2014 State of Nuisance Tidal Flooding

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Summary

NOAA water level gauges document an increasing frequency of tidal flooding around much of the U.S., which is driven primarily by local relative sea level rise. Here, we update the number of days during 2014 with a "nuisance" tidal flood, which surpasses the local NOAA elevation threshold for minor impacts (e.g., road closures and diminished storm-water drainage capability) established for emergency preparedness reasons. We examine conditions during 2014 at 27 long-term gauges across the U.S. and compare to flood frequencies recorded during 2013 as well as those expected to occur in 2014 based upon continuation of annual flood trends derived over the 1950-2013 period. During the 2014 meteorological year (May 2014 – Apr 2015), the mid-Atlantic coast was most impacted. Between Sandy Hook, NJ and Savannah, GA long-term *accelerating* trends continued unabated with several locations reporting 20 or more days of flooding and an increase from 2013. Along the West Coast (La Jolla and San Francisco) where local sea level rise has been less over the last couple decades, there were >5-10 days of nuisance flooding, which is close to the trend-expected values. Less-than-expected flooding occurred along the Northeast Atlantic and Gulf Coasts.

With the strengthening of El Niño predicted over 2015, nuisance flooding may become especially problematic along the West and East Coasts based upon historical patterns. With respect to the *steady* continuation of the 1950-2013 trends, nuisance flooding during 2015 is projected to further amplify because of El Niño-related conditions, with a >25% increase at Sandy Hook, NJ, Atlantic City, NJ, Baltimore, MD and Wilmington, NC, a >50% increase at Lewes, DE, Washington D.C., La Jolla, CA and a 75-125% increase at Montauk, NY, Norfolk (Sewells Point), VA and San Francisco, CA. This could result with the highest number of nuisance flood days on record at Sandy Hook, NJ, Lewes DE, Washington D.C. and Norfolk, VA.

Introduction

The National Oceanic and Atmospheric Administration's (NOAA) National Ocean Service (NOS) has operated the National Water Level Observation Network (NWLON) for over a century around the U.S. coast. NWLON water level gauges support safe navigation, economic-zone delineation and emergency storm preparedness as well as track long-term local relative sea level rise (RSLR) around the continental U.S., Hawaii and Island Territories and portions of Alaska (tidesandcurrents.noaa.gov/sltrends). A consequence of RSLR against built infrastructure is a decreased *freeboard,* which increases the probability for flooding during extreme events (Tebaldi et al., 2012; Salas and Obersekera, 2013) like occurred during Superstorm Sandy (Sweet et al., 2013) and this fact is important to consider when planning appropriate flood defenses. But the most-noticeable effect of RSLR is an increased frequency of less-extreme coastal flood events (aka "nuisance flooding") often occurring during sunny-day conditions. In fact, due to RSLR, the annual frequency of nuisance tidal flooding is rapidly growing around the U.S. with rates accelerating along many East and Gulf Coast locations (Ezer and Atkinson, 2014; Sweet et al., 2014). Impacts from such recurrent high-tide flooding include diminished stormwater drainage capacity (Obeysekera et al., 2011), waste-water system infiltration (Flood and

Cahoon, 2011), frequent road closures, and general deterioration of infrastructure and public assets (e.g., freshwater supplies) not designed to withstand frequent inundation or salt-water exposure.

In this report, we update the number of daily nuisance level floods that occurred during 2014 at 27 NOAA gauges in operation since 1950 and make comparison to the number of exceedances expected to occur by continuation of annual exceedance trends computed over the 1950-2013 period established by Sweet and Park (2014). Depending upon the specific nuisance flood level, trends in flood frequencies are characterized as upward-curving accelerations, linear-trend increases where sharp mean sea level punctuations occur during stronger phases of the El Niño Southern Oscillation (ENSO), or no discernable trend due to lack of exceedances above particularly high thresholds. In some locations, usage of an ENSO climate index enhances historical-trend characterization and we also compare to those values. Lastly, with the predicted strengthening of El Niño over the coming year (http://iri.columbia.edu/our-expertise/climate/forecasts/enso/current, accessed August 20, 2015), we give a 2015 outlook for nuisance flooding days at locations where ENSO has historically been a statistically significant factor.

Data and Methods

We tally daily-maximum water levels in 2014 at 27 NOAA gauges that exceed specific elevation thresholds for "minor" coastal flooding (Figure 1). Impact levels are established locally by Weather Forecasting Offices (WFO) of NOAA's National Weather Service (NWS) from years of impact monitoring. We refer to these as days with a "nuisance flood" as compared to the more-severe "moderate" and "major" flood elevation thresholds also established locally for some coastal (tide) gauges and tracked by the Advanced Hydrological Outlook System (water.weather.gov/ahps). Flood advisories or warnings are typically issued by the local WFO when water levels are predicted to surpass the nuisance or the moderate/major levels, respectively. Note that a year (or annual value) in this report represents a meteorological year (May – April), not the traditional calendar year, as to not split the winter season.

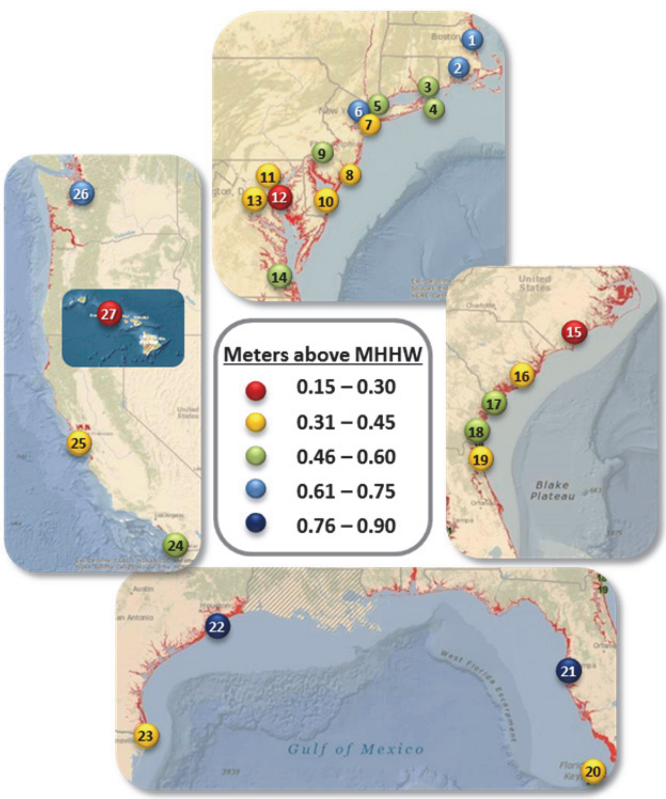

Figure 1. 27 NOAA gauges with station number (see Table 1) and nuisance level elevation thresholds (color-coded) assigned locally by the NWS shown relative to mean higher high water (MHHW) tidal datum defined over the 1983-2001 National Tidal Datum Epoch (CO-OPS, 2001). Red contours are interpolated elevations at or below local gauge nuisance levels as shown in the NOAA Sea Level Rise Viewer (http://coast.noaa.gov/slr).

2014 Nuisance Tidal Flooding

The mid-Atlantic coastline experienced the most nuisance flooding in 2014 (Figure 2a) with Wilmington, NC (71 days), Annapolis, MD (41 days) and Charleston, SC and Washington D.C. (both with 33 days) topping the list. The West Coast experienced a more modest number of days with nuisance flooding. Very few days with nuisance flooding were recorded along the U.S. Northeast and Gulf Coasts, which is partially related to the fact that these regions have higher nuisance flood levels (Figure 1). In 2014, more nuisance flooding (Figure 2a) occurred at gauges, on a whole, where local nuisance level thresholds (i.e., Figure 1) are lower (r=0.7 for quadratic fit between nuisance levels and number of 2014 nuisance floods, not shown) and similar to the pattern shown by Sweet et al. (2014). Such a geometric relationship – increasingly higher exceedances where nuisance flood levels are closer to high tide – reflect broad similarities in the distribution shape (~Gaussian) of daily maxima water levels at the NOAA gauges and the degree of sea level (mean) and storminess (variance) experienced during 2014. We note that interannual mean sea level variability at the Wilmington, NC gauge is linearly correlated with Cape Fear River discharge measured upstream (r=0.61, p value < 0.01 between 1982-2014 annual discharge and detrended mean sea level), but that its 2014 average discharge (~4000 cubic feet per second: waterdata.usgs.gov river gage 02105769) is below its annual average value (~5000 cubic feet per second). It remains unclear how short-period riverine discharge events may have affected the frequency of tidal flooding during 2014.

Compared to 2013 (May 2013 – April 2014), more flooding occurred along the mid-Atlantic, the West Coast and in Honolulu, HI (Figure 2b) as discussed in "climatic patterns". The number of nuisance-flood days that occurred in 2013 (blue bars) as compared to 2014 (red bars) at the 27 gauges in Figure 2b are linearly related (r=0.93; not shown) reflecting year-to-year consistency in local physical forcing. Or simply, locations with more nuisance floods during 2013, for the most part, had more flooding during 2014. The number of 2014 nuisance floods was on average 10% greater than occurred during 2013 at the 27 gauges largely due to continued local RSLR (land subsidence and regional/global sea level rise).

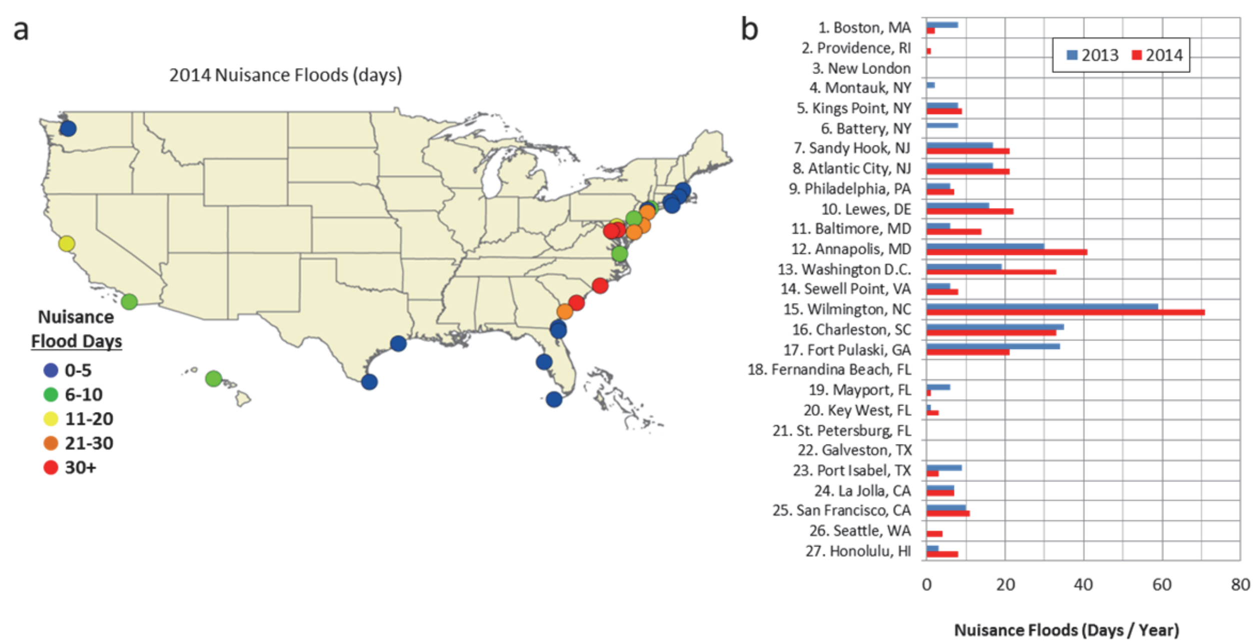

Figure 2. a) Days during meteorological year (May – April) 2014 with a nuisance level flood, which are also shown with b) the number of nuisance-flood days during 2013

2014 Climatic Patterns

During 2014 there were some notable shifts in climatic conditions affecting regional sea levels (Merrifield et al., 2015) and nuisance-flood frequencies. Within the Pacific, a positive ENSO phase (El Niño like) emerged with some associated changes in regional low-frequency mean sea level (Hamlington et al., 2015). As compared to 2013, the Aleutian Low pressure system in the Eastern North Pacific intensified, strengthening the cyclonic wind circulation over the Northeastern Pacific (Figure 3a) and contributing to downwelling conditions, higher sea surface temperatures (Figure 3b) and sea levels along the U.S. West Coast (Emery and Hamilton, 1985) and more nuisance flooding (Figure 2b). The intensification of the Aleutian Low is also indirectly associated with elevated sea levels within Hawaii (Firing et al., 2004), which increases the likelihood of nuisance flooding during higher tides. Although the sea surface temperatures in the North Pacific are ~1° C less than those in 2013 (purple-colored region in Figure 3b), they are 0-2° C above the 1981-2010 climatological mean and related to the "warm-water blob", which formed during the 2013 winter (Bond et al., 2014). Off of the U.S. East Coast, a weakening of the Bermuda High pressure region enhances northerly wind forcing off of the mid-Atlantic coast (Figure 3a) that favors on-shore wind transport, downwelling and elevated sea surface temperatures (~0.5° C, Figure 3b). Such conditions affect longshore pressure gradients (Chase, 1979) and can slow Gulf Stream transport, raising sea levels (Ezer et al., 2013) and the likelihood of nuisance flooding during high tides (e.g., Sweet et al., 2009).

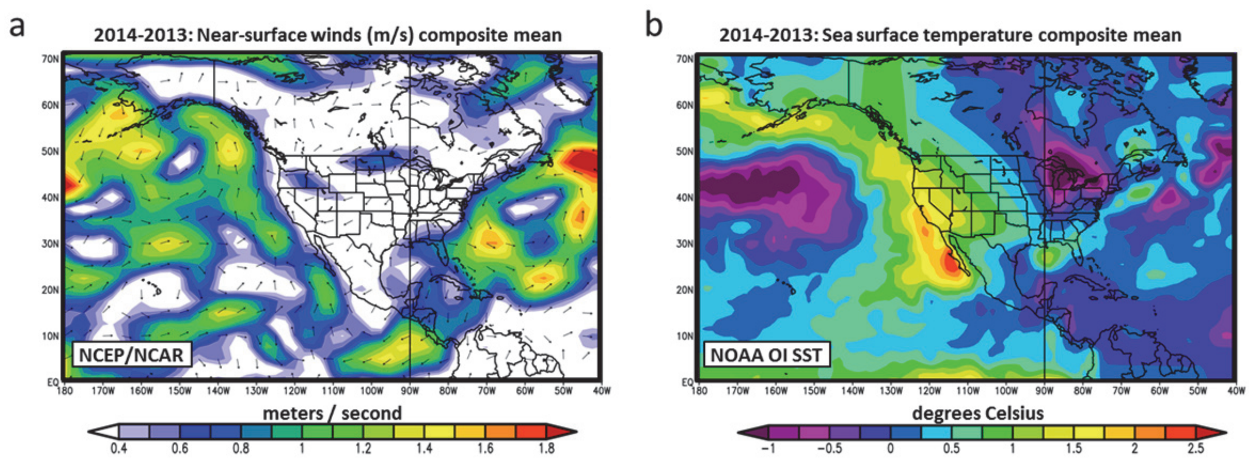

Figure 3. Differences in conditions between 2014 and 2013 meteorological years (May-April) in a) NCEP/NCAR reanalysis near-surface winds (Kalnay et al., 1996) and b) NOAA OI land and sea surface temperatures. Data: NOAA/ESRL Physical Sciences Division

Long-term Trajectories of Nuisance Tidal Flooding

NOAA gauges continue to track the rapid growth in the annual number of days with nuisance level flooding around the U.S. Figure 4a shows the 2014 values (i.e., Figure 2a) in series at each location with annual values measured since 1950. Annual increases are primarily driven by increasing local RSLR, which shifts annual water level distributions to higher elevations such that more-common tides and storm surges surpass the nuisance level threshold. In Table 1, we compare the number of nuisance floods observed during 2014 to the number expected to have occurred in 2014 from continuation of trends based upon 1950-2013 annual exceedances established by Sweet and Park (2014). The trends and their root mean square errors (RMSE, i.e., standard error of the regression) are based upon a least-squares linear or quadratic fit (> 90% significance level; p value < 0.1) and reflect the extent of historical variability of both annual mean sea level and daily maxima variance, which are likely to recur in the future. Nuisance flood trend estimates for 1960 are also in Table 1 to highlight long-term changes in flood frequencies around the U.S.

The number of nuisance flood days observed during 2014 compared to estimates by the gauge-specific trends varies regionally as shown in Table 1. Along most of the mid-Atlantic and West Coasts, the number of nuisance floods recorded in 2014 is close to trend estimates. One notable exception are the 71 nuisance-flood days recorded at Wilmington, NC in 2014, which is outside the 95% confidence interval (> 1.96 standard deviations) of the trend estimate (41 days). The increasingly nonlinear response in flood frequency at Wilmington may be to recent increases in mean sea level, which elevate a larger portion of the year-to-year (~Gaussian) distribution of daily maxima water levels above the nuisance flood level. Along the Northeast Atlantic (the Battery, Kings Point), the Gulf of Mexico (Port Isabel) and Honolulu coasts, 2014 observed values are mostly lower, but generally within the 95% confidence intervals based upon annual historic exceedances.

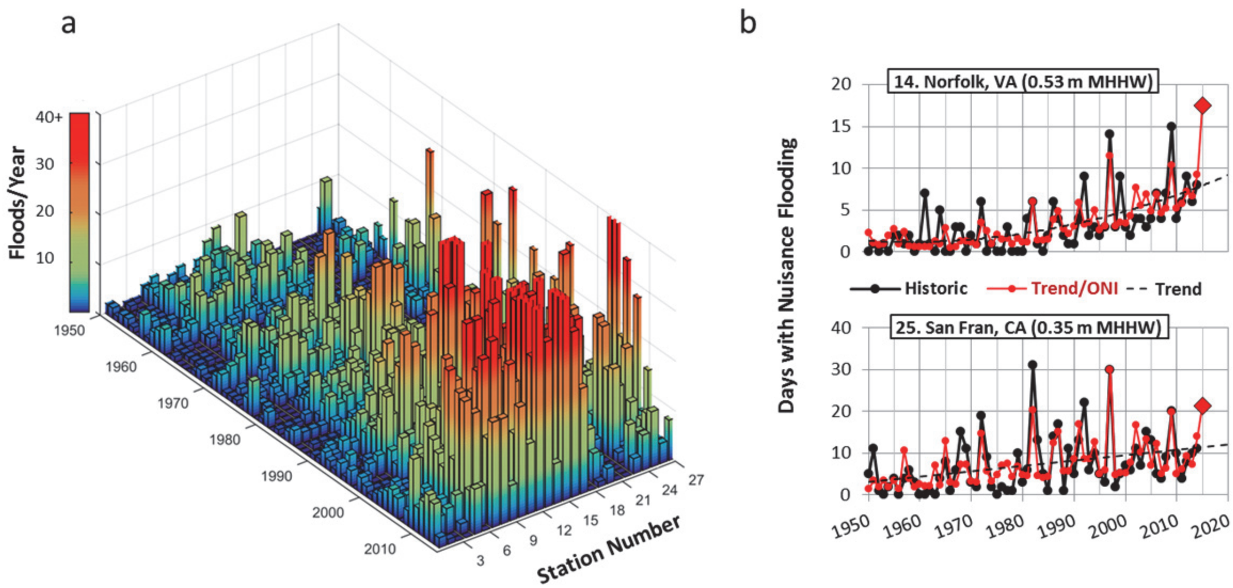

Figure 4. a) 1950 – 2014 meteorological year (May – April) changes in annual days experiencing nuisance level flooding for 27 U.S. NOAA gauges (station number listed in Table 1) and showing b) the least-squares trend (black dash) as a quadratic fit in Norfolk and a linear fit in San Francisco and their bivariate regressions (red line-dot) including the ONI climatic index with 2015 outlooks (red star).

2015 Nuisance Tidal Flooding Outlook

In Table 1 are outlooks for nuisance flooding during 2015 (May 2015 – April 2016) based upon continuation of the 1950-2013 historical trends. Outlooks for future years are assumed valid over the next decade or so, but not over the longer-term since they will not realize (and likely under-estimate) the geometric evolution in exceedance probabilities that will continue to occur relative to the fixed nuisance level elevations (Sweet and Park, 2014). At some locations, the outlooks are further amplified by ENSO influences as quantified through bivariate regression (where significant > 90% level, p values < 0.1) using the multi-model ensemble average of the Oceanic Niño Index (ONI) for 2015 provided by the International Research Institute (IRI) for Climate and Society (IRI, 2015). El Niño is predicted to strengthen in magnitude over the next year with a 2015 ONI average value of 1.68 (May 2015 – April 2016, updated August 20, 2015). Examples of the bivariate statistical fits and the 2015 outlooks (red stars) are shown for NOAA gauges in San Francisco, CA and Norfolk, VA in Figure 4b. Figure 5 illustrates the 2015 nuisance flooding outlooks for all locations based upon either the established local trend (2nd to last column) or trend/ONI combination (last column) in Table 1. Due to the strong El Niño predicted to occur, ocean-atmospheric patterns will likely result in more frequent nuisance flooding along some coastal regions. Along the West Coast, El Niño is associated with direct ocean forcing of high sea level anomalies (Enfield and Allen, 1980; Chelton and Davis, 1982), whereas along the mid-Atlantic, atmospheric patterns typically favor a more coastally oriented winter-storm track (Hirsch et al., 2001; Eichler and Higgins, 2006) that drive a higher frequency of storm surges (Sweet and Zervas, 2011; Thompson et al., 2013). Both conditions have historically been associated with more prevalent flooding during periods of seasonally high tides and within the extra-tropical storm season (Sweet et al., 2014).

Comparing the 2015 nuisance flood outlook based upon the trend/ONI bivariate model (last column) to historical trend only (2nd to last column) in Table 1, a >25% increase is projected to occur at Sandy Hook, NJ, Atlantic City, NJ, Baltimore, MD and Wilmington, NC, a >50% increase at Lewes, DE, Washington D.C., La Jolla, CA and a 75-125% increase at Montauk, NY, Norfolk (Sewells Point), VA and San Francisco, CA. The projected flooding for Sandy Hook, NJ, Lewes DE, Washington D.C. and Norfolk, VA could potentially result in these communities having the highest number of nuisance flood days on record.

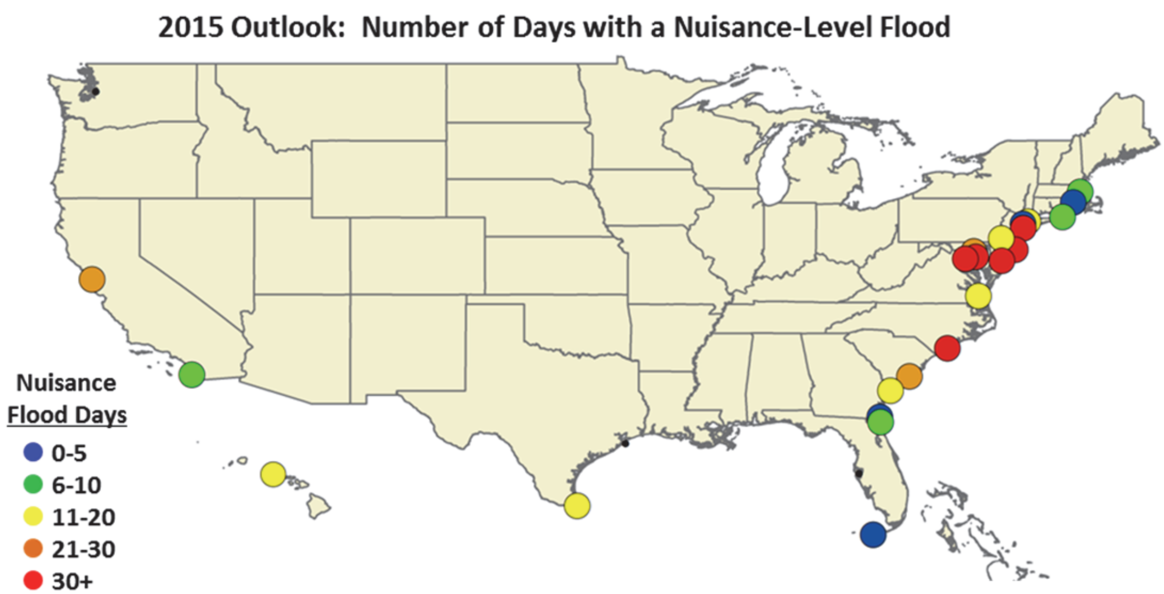

Figure 5. 2015 (May 2015 – April 2016) outlook for days with a nuisance level flood based upon historical trends in annual nuisance flood frequencies and likely amplification by El Niño (where applicable) as listed in Table 1. Locations with no historical trends and thus no 2015 outlooks are shown as black dots.

Table 1. Station number and name, NOAA-defined nuisance flood level, the number of nuisance flood days estimated for 1960 and 2014 based upon 1950-2013 trends (± 1 standard deviation), the number of floods actually observed in 2014 and 2015 outlooks based upon trend continuation and bivariate regression based upon inclusion of the 2015 ENSO ONI climate index prediction. Station names and 2015 outlooks are **bold** where projected flooding could result in the highest annual number of nuisance flood days on record. Only regressions significant above the 90% level (p values < 0.1) are provided. Flood days are rounded to the nearest day.

Station Number	Station Name	Nuisance Level (above MHHW)	1960 Flood Days (Trend[1])	2014 Flood Days (Trend[1])	2014 Flood Days (Observed)	Outlook: 2015 Flood Days (Trend[1])	Outlook: 2015 Flood Days (w/ ONI[1,2])
1	Boston, MA	0.68	2±2	7±2	2	7±2	---
2	Providence, RI	0.66	2±1	2±1	1	2±1	---
3	New London, CT	0.60	---	---	0	---	---
4	Montauk, NY	0.60	1±1	3±1	0	3±1	6±1
5	Kings Point, NY	0.52	4±4	17±4	9	18±4	---
6	Battery (NYC), NY	0.65	1±2	4±2	0	5±2	---
7	**Sandy Hook, NJ**	0.45	2±5	26±5	21	27±5	**40±5**
8	Atlantic City, NJ	0.43	2±5	26±5	21	27±5	36±5
9	Philadelphia, PA	0.49	2±4	13±4	7	13±4	---
10	**Lewes, DE**	0.41	5±5	23±5	22	24±5	**41±5**
11	Baltimore, MD	0.41	2±3	14±3	14	15±3	22±3
12	Annapolis, MD	0.29	4±8	44±8	41	45±8	---
13	**Washington D.C.**	0.31	7±9	31±9	33	32±9	**53±8**
14	**Sewells Point, VA (Norfolk)**	0.53	1±3	8±3	8	8±3	**18±2**
15	Wilmington, NC	0.25	1±8	41±8	71	43±8	62±7
16	Charleston, SC	0.38	3±5	26±5	33	26±5	---
17	Fort Pulaski, GA (Savannah)	0.46	3±5	17±5	21	18±5	---
18	Fernandina Beach, FL	0.59	0±1	2±1	0	2±1	---
19	Mayport, FL	0.44	0±2	6±2	1	6±2	---
20	Key West, FL	0.33	0±1	3±1	3	3±1	---
21	St. Petersburg, FL	0.84	---	---	0	---	---
22	Galveston (Bay), TX	0.79	---	---	0	---	---
23	Port Isabel, TX	0.34	1±5	16±5	3	16±5	---
24	La Jolla, CA	0.51	0±3	6±3	7	6±3	10±3
25	San Francisco, CA	0.35	4±6	11±6	11	12±6	21±5
26	Seattle, WA	0.65	---	---	4	---	---
27	Honolulu, HI	0.22	3±11	17±11	8	17±11	---

(1) based upon 1950-2013 linear/quadratic and ONI-bivariate regressions where significant > 90% level (Sweet and Park, 2014)

(2) 2015 ONI = 1.68 based upon multi-model ensemble projection average (iri.columbia.edu: August 20, 2015)

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