary

We investigated the water level response within two back-barrier bays before and after Hurricane Sandy to determine whether geomorphic changes left the mainland more vulnerable to flooding. The transfer of tides and low-frequency energy did not change significantly after the extreme conditions caused by Hurricane Sandy, resulting in at most a 0.01–0.02 m change in maximum sea level. The high water levels that occurred in 5 months following Hurricane Sandy in these back-barrier bays were caused by winter storms, not by barrier island breaching or geomorphic changes in the bays caused by Sandy. The coherence, transfer coefficients, and regression between water levels in Barnegat and Great South Bay and offshore suggest that water levels in these semienclosed back-barrier bays are mostly damped co-oscillations driven by offshore sea level, modified by the duration of offshore events and by the inlet and bay geometry. Offshore high water levels associated with storms are primarily responsible for the record high water levels observed in these bays following Hurricane Sandy.

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Data sources included National Oceanic and Atmospheric Administration for SH and NYB (http://tidesandcurrents.noaa.gov/stations.html?type=Water+Levels), U.S. Geological Survey for MAN and LIN (http://waterdata.usgs.gov/usa/nwis/uv?01408168, http://waterdata.usgs.gov/ny/nwis/uv/?01309225), NAO data from http://www.cru.uea.ac.uk/~timo/datapages/naoi.htm;, and AMO data from http://www.esrl.noaa.gov/psd/data/correlation/amon.us.data. We thank C. Sherwood, S. Dalyander, J. Warner, Z. Defne, R. Signell, and S. Lentz for their helpful comments and suggestions. We thank B. Schwab and H. Jenter for their suggestions. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. Authorship order is alphabetical.

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