The Impact of Tidal Phase on Hurricane Sandy's Flooding Around New York City and Long Island Sound

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How do the local impacts of Hurricane Sandy's devastating storm surge differ because of the phase of the normal astronomical tide, given the spatiotemporal variability of tides around New York? In the weeks and months after Hurricane Sandy's peak surge came ashore at the time of local high tide at the southern tip of Manhattan and caused record-setting flooding along the New York and New Jersey coastline, this was one question that government officials and critical infrastructure managers were asking. For example, a simple superposition of the observed peak storm surge during Sandy on top of high tide in Western Long Island Sound comes within 29 cm (less than a foot) of the top elevation of the Stamford Hurricane barrier system which would have been overtopped by 60 cm surface waves riding over that storm tide. Here, a hydrodynamic model study of how shifts in storm surge timing could have influenced flood heights is presented. Multiple flood scenarios were evaluated with Stevens Institute of Technology's New York Harbor Observing and Prediction System model (NYHOPS) having Hurricane Sandy arriving any hour within the previous or next tidal cycle (any hour within a 26-hour period around Sandy's actual landfall). The simulated scenarios of Sandy coming between 7 and 10 hours earlier than it did were found to produce the worst coastal flooding in the Upper East River, Western and Central Long Island Sound among the evaluated cases. Flooding would have generally been worse compared to the real Sandy in Connecticut and the areas of New York City around the Upper East River between the boroughs of Queens and the Bronx,

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exceeding record flood heights. However, the New York Harbor region would still have seen its record flood elevation exceeded, so the storm's impact could have been more widespread. The hydrodynamic model results suggest that the still-water levels would have risen to within 75 cm of the top elevation of the Stamford storm surge barrier, 46 cm lower than the naïve superposition of astronomical tide and storm surge.

Keywords: Hurricane Sandy; coastal hazards; New York city; long island sound; hydrodynamic model; linear superposition; inundation mapping; tidal phase; storm surge; tide-surge modulation; East River; Stamford hurricane barrier; sea level rise; coastal inundation; coastal resilience; collaborative research.

1. Introduction

Hurricane Sandy (Sandy) formed as a tropical depression southwest of Jamaica on October 22, 2012. Sandy strengthened to a Category 3 hurricane as it moved northward across Cuba and into the Bahamas before taking a more northeastward track off the eastern seaboard of the United States as a Category 1 hurricane. Although weaker, the size of the storm greatly increased with tropical storm force winds reaching the eastern seaboard 400 km from the center of the storm. In the early morning hours of October 29, Hurricane Sandy encountered an anomalous blocking high pressure system over the North Atlantic that steered the hurricane toward the Mid-Atlantic coast. As Sandy moved over the Gulf Stream it briefly strengthened to a Category 2 hurricane just 12 hours before landfall. Moving over the cooler waters of the continental shelf east of New Jersey, Sandy's central heat engine quickly weakened and the cyclone began a post-tropical transition into an extratropical storm (a horizontal-temperature-gradient-driven, mid-latitude, low pressure weather system). Hurricane Sandy retained its unusual large wind field until it made landfall on Brigantine Island at 8 PM Eastern Daylight Time (EDT) on October 29 as a Post-Tropical Cyclone.

Two hours prior to landfall sustained easterly winds of 18 m/s, gusting to 30 m/s were measured at Sandy Hook, NJ, the entrance to the lower New York Harbor. The large wind field generated an extreme storm surge (abnormal rise of water above the predicted astronomical tide) north of the eye at landfall. Results from the penultimate National Weather Service (NWS) probabilistic storm surge forecast model guidance before Sandy's landfall are seen in Figure 1. By then, the NWS forecasts were honing in to the correct magnitude of the impending "maximum storm surge." The "maximum storm surge," or "maximum tidal residual water level," can be defined as the maximum deviation of total observed water elevation above normal astronomical tide, due to the storm. By "normal astronomical tide" we mean the local hydrodynamic translation of the long tide waves created by the gravitational pull of the celestial bodies on the world's

Figure 1. Peak Storm Surge Forecast for Hurricane Sandy

Notes: Forecast guidance data (30 percent Exceedance Values shown here) are from the National Hurricane Center's (NHC) SLOSH-model-based probabilistic ensemble initialized on October 29, 2012 12:00 PM UTC (8 AM EDT), 12 hours before landfall.

oceans; in other words, the rise and fall of water predicted by harmonic analysis and published in the tide tables of the National Ocean Service (NOS). If, in turn, the maximum storm surge were to coincide with normal high water locally, then Figure 1 can be thought of as an estimate of peak inundation level above ground. Implicit to this latter estimation is the definition of “upland” as the lands exposed above the mean high water (MHW) shoreline boundary (NOAA 2000). Less conservatively, the Mean Higher High Water (MHHW) boundary is used by the National Hurricane Center (for Hurricanes) and the NOAA Meteorological Development Laboratory (for Extra-Tropical Storms) to define the start of upland in ground inundation estimates, including those for Sandy (Blake *et al.* 2013; Forbes *et al.* 2014). Given complications with regard to the normal tide cycles and their predictable variation among days, months, and years, secular effects such as sea level rise, and design elevation of shoreline structures such as sea walls, surge barriers, and table tops, it is important to realize that a high water datum (e.g. MHW or MHHW) is only an estimate of what the shoreline and upland regions really are at any given day and can only be first-order accurate. Regardless, a 10-foot (3 m) peak storm surge coinciding with normal high water would be expected to inundate the upland ground approximately 10-foot-deep at the shore, on a first-order basis. The probabilistic model ensemble shown in Figure 1 was predicting a 30% chance that “peak storm surge” would exceed 2.7 m (9 ft) in New York Harbor, locally 3.0 m (10 ft) at the back of Raritan Bay, and 2.4 m (8 ft) in Jamaica and Newark Bays, East River and Western Long Island Sound, and lower Manhattan. These peak storm surge values (Figure 1) provided estimates for a 30 percent probability of exceedance for inundation levels above ground “if the peak surge occurred at the time of high tide” (Forbes *et al.* 2014). The NHC modeling ensemble, based on the SLOSH computer model (Sea, Lake, and Overland Surges from Hurricanes: Jelesnianski *et al.* 1992; Taylor and Glahn 2008; Forbes *et al.* 2014), did not account for astronomical tides and their normal tidal cycle, solving only for storm surge. Astronomical tidal cycles, as predicted by the NOS tide tables, can be added to the storm surge solution independently through the process of linear superposition: the prediction of the normal tide at any time in the future and at a given place is added to the independently-predicted level of storm surge for the same time and place, to calculate a total water level prediction (e.g. Forbes *et al.* 2014).

Immediately following landfall, as Sandy moved across southern New Jersey toward Pennsylvania, the strong east-northeast wind field that battered NY Harbor abruptly shifted to a 20 m/s southerly wind field. By then, large areas of New York City were underwater (Figure 2), and electricity was out for a large part of the New York Metropolitan Area, including municipalities in NJ, CT, and Long Island (around 5.5 million people lost power in these three states alone: Aon Benfield 2013).

Figure 2. Illustration of Lower Manhattan and the East River Waterfront of the NYC Boroughs of Brooklyn and Queens under Water During Hurricane Sandy's Peak Storm Surge

Notes: Flood extent computed from Modeling Task Force (MOTF) data over the NYC Digital Elevation Model (DEM) as described in the Methods section (FEMA MOTF no date).

The maximum observed storm tide (total water level) measured among several NOAA gages along the coast from North Carolina to New Hampshire was 2.86 m (9.38 ft) above Mean High Water (MHW; 1983–2001 tidal epoch) at Bergen Point West Reach, NY — situated between Newark Bay and Upper New York Harbor. It occurred on October 29 9:24 PM EDT, just under 2 hours after Sandy made landfall, and 30 minutes after normal astronomical high tide was predicted to occur at that station; the storm-surge/residual part of the total water level was thus registered to be 2.87 m (9.42 ft), almost equal to the amount of water above MHW (2.86 m). Thus, notwithstanding second-order complications as sea level rise and tidal inequality, Bergen Point proved to be a good textbook example of the “worst case” scenario of peak storm surge superimposed on normal high tide. The National Hurricane Center listed prevalent observed inundations in the order of 1.2–2.7 m (4–9 ft), expressed above ground level, at Staten Island and Manhattan due to Sandy's storm tide (Blake *et al.* 2013). The observed inundations there match well

with the values implied by the NHC forecast seen in Figure 1. The range of forecast inundations in the official NHC advisories was 1.8–3.4 m (6–11 ft) above ground level (Forbes et al. 2014).

However, the maximum storm surge/residual (total water level minus normal astronomical tide) across this region was measured at Kings Point, NY — in Western Long Island Sound — and reached 3.86 m (12.7 ft) above tidal predictions on October 29 19:00 EDT, which was an hour prior to Sandy's landfall (NOAA-NWS 2013). And yet, inundations above ground in Long Island, Brooklyn and Queens, were reported to be only 0.9–1.8 m (3–6 ft), while in the Bronx and Westchester County they were reported to be even smaller, 0.6–1.2 m (2–4 ft) (Blake et al. 2013). Compared to the values shown in Figure 1 and Forbes et al. (2014) two things are evident: (a) The NHC, SLOSH-based, *storm surge* forecasts issued 12 hrs before Sandy's landfall were about 30 percent lower than predicted for Western Long Island Sound even at the 30 percent exceedance level, and (b) observed ground inundations there were smaller compared to New York Harbor, because the maximum storm surge did not coincide with local high tide. Tides in these water bodies of the New York Metropolitan region are complicated by the fact that two tide waves enter from the ocean twice-daily, one through the Sandy Hook-Rockaway transect, and one, 3 hours later, from Long Island Sound reaching the East River tidal straight that connects the NY Harbor to the Sound and separates the coastlines of Bronx and Manhattan from the coastlines of Queens and Brooklyn.

At the southern tip of Manhattan at The Battery tide gage, peak storm surge and high water also coincided, and maximum water levels reached 2.84 m (9.32 ft) above local MHW, or, equivalently, 3.44 m (11.29 ft) above the NAVD88 geodetic datum used as reference for orthometric heights in topographic land maps. Several other vertical datums (0-reference levels) can be used to quantify the same water elevations, a technical complication that has been criticized both before and after Sandy for creating confusion with a public interested to know how much water they will get over their ground: the same peak water level referenced above local Mean Lower Low Water is 4.28 m (14.06 ft) at The Battery. Regardless of the vertical reference datum, NOAA has determined that the recurrence interval of such extreme water levels is greater than 200 years (US Army Corps of Engineers 2013). Indeed, the coincidence of max surge plus high tide produced a historic flood that inundated much of the 500-year Federal Emergency Management Agency (FEMA) floodplain around the inner New York Harbor (Figure 3). However, in the Upper East River and Western Long Island Sound maximum surge occurred very close to the time of the local normal low tide, causing flooding that was contained for the most part within the 100-year FEMA flood plain. Normal

Upland areas shown with yellow were flooded during Hurricane Sandy. The image covers lower Manhattan near The Battery and part of the Lower East River.

FEMA Base Flood elevations:
Light pink areas are within the 1 percent exceedance probability ("100-yr flood plain"), while more inland yellow areas are within the 0.2 percent exceedance probability ("500-yr flood plain").

Figure 3. Comparisons of Hurricane Sandy Flooding Extents Against FEMA Base Flood Elevation Recurrence Intervals

tidal ranges there are around 1.5–2.1 m (5–7 ft), so one could expect, through the linear superposition principle, that if the storm had arrived and raised its maximum surge about 7 hours earlier coinciding with that morning's local high tide, the water levels (and ground inundations) would have been 1.5–2.1 m (5–7 ft) higher than they actually were.

Further east of New York City, at the city of Stamford, CT, on the northern shores of Long Island Sound, that "worst case" scenario had raised the possibility of a Katrina-like event, given that such water levels would have reached the top of a 43 year old tidal barrier built and maintained by the US Army Corp of Engineers to protect the city center from the flooding seen during the 1938 and 1944 hurricanes that devastated the city; the barrier today provides protection to about 2.4 km² (600 acres) that include part of the Stamford business district (Morang 2007). Thus, many residents of the outer boroughs and south-west Connecticut were spared the outright catastrophe that would have occurred, and for which local officials were originally raising dire warnings.

How close was it really? At Stamford, the Corps closed the barrier on Saturday October 27, two days before the peak of the storm. Based on Army Corp of Engineers documents, the Stamford hurricane barrier was designed for a storm surge of 3.17 m (10.4 ft), coinciding with a mean spring high tide of 1.34 m (4.4 ft) NGVD29 (an older geodetic datum, superseded by NAVD88), resulting in a 4.51 m (14.8 ft) NGVD29 design still-water elevation [In the 1960s, Mean High Water Springs, an estimate of the average water level reached during the peak of a normal spring tide cycle, a "mean spring high tide," was 1.34 m (4.4 ft) above the National Geodetic Vertical Datum of 1929, NGVD29]. The actual top elevation of the

barrier was built to 5.18 m (17 ft) NGVD29, to allow for probable 0.6 m (2 ft) waves riding over the tide and surge during the design storm (Morang 2007). That design storm was a synthetic hurricane (based on a ramped up version of the 1944 hurricane) with an inferred minimum central pressure of 941 mb (27.8 inHg). Sandy's minimum central pressure was comparable, at 939.6 mb (27.75 inHg). Locally at Stamford the barometer dropped to minimum 969 mb (28.0 inHg). Further, Sandy's maximum storm surge was 3.426 m (11.24 ft), higher than the surge of the design storm. A week after Sandy, an article titled "*Weighing Sea Barriers as Protection for New York*" published in the New York Times heralded: "much of Stamford, a city of 124,000, sat securely behind a 17-foot-high barrier that easily blocked an 11-foot surge. . . and helped prevent about USD\$25 million dollars in damage to businesses and homes." 3.362 m (11.03 ft) NGVD29 was in fact the peak observed total water level during Sandy, around 10 pm EDT, October 29 2012 (Figures 4–5). The actual storm surge reached at least 3.426 m (11.24 ft),

Figure 4. Observed Water Level Time Series (Blue Dots, Ft or M NGVD29) and Predicted Normal Tide (Green Dots) at the Ocean-Side of the Stamford Hurricane Barrier around Sandy's Landfall

Notes: The pink line shows the difference of the two, the storm surge, while the red dots show the observed levels behind the barrier. The horizontal red line indicates the level needed for start of damage behind the barrier.

Figure 5. Harbor (Left) and Ocean (Right) Levels across the 90 ft wide Navigation Gate — Part of The Stamford Hurricane Barrier System — that was Closed During Sandy

Notes: Photograph taken just after peak tide was attained at Stamford, CT, October 30 2012. Army Corps of Engineers, with permission.

3 hours earlier, around 7 PM EDT, less than an hour after lower low water of that day (Figure 4). Given that the barrier was designed with a 3.17 m (10.4 ft) surge in mind, the word *easily* may sound precarious. Saving grace, literally, was the fact that the peak surge did not coincide with high spring tide, but rather was near low spring tide. At 7 pm, the normal tidal cycle was near low water at -0.94 m (-3.1 ft) NGVD29. 7 hours earlier, at noontime that day, the normal predicted tide would have been at its peak, absent Sandy, at $+1.46$ m ($+4.8$ ft) NGVD29. The principle of superposition would predict that were Sandy's peak 3.426 m surge to occur 7 hours earlier at normal higher high water, the still water levels would have reached $3.43 + 1.46 = 4.89$ m (16.04 ft) NGVD29 (2.5 m or 5 ft higher than the real Sandy and within less than 29 cm — less than a foot — from the barrier's top elevation at 17 ft NGVD29).

Assuming the stone-slope-protected earth fill dikes and concrete/sheet-pile-bulkhead wall barrier system would have survived the still-water pressure, the barrier would likely have been overtopped by the waves riding on that surge, and the areas protected by the would have become vulnerable to salt water flooding. New York Harbor Observing and Prediction System (NYHOPS) simulated significant wave heights reached 1.07 m (3.5 ft) in Stamford harbor at the peak of the

storm, video observations in the harbor at Avalon (<https://www.youtube.com/watch?v=HiOisYRJO1M>) confirm the presence of moderate-sized waves, and the harbor waterfront around the barrier is a FEMA VE zone due to the possibility of storm-induced velocity action from waves over 0.9 m (3 ft) in height. Wave heights varied locally: At the narrow, sheltered, navigational part of the barrier, the steel flap gate that, during Sandy, was raised to close the channel that connects the outer Stamford Harbor to its inner East Branch (Figure 5), minimal wave conditions were noted by United States Army Corps of Engineers (USACE) personnel during Sandy's peak. The locally calm conditions there during Sandy were possibly due to the local wind field's orientation with regard to the channel; USACE photo evidence during Hurricane Irene, 14 months earlier, shows 0.6 m (2 ft) waves present (Errico-Topolski, pers. comm. 2014). Also note that the fact that that day's higher high water was 0.12 m (0.4 ft) above the 1960s mean high water spring tides (1.46 m instead of 1.34 m MHHW used in the designed storm) has to do with the rate of local sea level rise over the last 50 years, a long term average of 0.26 m (0.84 ft) per century as observed at nearby Bridgeport, CT.

Yet, because of the complex dynamics of the NY Harbor — Long Island Sound system, and their narrow East River connection, such theoretical superposition of peak high water and surge tends to be inaccurate, and a numerical model that resolves both tides and surges is needed to investigate these scenarios. Here, we have used the NYHOPS numerical hydrodynamic model that includes forcing from tides, waves, meteorology and hydrology to estimate what the actual flood levels would have been in the western Sound if Sandy's landfall timing came earlier or later, coinciding with a different tidal stage.

Early in 2013, in collaborative research with New York City for their report "A Stronger, More Resilient New York," by Mayor Michael Bloomberg's Special Initiative for Rebuilding and Resiliency (City of New York 2013), we used the NYHOPS numerical model to estimate what the actual flood levels would have been in the Upper East River and Western Long Island Sound if Sandy came a few hours earlier or later, coinciding with different local tidal phases. The NYHOPS model was used to run scenarios of inundation for these different temporal scenarios for Sandy's landfall and create maps of changes in inundation around the City's 5 boroughs, and, later, Long Island Sound, thus exposing and quantifying flood risk in areas that could have been impacted even more by this storm, like Western Long Island Sound, Queens and the Bronx. The error in the time of landfall in the official NHC forecast issued 4 days before Sandy hit the coast at Brigantine, NJ was about 8–10 hours. This then provides for a margin of uncertainty with regard to the phasing of storm surge and local tide that is important to consider in early storm preparations and decisions.

2. Methods

2.1. New York harbor observing and prediction system (NYHOPS) model

The New York Harbor Observing and Prediction System (NYHOPS) model is a comprehensive hydrodynamic model based on the sECOM code (Stevens Estuarine and Coastal Ocean Model). The computational grid of the NYHOPS covers 7 US states and is itself nested to an even larger Northwest Atlantic model. sECOM (Blumberg *et al.* 1999; Georgas and Blumberg 2010) is a 3 dimensional, free surface, hydrostatic, primitive equation estuarine and coastal ocean circulation model (Figure 6). Prognostic variables include water level, 3D circulation fields (currents, temperature, salinity, density, viscosity, and diffusivity), wind-generated wave height and period. It is a successor model to the ECOM/POM combination that is in use by almost 3000 research groups around the world with over 600 papers having been published with them as the modeling engine (Blumberg and Mellor 1987). Its operational forecast application to the New York/New Jersey

Figure 6. Schematic of the sECOM Modeling System Showing Computational Modules

Harbor Estuary and surrounding waters (NYHOPS) is found online (<http://www.stevens.edu/maritimeforecast>) dating back to 2006 (Bruno et al. 2006; Georgas 2010), and includes forecasts of chromophoric dissolved organic matter and associated aquatic optical properties through coupling to a water quality model (Georgas et al. 2009).

In its 3-dimensional NYHOPS application to the waters of New York and New Jersey (Georgas 2010; Georgas and Blumberg 2010) (Figure 7), the computational domain is discretized on a variable resolution grid (147 × 452 horizontal cells, 15,068 of which are designated as water). The complete NYHOPS grid encompasses the entire Hudson-Raritan (New York/New Jersey Harbor) Estuary, the Long Island Sound, and the New Jersey and Long Island coastal ocean. The horizontal resolution of the grid ranges from approximately 5.6 km at the open ocean boundary to less than 50 m in several parts of the NY/NJ Harbor Estuary. The vertical resolution of the NYHOPS grid is 10 sigma (bottom-following) layers at depths shallower than 200 m, providing forecasts at 150,680 points averaged every 10 minutes.

Through many years of continuous model development, the accuracy and applicability of NYHOPS has improved markedly. Several comprehensive skill assessment studies have been carried out (Fan et al. 2006; Georgas et al. 2007; Georgas and Blumberg 2010; Bhushan et al. 2010; Di Liberto et al. 2011; Orton

Figure 7. Google Interface for NYHOPS Model Forecasts

et al. 2012) and in each case NYHOPS' performance has been exemplary. Today the model is used in the NYHOPS domain with confidence to address emergency issues such as safe navigation, water quality concerns, and beach erosion and flooding. NYHOPS' forecasts are shared daily with the NWS, the United States Coast Guard (USCG), and the NOAA office of Response and Restoration (OR&R). They are also used effectively by NY Harbor's commercial and recreational community — sailors, power boaters, swimmers, and fishermen.

With regard to the recent NYC meteorological event history, scenarios tested include the ones presented here and ones comparing Sandy with a Sandy "flying over" the warmer ocean that Irene flew over, further fuelling its wind field (*Glenn et al.* 2013).

2.2. Forecasts and Hindcasts of Sandy

The speeds at which Hurricane Sandy and, some 14 months before it, Hurricane Irene approached the New York/New Jersey coastline were much slower than some historical hurricane strikes in this area, yet not having sufficient time or detailed enough actionable information was an issue. In its service assessment for Sandy, the National Weather Service (*NOAA-NWS* 2013) noted that:

"NHC (The National Hurricane Center) issued the initial storm surge inundation forecast of 4 to 8 ft above ground level for the New Jersey, New York, and Connecticut coastlines in its 1500 Coordinated Universal Time (UTC) 27 October public advisory, well over 2 days prior to landfall of the center of the cyclone. While surge forecasts were consistent with the observed conditions as the storm approached landfall, the amount of lead time for surge and the way it was communicated represent two areas the Sandy Assessment Team found to be most in need of improvement. . . . The second issue related to NOAA/NWS web pages is the need to go several clicks beyond the main web page. . . . The FEMA Region II staff stated they often use non-NOAA websites because those pages are less technical and more effectively improve situational awareness. NYC OEM uses the Stevens Institute of Technology Storm Surge Interface because it is cleaner and requires fewer mouse clicks to navigate."

The above mentioned service report (*NOAA-NWS* 2013) refers to the Stevens Storm Surge Warning System (www.stevens.edu/SSWS). SSWS presently uses predictive operational hydrodynamic forecast models — NYHOPS, two others from NOAA, and one from Stony Brook University — to communicate forecast flooding at several fixed locations in and around New Jersey. The system provides

a graphical comparison between both real-time observed and model-based forecast total water level (storm surge plus tide) time series against National Weather Service flood elevations at these locations. If total water levels are forecast to exceed NWS-set flood levels at a coastal station, automated e-mails are sent out to service subscribers. The utility and simplicity of the system is well documented.

The operational NYHOPS predictions shown in SSWS use wind, pressure, and surface heat flux forcing derived from the 12 km-resolution 3-hourly NCEP North American Mesoscale Model (NAM) meteorological predictions. NAM is run operationally four times per day. NYHOPS remotely acquires all NAM cycles at initialization time, and then uses the latest NAM predictions available to run its 24 hr hind cast and 72 hr forecast cycles. The NAM cycles used during Sandy in NYHOPS shown here were themselves initialized on 2012-10-27 18z (UTC), 2012-10-28 00z, 06z, 12z, 18z, and 2012-10-29 00z. This is the operational setup for NYHOPS forcing, and has been proven to create accurate predictions (within 15 cm, or 0.5 ft) most of the time. However, thus forced, NYHOPS under-predicted the total water level in the New York Harbor, with a magnitude similar to the NHC and NOAA MDL forecasts (≤ 0.9 m, or ≤ 3 ft). This is the product that, to this day, remains in the online SSWS archives.

After Sandy had passed, we studied the reason for this under-prediction by forcing NYHOPS with different meteorological fields obtained from pre-Sandy forecasts of several different 36–48 h lead-time meteorological models that were made available to us. We found that a meteorological forecast from a lead-time of 47 h prior to landfall from the Rutgers WRF (RU-WRF) model showed the lowest wind velocity Root-Mean-Square errors of all the models, and produced the most accurate storm tides in NYHOPS compared to observations, with the NAM-forced NYHOPS under performing all others tested (Orton *et al.* 2012 in preparation). More recent research has since shown that using the RU-WRF meteorological forecasts to force NYHOPS produced only slightly (by a few cm) greater Root-Mean-Square errors than the best NYHOPS model results we have gotten to date that were based on a proprietary reanalysis of wind fields and pressure (Orton *et al.* in preparation).

For the RU-WRF-based NYHOPS setup, and with the assistance of Rutgers university researchers, NYHOPS was forced with wind, pressure, and surface heat flux variables from the 3 km-resolution, hourly, Rutgers University WRF model (RU-WRF), ran operationally once a day. The forecast cycles used were 2012-10-27 00z, 2012-10-28 00z, and 2012-10-29 00z.

Note also that internal calculation of surface stress in NYHOPS takes into account surface wave roughness explicitly (using surface wave characteristics internally and simultaneously calculated across the NYHOPS domain by the NYHOPS code) through the Taylor-Yelland drag formulation. All models were run

both with (Taylor and Yelland MJ 2001) and without (Large and Pond 1981) explicit wave stress. Consistent with the findings of Orton *et al.* (2012) for NYHOPS sensitivity runs during Tropical Cyclones Irene and Lee, explicit accounting of the extra wave drag using the Taylor-Yelland formulation (and waves internally calculated by NYHOPS) produced better total water level (and peak surge) predictions for Sandy compared to the implicit Large and Pond formulation.

Figure 8 compares the NYHOPS results for Sandy at the Battery, NY, between the operational, NAM-forecast-forced NYHOPS, and the RU-WRF-forecast-forced

Figure 8. The Record of Observed Water vs. Modeled Levels for the NYHOPS Forecast Model Forced by the NAM Forecasts (Top) Compared to NYHOPS Forced by the RU-WRF Forecasts (Bottom) at the Battery, NY, for the Entire Duration of Sandy

NYHOPS. The latter proved to be a significantly better prediction of what actually occurred during Sandy. This of course may not always be the case.

2.3. NYHOPS runs to investigate effect of tidal phase on Sandy Flooding

To investigate the effect of tidal phasing to Sandy flooding, we selected the RU-WRF forecasts to force NYHOPS with, and then ran the NYHOPS model many times, each time setting Sandy's arrival to be an hour further in the past (or in the future) than in reality, within an overall window of a tidal day. The previous high tide was the day's higher-high tide, due to the diurnal inequality. To ensure that we accounted fully for the two semidiurnal cycles within the NYHOPS region, we offset Sandy's meteorological forcing at hourly increments between -14 hrs and $+12$ hrs. We thus ran the model 27 times and collected the maximum water elevations and the times they would have occurred from each model cell.

We also compared to predictions of maximum water levels based on the simple principle of linear superposition at select stations. To do that, tides and observed water levels during Sandy were downloaded from NOAA NOS at each station. Storm surge time series were calculated as the difference between observed and tidally-predicted water levels. Then, the time series of storm surge were offset hourly from Sandy -14 hrs to Sandy $+12$ hrs similarly to what was done with the RU-WRF meteorological forcing above. The shifted storm surge time series were then added to the real astronomical tide to create synthetic (superposition based) total water levels. 27 time series at each station were created, and the maximum water elevations thus predicted were collected from each, along with the times such elevations were predicted to occur based on superposition.

2.4. Flood plain and inundation projections

The water elevation differences between the Hurricane Sandy event and the hypothetical Sandy events with time-shifted meteorology were provided by NYHOPS model data. A "bathtub" technique was utilized for extrapolating these results over land areas that are not part of the model grid (e.g., [Gesch 2009](#); [Titus and Richman 2001](#)), and the FEMA Modeling Task Force (FEMA MOTF no date) field-verified dataset was used to offset model results to observations, as summarized below.

First, a spatially-continuous, gridded (a raster surface) water elevation dataset was created using the NYHOPS data modelled for the real Sandy event using the RU-WRF model forcing. The maximum water elevations within the event time frame at all the NYHOPS grid cells were interpolated by the inverse distance

weighted (IDW) method to a 5 m-resolution grid. Then, a second water elevation surface was made using the NYHOPS data modelled for the hurricane coming 9 hours earlier, as it was found to be one of the most devastating scenarios modeled. The maximum water elevations during the 9-hour-earlier event were interpolated using the same IDW method to the same 5 m resolution grid. Next, the difference surface was created by subtracting the first surface from the second surface, representing the increase (or decrease) in surge if Hurricane Sandy had come 9 hours earlier.

The flooding areas for Sandy were obtained by subtracting the land elevation surface from FEMA MOTF's maximum water elevation surface. The FEMA's water elevation surface is a product of interpolating and extrapolating the high water mark data available in the regions, to 30 m resolution. The land elevations are a mosaic of different LiDAR-derived Digital Elevation Models (DEMs) — a 5 m-resolution DEM for the New York City based on a 0.3 m-horizontal-resolution survey in 2010 averaged to 5 m-resolution, three 3 m-resolution DEMs for West Chester, Nassau and Suffolk, NY based on a series of surveys conducted from November 26, 2011 to April 7, 2012, and a 3 m-resolution DEM for Connecticut based on LiDAR data collected in 2000.

The FEMA's water elevations and the land elevations, both based on NAVD88, were interpolated to 5 m-resolution surfaces, before the latter was subtracted from the former to obtain the flooding areas for Sandy. Finally, the flooding areas for Sandy coming 9 hours earlier were obtained by subtracting the land elevations from the sum of the FEMA's maximum water elevations and the NYHOPS modeled water elevation differences, all with 5 m resolution.

3. Results

3.1. NYHOPS/RU-WRF hind cast of Sandy

Figure 9 shows water level time series comparisons between the NYHOPS model results for Sandy forced by the Rutgers WRF forecasts against total water level observations at stations in and around the New York Metropolitan area. Given the better predicted wind fields from RU-WRF, the NYHOPS predictions were excellent. The root-mean square error between model and observations ranged from 0.1 m at Montauk, NY to 0.27 m at Albany, NY, 240 km inland of New York City. Representative errors for peak water levels were less than half a foot. Station to station, the results shown in Figure 8, compare favorably to Sandy hind casts made with the 2D SLOSH model (Forbes *et al.* 2014).

Sandy spent more time blowing over the waters of the Mid-Atlantic Bight north of Cape Hatter as until it made landfall than many historic hurricanes. Excluding

Figure 9. Comparison of NYHOPS Model Results (Blue) Against Water Level Observations (Red)
Notes: Root-mean-square errors (rmse) are given in each panel, with a mean of 0.17 m.

forerunner surge, its primary surge duration was on the order of a semi-diurnal tidal period. The magnitude of the storm surge within the NYHOPS domain was also similar to the order of local tidal ranges, but with large variation locally and especially where the storm surge was the largest: In Western Long Island Sound and New York Harbor, a dual storm surge converged, first through Long Island Sound forced by the East-Northeast winds prior to Sandy, and then through the New York Bight Apex and the lower Harbor as Sandy came to shore and the surface winds shifted to South-Southeast, then slowly rotated clockwise to W-SW over the next 36 hours (Figure 10).

Usually the tidal water levels at Kings Point trail the tidal water levels at the Battery by 3.5 hrs. The tidal current within the upper East River is progressive, with maximum eastward ebb almost coinciding with low waters at College Point and maximum elevation gradient between the Battery and Kings Point. As the tidal waters at the Battery rise before the waters at Kings Point, the induced pressure gradient forces East River flow that is directed toward the Sound. That normal tidal cycle seems to have been interrupted in the early evening of October 29 2012, as the waters of the Western Sound were pushed by Northeasterly winds downstream toward the East River on a rising Battery tide. Kings Point water levels rose fast,

Figure 10. Wind Speed (m/s) and Direction (Arrows Point to Where the Wind Blows) During Sandy at Robbins Reef, New York Harbor. Dates in EDT

nearly 1 m/hr (3 ft/hr) between 5:30 PM and 6:30 PM EDT, and reached the Battery levels around 6:30 PM EDT. That equalized the Sound-directed pressure gradient, and the whole East River from the Battery to Kings Point rose in tandem until almost 7pm EDT, when peak surge at Kings Point occurred (at 3.86 m, or 12.65 ft above tide), coinciding with local low tide there (and seen as a first peak of 2.55 m (8.36 ft) NAVD88 in the observed total water level), and when the Sandy winds shifted to a southeasterly direction. As the water level at Kings Point stayed flat for about an hour due to a rising tide and a dropping surge, rising water levels at the Battery felt an increasing surge from faster rising harbor waters pushed in by the strong SE winds. This increase in the Battery water levels compared to Kings Point restored the normal pressure gradient for that phase of the tide and made the Upper East River flow again toward the Sound. The surge and total water level at the Battery peaked at 9:25 PM EDT [at 2.89 m (9.41 ft) surge, and 3.44 m (11.28 ft) NAVD88, respectively], half an hour after local high tide. In the meantime, the astronomical tide at Kings Point was rising fast, offsetting the locally decreasing surge, and the total water level at Kings Point peaked just after 10 PM at 3.12 m (10.24 ft) NAVD88 before dropping rapidly as the winds rotated further to South-SouthWest.

3.2. Summary of ranges among simulations

Figure 11 shows results of the NYHOPS model runs with Sandy's meteorology shifted hourly, along with corresponding estimations made by linear superposition,

Figure 11. Time and Height of Peak Water Level if Sandy had Come Between 14 hrs Earlier and 12 hrs Later (–14 to 12, as labeled), Based on the Superposition Principle (left), Versus the NYHOPS Dynamic Modeling (right) at Kings Point (top) and The Battery (bottom)

Notes: Green dots are for the real Sandy (0 hrs). Red dots show the maximum of all peaks. For illustration, as described in the text, the normalized astronomical tide (black curve) and storm surge (green curve) of the real Sandy are also shown.

at The Battery and Kings Point, NY. All 27 peak water levels from each of the 27 scenarios investigated are shown (height above NAVD88, and when they were predicted to occur), and labeled hourly relatively to Sandy's true timing (positive if Sandy had come later by $\times$ hours and negative if Sandy had come earlier by $\times$ hours). The maximum of all the peaks is highlighted with red, and Sandy's true peak water level (0 hr-shift) is highlighted with green. For illustration of the phasing of tide and surge, the pure astronomical tide prediction and observed surge during Sandy are also shown, both normalized by the tidal range (so the tide ranges from 0 to 1).

Because Sandy's storm surge developed slowly, with primary surge spanning almost a complete tidal cycle, both the principle of superposition and the NYHOPS

model show that the times of peak water levels would be concentrated around normal high waters when the astronomical tide would be at its peak. This was consistent for all stations along the coast of NJ, NY, and CT (not shown). This is also because, as seen in Figure 11, magnitudes of storm surge and tidal ranges were of the same order during this event, causing peak total water levels not to coincide with peak storm surge. Thus, a 7 hr-shifted storm surge does not translate to a 7 hr-shifted peak water level.

Notwithstanding these common qualities, Figure 11 shows that the peaks predicted by the dynamic NYHOPS model are not always the same, and many times vary significantly, compared to the linear superposition peaks. As (a) the tide and surge during Sandy were of the same magnitude, (b) both waves were modeled dynamically and dependently, and (c) both tides and surges are captured with only a small error by the model, their physical interaction must be the main cause of these differences. These differences seem to be exacerbated in Long Island Sound as one moves from east to west towards Kings Point (not shown). Because of the near-resonance of Long Island Sound, tidal ranges are regionally the largest there. During Sandy, the maximum surge was also measured at Kings Point. Overall, this dynamic surge-tide interaction has a dampening effect on the peak water levels possible from a Sandy-like event, compared to linear superposition at Kings Point. At the Battery and at Kings Point, plots of storm surge against tide for each of the 27 NYHOPS-simulated scenarios revealed a classic tide-surge interaction (e.g., Prandle and Wolf 1978): storm surges that peaked near high tide were lower (by order 2 ft) than storm surge peaks that occurred near low tide (not shown); at Kings Point in particular, where tides are greater, most storm surges peaked closer to low tide, not high tide. Thus, as seen in Figure 11, and compared to superposition, the combined effect of this tide-surge interaction was the decrease of peak total water levels and their concentration closer to high tide at Kings Point, while at the lower-tidal-range-Battery peak water levels are of similar magnitude but spread more toward low water from amplified low-water surges.

Separately, Figure 11 shows that although for much of New York Harbor Hurricane Sandy's timing close to high tide was as bad as it could be, things could have been much worse elsewhere (though not as bad as one could estimate by superposition). At Bridgeport, CT (not shown), and Kings Point, NY, even an hour later would have produced 0.3 m (1 ft) more water. Overall, if Sandy had arrived closer to the previous, higher high water of the day, things could be markedly worse around Long Island Sound and Upper East River.

The scenarios of Sandy coming between 7, 8, 9 or 10 hours earlier than it did have been found to produce the worst storm surge flooding in the Upper East River within the evaluated cases (Figure 11). Between the four, the case having Sandy

Figure 12. NYHOPS-simulated Water Level Time Series for Sandy (Green), and if Sandy had Arrived 9 hrs Earlier than it did (Red), for Kings Point, NY

arrive 9 hrs earlier than actual landfall was the worst, though slightly. Maximum flooding was predicted to be within 30 minutes from high astronomical tide at Kings Point (Figure 12). Flooding would have generally been worse in the area around the Upper East River west of Hells Gate, with the rest of the City's waterfront seeing still record-breaking but somewhat lower levels. The waters of Western Long Island Sound just west of the City's borders would have seen the highest water levels. Results at other stations are shown in Figure 13.

If we were to just superimpose (add) the maximum surge level that occurred at Kings Point during Sandy (3.86 m, or 12.65 ft, as per above), on the higher high astronomical tide that was predicted for 7 hrs earlier (1.30 m, or 4.26 ft, NAVD88 at 12 noon October 29 2012), we would have predicted that Kings Point water levels could have risen to a devastating 5.15 m (16.91 ft) NAVD88 if Sandy had happened 7 hrs earlier (Figure 11). The same calculation for a Sandy surge coming 2 hrs earlier still, 9 hrs before actual landfall, would be 4.82 m (15.83 ft) NAVD88, as it would be at somewhat lower astronomical tidal stage. As mentioned above, the maximum water level in our model run experiments with Sandy, was found to occur with Sandy coming 9 hrs early. That peak water level was found to be 4.12 m (13.52 ft) above NAVD88 (Figures 11–13) occurring near the time of high tide, just before noon local time October 29 2012. This maximum level is then 0.70–1.04 m (2.3–3.4 ft) lower than that expected by superposition of max tide and max surge. We believe that this is explained by the simple fact that the principle of superposition does not consider the flow through the East River tidal strait that acts as a conduit for the interaction between the two waves that enter through the Lower

Figure 13. Observed Water Elevation (Observed) and NYHOPS Results for Sandy if Sandy had Arrived 9 hrs Earlier than it did (Modeled) at Stations in and Around New York Harbor

Harbor and Block Island Sound reaching it at different tidal phases. We thus believe that our numerical model that considers the dynamics of these interconnected waterways provides the better result.

3.3. Regional differences in inundation depths

Figure 14 presents the main impacts with regard to NYC borough flooding of the scenario of Sandy coming 9 hrs earlier. Areas highlighted with red color would have seen more widespread flooding and order 0.9 m (3 ft) or deeper depths, while green and blue would have seen somewhat less widespread flooding: inundation depths around 0.3 m (1 ft) lower (green) or 0.6 m (2 ft) lower (blue). The figure shows that the peak water level changes would have been quite distinct in terms of their geographical location. The Bronx and northern Queens would have been hit harder, while Staten Island, and then Brooklyn and Manhattan would have seen less water. However, the New York Harbor region would still have seen its record flood elevation exceeded, so the disaster losses could have been more widespread over the city boroughs. Many of the same areas in the City that were underwater during Sandy, including subways and tunnels would have still flooded.

4. Discussion

4.1. *What an extra 0.9–1.2 m (3–4 ft) of water from the Sandy-9 hrs scenario would have meant for neighborhoods and critical infrastructure along the Upper East River and Eastchester Bay*

Figure 14 shows that generally worse flooding would have been endured along the Bronx and Queens waterfronts if Sandy had come 9 hrs earlier, bringing its peak

Figure 14. Regional Differences in Inundation Depths Between Sandy and the Sandy-9 hrs Scenario for New York City Boroughs

Figure 15. Regional Differences in Inundation Depths Between Sandy (Left) and the Sandy — 9 hrs Scenario (Right) Along the Upper East River/Western Long Island Sound from Rikers Island to the West to Eastchester Bay to the East

surge closer to local higher high tide of the day there. Inundation in these northern borrows of New York City and the southwestern shores of Connecticut would have then been closer to the 0.2 percent-chance (“500yr”) floodplain, while flooding would have been less in NY Harbor. Figure 15 shows the simulated expansion of flooded areas and the local rising of inundation depths. Under that scenario, salt water would have inundated critical infrastructure facilities, including the Consolidated Edison Power Plant in Astoria, Queens (not shown), and the four New York City Department of Environmental Protection Water Pollution Control Plans (NYCDEP WPCP) on the Upper East River Waterfront: Bowery Bay, Tallman Island, Hunts Point, and Wards Island. In general, many more houses, parking lots, and subway stations around the Upper East River waterfront would have been reached by floodwaters. North and South Brother Islands would have been fully submerged. The salt water flooding at La Guardia Airport (LGA), one of the historic photographs from the Sandy event as it happened, would have been 3.5 ft (1 m) deeper, and the storm surge would have reached and flooded the Grand Central, south of LGA. In Flushing, Queens, a much larger area between Flushing Bay and Flushing airport would have been flooded, around the New York State Division of Motor Vehicles and the Metropolitan Transportation Authority’s

College Point Depot. Powel Cove and the Malba neighborhood east of College Point would be flooded as well.

Along the north shore of the Upper East River, flooding would have been much worse in the Westchester Creek area. The head of that Creek could have been connected by flood waters to the Hutchinson River mouth at Eastchester Bay through the Northeast Corridor train tracks. The Hutchinson Parkway would have been almost entirely submerged southwest of Eastchester. The Bruckner Expressway might have been breached. It is possible that the Throgs Neck neighborhood of South East Bronx would have become an island. Specific facilities in the Bronx that would be affected include the New York City Housing Authority, Mercy College, and a part of the Hunts Point Food Distribution Center, the main food distribution center for New York City. Approximately 50% or more of the Palmer Inlet neighborhood around the Bronx Country Club would have been reached by flood waters. All of City Island north of Beach Street would have been flooded.

4.2. What the Sandy-9 hr scenario would have meant for Stamford, CT, and its Hurricane Barrier; Implications for Climate Resiliency

It was found that maximum water levels at the western Sound and upper East River would have occurred if Sandy had arrived not 7, but 9 hours earlier than it did (Figure 11). This would have made peak storm surge at Kings Point occur just a couple of hours before the morning high tide of October 29 2013, raising water levels not 1.5 m (5 ft), but 1 m (3.5 ft) higher than what actually happened during Sandy. The simple superposition of the observed peak storm surge on top of high tide in Western Long Island Sound exceeds the still-water elevation used to design the Stamford, CT storm surge barrier by 38 cm (1.25 ft), and comes only 29 cm (0.96 ft) below the dike-wall barrier system's top elevation. The NYHOPS hydrodynamic model results suggest that the waters would have risen to within 75 cm (2.5 ft) of the top elevation of the Stamford storm surge barrier, 46 cm (1.5 ft) lower than the naïve superposition of astronomical tide and storm surge. Yet the USACE barrier at Stamford, assuming structural robustness as per design, would not have been overtopped, and downtown Stamford would have still been spared.

The USACE surge barrier did keep, as many noted, much of Stamford dry during Sandy (see, for example, [NY Times 2012](#) and [CT News 2012](#)). This success of the barrier project during Sandy cannot be understated. It is a testament that the capital investment made in the mid-20th century upheld the long term promise to protect Stamford against a repeat of the destruction and death that the hurricanes

of 1938 and 1944 caused. Yet Stamford would not be safe forever without further action. The latest US National Climate Assessment (Walsh *et al.* 2014, Key Message 10) states that the average water level of the world's oceans is projected to rise by 1 to 4 ft (0.3–1.2 m) by 2100 due to climate change; The extra 0.75 m (2.5 ft) that was found here to be needed to reach the hurricane barrier's top elevation if Sandy were to have stricken near high tide in 2100 is in the middle of that projection. Based on a localized scenario of sea level rise due to climate change, by the end of this century average sea level at Stamford may be 1.1 m (3.6 ft) higher than during Sandy (the latest 75th percentile projection of the New York Panel of Climate change is 1 m, or 3.3 ft, by the 2080s; Horton *et al.* submitted). The simulated image on Figure 16 depicts what would happen at Stamford if a Sandy-like event arrived near high tide in the year 2100 under that

Figure 16. Stamford Flooding Extent and Inundation for a Sandy Event Occurring Near High Tide (Based on the Modeled Sandy-9 hrs Scenario) at the End of this Century, After Accounting for a 3.6 ft (1.1 m) Sea Level Rise (SLR) Scenario

scenario. As extreme storms like Sandy are — based on International Panel for Climate Change predictions — more likely than not to happen more frequently in the future, Stamford now faces a choice whether to adjust its coastal flooding defenses before the next big one strikes the region. Several news reports welcomed investments in the interior storm-water-runoff pumping systems that drain the catchment basins behind the Stamford Hurricane Barrier. Though undoubtedly helpful for storm water management behind the closed barrier, this investment does not fully address the potential for future rising ocean levels and stronger storms overtopping that barrier.

5. Conclusions

A hydrodynamic model study of how shifts in storm surge timing could have influenced flood heights in New York Harbor and Long Island Sound was presented. Multiple flood scenarios were evaluated with Stevens Institute of Technology's New York Harbor Observing and Prediction System model (NYHOPS) having Hurricane Sandy arriving any hour within the previous or next tidal cycle (any hour within a 26-hour period around Sandy's actual landfall). The present study showed that the large devastation seen during Hurricane Sandy could, in fact, have easily been worse in large areas of the greater NY metropolitan area, notwithstanding all the good work that engineers and public officials did to prepare. Some uncertainties in predicting and forecasting local, above-ground inundations from coastal storms were explained and put in perspective, using Sandy as a case study.

For this historic storm, the temporal interplay of its arrival in comparison to the local astronomical tidal phase at least partially defined which neighborhoods and towns were hit the hardest with regard to flood extent and depth. For this slow-developing storm surge, the physically comprehensive dynamic model showed that peak water levels and inundations would be smaller than expected from a linear superposition of tide and surge. Peak water levels and inundations were also found to occur near the time of normal high- rather than low- (NOS-predicted) water, regardless of landfall timing with regard to local tidal phase, due to classical tide-surge interaction further complicated by the East River connection of New York Harbor to Long Island Sound.

If the same storm happened to have come ashore 7 to 10 hours earlier than it did, the salt-water flooding impact to communities along the Upper East River and West-Central Long Island Sound would have been much worse. Some specific areas and critical infrastructure vulnerabilities were highlighted for New York, NY, and Stamford, CT. However, the New York Harbor region would still have seen its

record flood elevation exceeded, so the disaster losses could have been more widespread over the city boroughs. The latest National Climate Assessment raises the level of confidence on expected storminess and precipitation increases over this present century in the Northeast US. These trends are superimposed on rising sea levels. Flooding is now expected once every four years over a nominal Manhattan sea wall elevation of 1.7 m (5.6 ft) NAVD88 (Talke *et al.* 2014). As present and future flooding vulnerabilities are studied, exposed, and hopefully mitigated with resilient measures, today's flood plains will need to be dynamically redrawn (e.g. Orton *et al.* in preparation).

Based partly on the analysis presented here, the City of New York recognized that Hurricane Sandy did not necessarily represent a worst-case scenario and that planning efforts could not just focus on resisting another Sandy-like event. Future coastal storms could have different impacts in many different parts of the city and sea level rise would make flooding more likely, threatening the city's neighborhoods and infrastructure. This recognition was one element that helped the City develop a comprehensive climate resiliency plan, based on the concept of multiple lines of defense, and led to the launch of 257 unique initiatives, based on the best available climate projections, to strengthen the coastline, upgrade buildings, protect infrastructure, and make neighborhoods safer and more vibrant. The latest progress report available at www.nyc.gov/PlaNYC shows the early progress made and points the way toward further implementation efforts in collaboration with a wide range of partners.

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