6. HURRICANE SANDY INUNDATION PROBABILITIES *TODAY AND TOMORROW*

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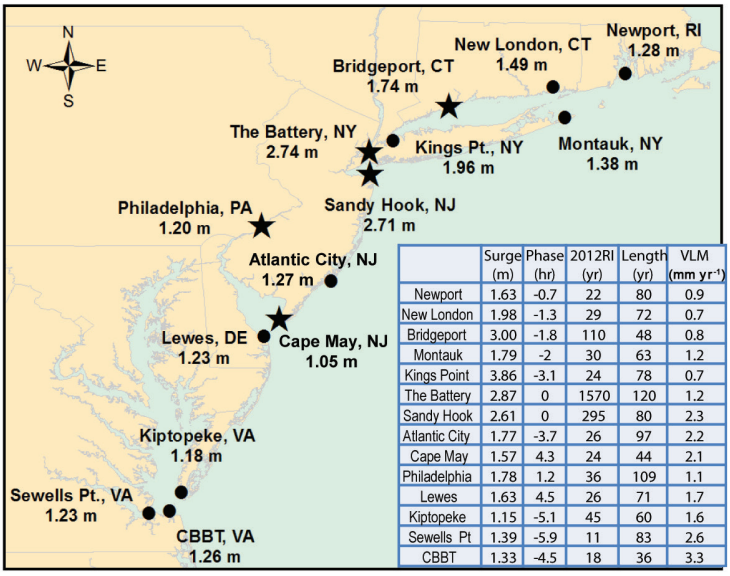
Introduction. Hurricane Sandy slammed into the U.S. mid-Atlantic seaboard on 29–30 October 2012 causing widespread damage and functional disruption to critical infrastructure resulting in repair and mitigation expenditures funded at $60.2 billion U.S. dollars (GPO 2013). Sandy's impacts exposed many unrealized sector-specific thresholds and general-public vulnerabilities across a region generally accustomed to Nor'easters (Hirsch et al. 2001; Colle et al. 2010; Sweet and Zervas 2011), but not hurricane strikes. As rebuilding occurs, concerns remain as to how sea level rise (SLR) will change probabilities of future events leading to recurring economic losses within an increasingly crowded coastal zone (http://stateofthecoast.noaa.gov/population). Here, we summarize tide gauge water level statistics from Sandy and discuss how the probabilities of exceeding its peak impact elevations (relative to *today's* reference frame) have changed since the mid-20th century from relative SLR (SLR_{rel}) and provide future estimates based upon SLR_{rel} scenarios.

Data and methods. Peak water level measurements during Sandy were recorded by National Oceanic and Atmospheric Administration (NOAA) tide gauges (Fig. 6.1; http://tidesandcurrents.noaa.gov). In the case of the Sandy Hook gauge, which was destroyed before reaching its peak, an average of two high-water marks at the adjacent U.S. Coast Guard base (McCallum et al. 2012) were used instead of the last value recorded. Exceedance probabilities are quantified by a generalized extreme value (GEV) model of annual maxima whose cumulative distribution is described by location (centering), scale (dispersion), and shape (distribution tail) parameters (Coles 2001).

We provide time-dependent return intervals (expected time between recurring events and the inverse of the exceedance probability) associated with peak Sandy storm tide levels (tide + surge; referred to as impact levels) based upon GEV models shown with 95% confidence intervals at http://tidesandcurrents.noaa.gov/est. The return curves are based upon records through 2010 (Fig. 6.1a), except for the Battery, Bridgeport, and Sandy Hook where impacts from Sandy warranted a recomputation of the stations' probability models through 2012 since GEV models are sensitive to outlier influences (Fig. 6.1a). The GEV models are also sensitive to record length, implying that if Sandy Hook's record was as long as the Battery's, its return interval for Sandy would be longer (Fig. 6.2a). All levels are relative to 1983–2001 epoch mean higher high-water (MHHW; http://tidesandcurrents.noaa.gov/datum_options) tidal datum to normalize for varying tidal ranges.

Current (2012) and historical (1950) return intervals for Sandy's impact levels are obtained by raising or lowering, respectively, a station's GEV model by its long-term relative mean sea level (MSL) trend



	Surge (m)	Phase (hr)	2012RI (yr)	Length (yr)	VLM (mm yr^{-1})
Newport	1.63	-0.7	22	80	0.9
New London	1.98	-1.3	29	72	0.7
Bridgeport	3.00	-1.8	110	48	0.8
Montauk	1.79	-2	30	63	1.2
Kings Point	3.86	-3.1	24	78	0.7
The Battery	2.87	0	1570	120	1.2
Sandy Hook	2.61	0	295	80	2.3
Atlantic City	1.77	-3.7	26	97	2.2
Cape May	1.57	4.3	24	44	2.1
Philadelphia	1.78	1.2	36	109	1.1
Lewes	1.63	4.5	26	71	1.7
Kiptopeke	1.15	-5.1	45	60	1.6
Sewells Pt	1.39	-5.9	11	83	2.6
CBBT	1.33	-4.5	18	36	3.3

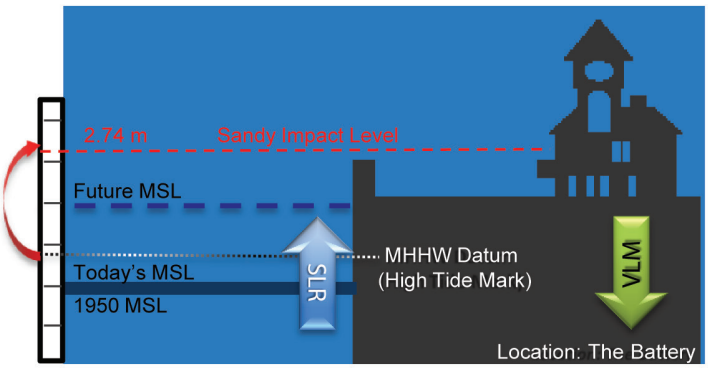


Fig. 6.1. (a) Hurricane Sandy's impact levels (above MHHW) at NOAA tide gauges (shown as dots or stars, with stars signifying highest-ever storm tide) with the table showing maximum storm surge recorded, phase of maximum surge relative to peak storm tide level near high tide (±6.4 hr near low tide), 2012 return interval (RI) of Sandy's impact levels, length of record used for RI computation, and sinking vertical land motion (VLM) rates. (b) Schematic (not to scale) describing the reference frame for measuring Sandy's impact levels at the Battery and how SLR and VLM contribute to SLR_{rel} changes.

(http://tidesandcurrents.noaa.gov/sltrends), except for Philadelphia where the mean high-water (MHW) trend is applied (discussed below). Future (2050 and 2100) return intervals associated with Sandy's impact levels are formulated by applying four SLR_{rel} scenarios, which incorporate a global mean SLR component estimated for 2100 by the U.S. Global Climate Research Program 2013 National Climatic Assessment (Parris et al. 2012, below):

- Low (0.2 m)
- Intermediate Low (0.5 m)
- Intermediate High (1.2 m)
- High (2 m)

The Low SLR_{rel} scenario assumes a continuation of global mean SLR estimates for the 20th century (1.7 mm yr^{-1}; Church and White 2011) and site-specific (sinking) vertical land motion (VLM; Zervas et al. 2013) rates shown in Fig. 6.1a, whereas the other scenarios that incorporate a range of warming and ice-melt projections also include a quadratic parameter. SLR_{rel} amounts by 2050 and 2100 under each scenario (Fig. 6.2b) initiate in 2013 following USACE (2011) guidelines:

$SLR_{rel}(t) = 0.0017(t_2 - t_1) + b(t_2^2 - t_1^2) + VLM$ where t_1 (t_2) is the time between the beginning (ending) year of interest and 1992 and b is a constant (1.56E-04 High, 8.71E-05 Intermediate High, and 2.71E-05 Intermediate Low).

Future extremes are expected to track the projected SLR_{rel} scenarios and their distribution is modeled using a time-dependent GEV location parameter. Changes to annual maximum variance and outlier occurrences relative to their historical distributions (affecting GEV scale and shape parameters, respectively) from *storminess* variability/change (Menendez and Woodworth 2010; Grinsted et al. 2012) is a current topic of future climate research (Lin et al. 2012; Grinsted et al. 2013) and not considered here from lack of incorporation guidance (Hunter 2010; Tebaldi et al. 2012). Nor are changes to storm-surge or tide-range characteristics from MSL-changing feedbacks, although the latter has increased significantly (~1.5 mm yr^{-1}) relative to its MSL trend in Philadelphia from 20th century channel deepening (Zervas 2003).

How have the return intervals for Sandy's impact levels changed since 1950? Hurricane Sandy broke 16 historical storm-tide levels along the East Coast (Fanelli et al. 2013). Though Sandy's magnitude on the Saffir-Simpson hurricane wind scale was not particularly large, its westward strike heading was very abnormal (Hall and Sobel 2013). Since 1851, nine other hurricanes (Category 1 and 2) have made landfall with similar proximities but all were heading north-northeastward (http://csc.noaa.gov/hurricanes). Also important

was that Sandy's massive storm surge within New York harbor coincided with peak high tide at Sandy Hook and the Battery contributing to their ~2.7 m storm tide (above MHHW). A couple stations experienced larger storm surges (Kings Point and Bridgeport) but were at lower tide stages (Fig. 6.1a) and not at peak storm tide levels.

Throughout the mid-Atlantic coast, SLR_{rel} has decreased return intervals (i.e., increased probabilities) of Sandy-level inundation events (Fig. 6.2c). For instance, Sandy had a probability equivalent to an occurrence every 295 and 1570 years at Sandy Hook and the Battery, respectively. However, in 1950, MSL was lower and required a larger storm tide to reach Sandy's impact levels. A storm with Sandy's impact level of inundation then would have had to return intervals of 435 and 2330 years, respectively. This represents a one-third decrease in return intervals over this period at these locations. This model also suggests that from Atlantic City southward, a once-in-a-century event or beyond in 1950 can now be expected to recur every couple of decades (approximately two-thirds decrease in return intervals) due to SLR_{rel}.

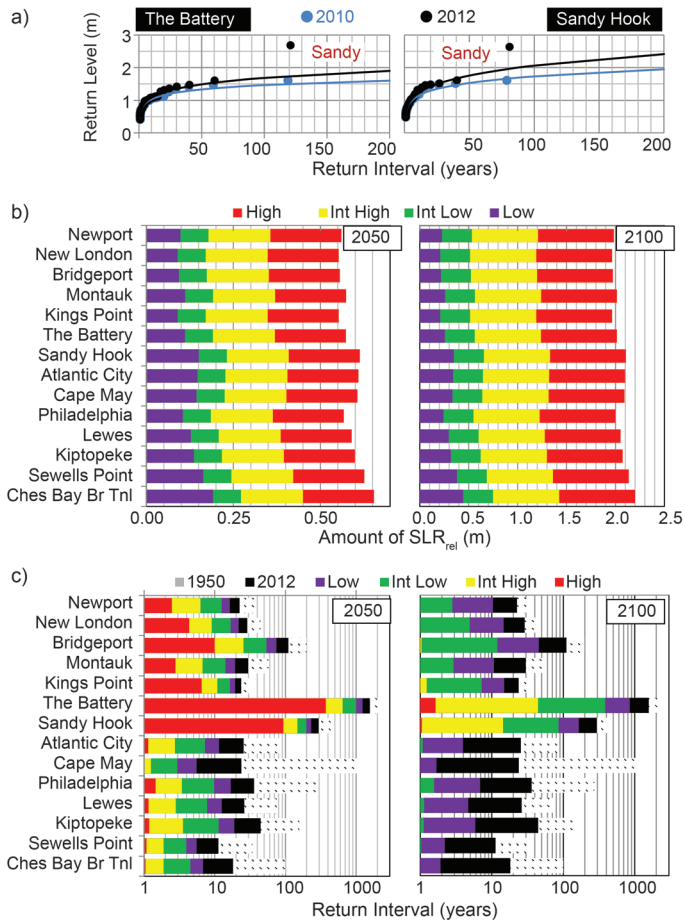


Fig. 6.2. (a) Generalized extreme value (GEV) return curves for the Battery and Sandy Hook with annual maximum storm tide levels (dot) through 2010 (blue) and recomputed for data through 2012 (black) that include Hurricane Sandy; Sandy's return interval is the x-axis value when the black line intersects the Sandy value on the y-axis (not shown). (b) The amount of SLR_{rel} by 2050 and 2100 under each scenario utilized in (c), which shows the time-dependent comparisons of return intervals associated with Hurricane Sandy-impact levels between 1950 (gray) and 2012 (black) by application of each station's long-term relative mean sea level (MSL) trend and in the future (2050 and 2100) by application of four SLR_{rel} scenarios.

How might return intervals for Sandy's impact levels change in the future? Results for 2050 and 2100 (Fig. 6.2c) illustrate how the return intervals matching Sandy's impact levels (Fig. 6.1) will decrease in all four SLR_{rel} scenarios. By 2050, return intervals under the Low scenario are slightly more frequent than in 2012. High-scenario forcing suggests Sandy-level events recurring ~annually (red disappears) south of Atlantic City, whereas by 2100, they become ≤ annual events under the Intermediate High and Intermediate Low scenarios (yellow and green disappear). Northward between Newport and Kings Point, though Sandy's impact levels (Fig. 6.1a) were generally higher, the corresponding 2012 return intervals were similar (Fig. 6.2c). However, the decay of the return interval in this region by 2050 and 2100 is slower, i.e., ≤10 years in 2050 for High and in 2100 for Intermediate Low scenarios. This is consistent with frequent exposure to powerful Nor'easters captured in the GEV models as well as higher VLM rates southward (Fig. 6.1a). At the Battery and Sandy Hook, the return intervals become approximately 50- and 20-year events in 2100, respectively, under the Intermediate High scenario and ≤2 years under the High scenario.

Concluding remarks. Impacts of Hurricane Sandy were record setting, largely attributable to its westward strike heading (~1-in-700 year probability; Hall and

Sobell 2013), massive storm surge, and damaging inundation. Peak storm-tide levels, which occurred near local high tide, had staggering recurrence probabilities (e.g., 1570 years at the Battery, Fig. 6.1a). Though the data records do not always span such long intervals, Sandy was phenomenal based on historical data. Our model aspects (e.g., flatter GEV return curve at the Battery than at Sandy Hook, Fig. 6.2a) are sensitive to tide gauge record length, which miss a relevant 1821 hurricane strike (Scileppi and Donnelly 2007). This may explain why our direct statistical recurrence estimates for Sandy at the Battery are longer than the ~1000-year estimate (MHHW adjusted) simulated under historical climatic conditions by circulation-hurricane models (Lin et al. 2012).

Another important but less-salient factor attributable to Sandy impacts is the effect of SLR. Climate change-related SLR exacerbates extreme-event inundation relative to fixed elevations (Hunter 2010; Tebaldi et al. 2012, Obeysekera and Park 2012). Accordingly, we estimate that SLR_{rel} over 1950–2012 from global SLR (thermal expansion and ice melt), VLM (subsidence), and ocean circulation variability has contributed to a one- to two-thirds decrease in Sandy-level event recurrences. Our future scenarios of Sandy-level return intervals are concerning, as they imply that events of less and less severity (from less powerful storms) will produce similar impacts (Field et al. 2012). Further aggravating, the frequency and intensity of major storms/surges are likely to increase in a warming climate (Lin et al. 2012; Grinsted et al. 2013). Our scenarios scale similarly with future-climate/circulation/hurricane models (Lin et al. 2012) and show that present (Boon 2012) and future SLR accelerations will nonlinearly compress the time-dependent recurrence intervals in a nonuniform fashion across the region. Lastly, the scenarios do not include regional SLR contributions from ocean freshening and circulation slowdown (Sallenger et al. 2012; Ezer et al. 2013), which affect regional coastal flooding (Sweet et al. 2009) and may add ≥0.25 m to overall mid-Atlantic SLR_{rel} (Yin et al. 2009). Coastal communities are facing a looming SLR_{rel} crisis, one that will manifest itself as increased frequency of Sandy-like inundation disasters in the coming decades along the mid-Atlantic and elsewhere.