

## 2016 State of U.S. High Tide Flooding and a 2017 Outlook

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### Summary

The number of days with high tide flooding in 2016 was above the local flood-frequency trend at the majority of the 28 locations examined (more than half of the trends are accelerating in time). Three all-time records for annual-flood days were either tied (Key West, FL) or broken (Charleston, SC; Savannah, GA). If an El Nino develops this coming year (May 2017 - April 2018) as model guidance suggests is possible, the frequency of daily floods may be compounded relative to long-term trends, upwards of 25% or more at several U.S. West and East Coast locations.

### Overview and Background

Tide gauges of the National Oceanic and Atmospheric Administration (NOAA) have been measuring water levels for over a century along the U.S coastline (<https://tidesandcurrents.noaa.gov>). They 1) measure in real-time and predict the daily tides for safe maritime navigation, 2) monitor storm-surge conditions for emergency preparedness and 3) track 'relative' sea levels (RSL) due to long-term changes in sea surface height and land elevations.

Tide gauges are observing a rapid - accelerating in dozens of locations - change in annual high tide flood frequencies along the U.S. coastline over the last several decades due to RSL rise (Ezer and Atkinson, 2014; Sweet et. al., 2014; Sweet and Park, 2014). Flooding assessed in this report is defined as a water level reaching or exceeding the local elevation threshold set at NOAA tide gauges by NOAA Weather Forecasting Offices and local emergency managers for 'minor' impacts to some infrastructure (<http://water.weather.gov/ahps>). When such flooding is anticipated, NOAA typically issues a coastal flood 'advisory' (NOAA, 2014). NOAA also establishes thresholds for more severe flooding (i.e., moderate and major) associated with a coastal storm 'warning' for serious risks to life and property, which will continue increasing in frequency with RSL rise (Sweet et al., 2017). Minor high tide flooding has been described as "recurrent", "sunny-day", "shallow coastal" and "nuisance" flooding. Common is that the underlying driver of this frequency change is RSL rise, as infrastructure was never built to be exposed to typical tides and storms. In the coming future, however, the cumulative toll of such flooding will become a more serious, disruptive and costly issue as its frequency/depth/extent grow over time (Sweet and Park, 2014; Dahl et al., 2017; Moftakhari et al., 2015, 2017; Sweet et al., 2017).

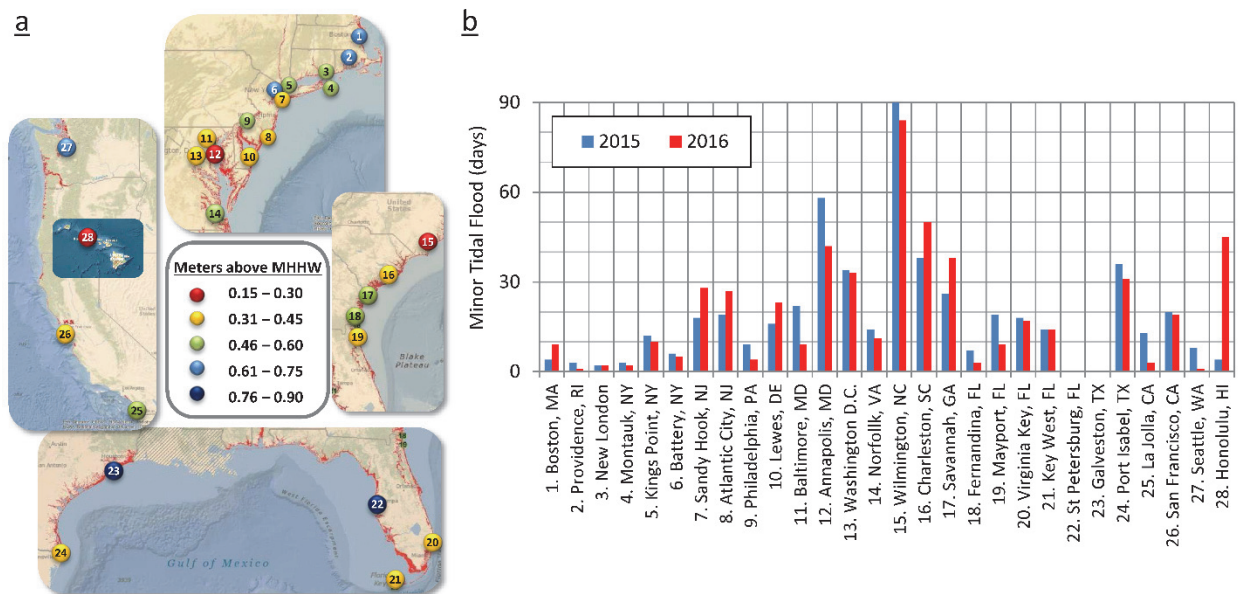
This report updates the number of days during the 2016 meteorological year (May 2016 – April 2017) with a minor coastal flood at NOAA tide gauges ([tidesandcurrents.noaa.gov](https://tidesandcurrents.noaa.gov)) (Figure 1a). It also provides an experimental annual 'outlook' for flood frequencies during 2017 (May 2017 - April 2018) based upon methods of Sweet and Park (2014), building upon two previous assessments made for 2014/2015 and 2015/2016 (Sweet and Marra, 2015; Sweet and Marra, 2016). As communities become increasingly exposed to tidal flooding from RSL rise, annual monitoring and predictive next-year 'outlooks' may help in preparedness budgeting (e.g., for mobilization to repeatedly close streets, installation of pump systems, storm-drain in-flow preventers, sand bags, etc.).

**2016 Conditions**

During 2016, high tide flooding was most frequent (>30 days) along parts of the mid-Atlantic, Gulf and Hawaiian Coasts (Figure 1b) due to anomalously high sea levels (tidesandcurrents.noaa.gov/sltrends). Three all-time records were broken (Table 1: 50 flood days at Charleston, SC and 38 days at Savannah, GA) or tied (14 days at Key West, FL). Relative to 2015 values, flood frequencies during 2016 ranged by about ±50% locally in some locations (e.g., about a 50% increase at Savannah, GA). The one notable increase in flood frequency during 2016 occurred in Honolulu, HI (1000% increase) where prolonged high sea surface heights have contributed to higher seasonal tides, flooding and public concern<sup>1</sup>.

High tide flooding was most frequent in Wilmington, NC with 84 days. This location’s elevation threshold is one of the lowest in the country and impacts are mostly in terms of minor flooding of roadways near the tide gauge location. At this level, tidal waters are also known to infiltrate the downtown storm-drainage system and pond along some downtown Wilmington roadways<sup>2</sup>. Storm-water infiltration is problematic because it degrades drainage capacity in gravity-driven storm-water systems and rain can compound flood severities (Wahl et al., 2015; Wdowski et al., 2016).

Along the Southeast Florida coast, high tide flooding was relatively modest in frequency, but was problematic<sup>3</sup> due to the extremely flat, low-lying, and porous (and populated) landscape. The Virginia Key (Miami region) tide gauge recorded 17 days with flooding, which was near its all-time record (18 days in 2015). The Southeast Florida coast (and much of the Southeast Atlantic Coast) has had very high RSL rise rates of about 5 mm/year over the last couple of decades. Coupled with slowdowns in Gulf Stream transport (that raises coastal sea levels), these effects are contributing to a rapid increase in high tide flood extent, depth and frequency (e.g., Sweet et al., 2016).



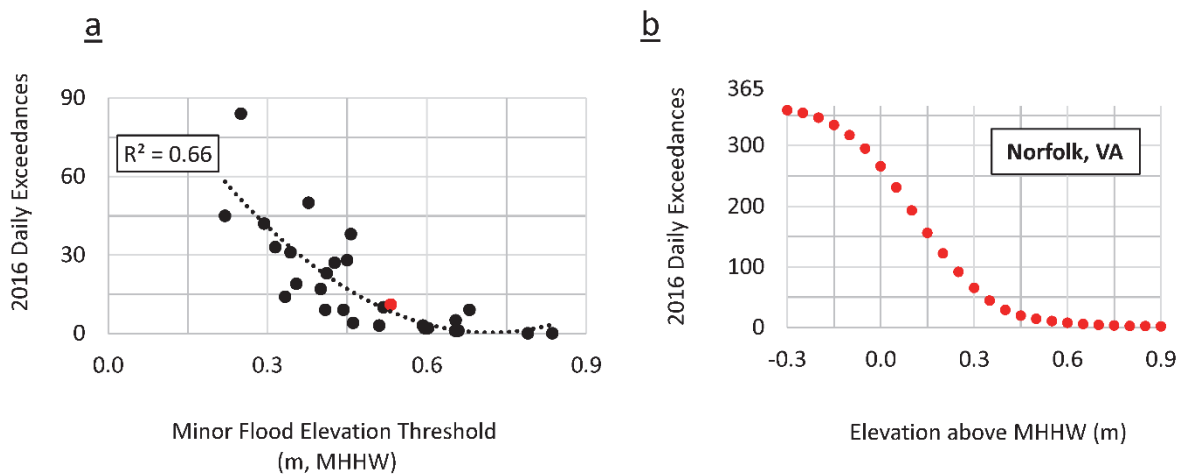
**Figure 1.** a) 28 NOAA tide gauges and minor flood elevation thresholds relative to mean higher high water (MHHW) with exposed topography (red) mapped by the NOAA SLR Viewer (<https://coast.noaa.gov/slr>), b) days in 2015 and 2016 with minor high tide flooding.

<sup>1</sup><http://khon2.com/2017/05/22/disaster-response-readied-for-king-tide-flood-risk/>

<sup>2</sup><http://water.weather.gov/ahps2/hydrograph.php?wfo=ilm&gage=wlon7>

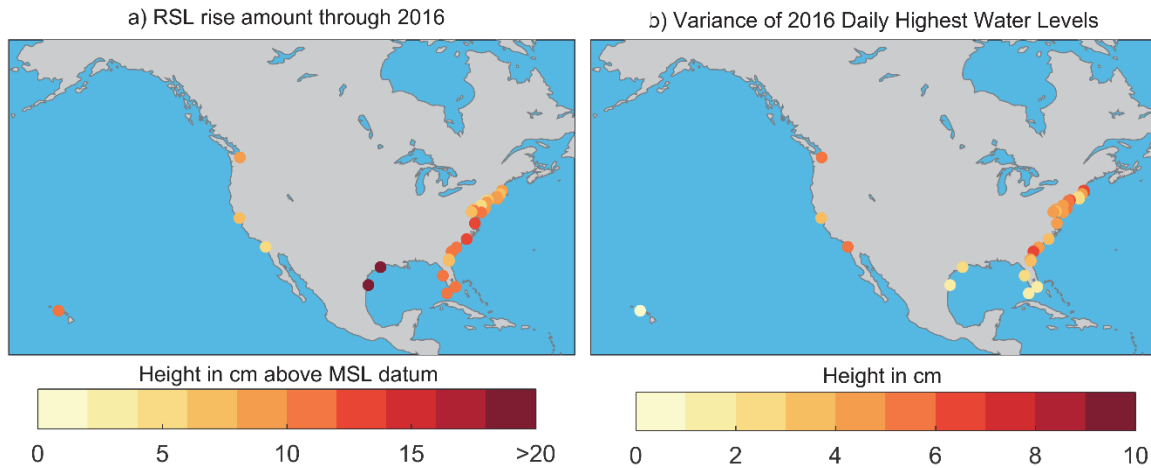
<sup>3</sup><https://www.nytimes.com/2016/11/18/us/intensified-by-climate-change-king-tides-change-ways-of-life-in-florida.html>

Patterns in Flood Frequencies. In most locations, flood frequencies in 2016 exceeded their local trends (Table 1). Comparing all locations, a general pattern exists: where elevation thresholds are lower (i.e., Figure 1a), much more flooding occurred (e.g., Wilmington); where thresholds are higher such as in St. Petersburg and Galveston (reflecting hurricane-flood mitigation), flooding was mostly nonexistent (better discussed in terms of annual exceedance probabilities). The annual number of high tide exceedances across all 28 locations is correlated to the flood elevation threshold, and the exceedance curve resembles a 'bell-shape' distribution as shown in Figure 2a (as in Park and Sweet, 2014). The fit of the distribution is reasonable ( $R^2 = 0.66$ ) even when accounting for 'noise' introduced by varying characteristics across sites. For comparison, an empirically derived exceedance curve for elevations between -0.3 to 0.9 meters above mean higher high water (MHHW) at a single gauge location is shown for 2016 in Norfolk, VA (Figure 2b).



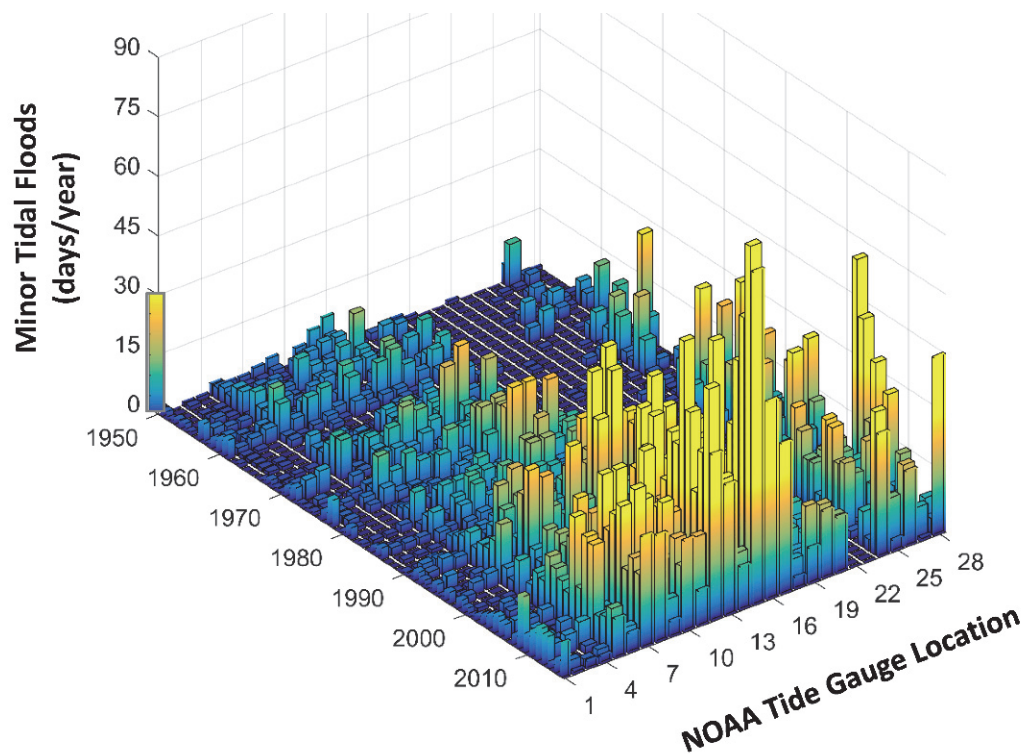
**Figure 2.** a) 2016 flood days and flood elevations for the 28 tide gauge locations and b) an empirically derived exceedance probability curve between -0.3 and 0.9 m above MHHW for a single tide gauge location at Sewells Point (Norfolk), VA.

The extent that a location's flood frequency deviated from the spatial pattern in Figure 2a (e.g., distance between any specific dot and black dashed line in Figure 2a) is dependent upon the mathematical product of two additional factors: the cumulative amount of RSL rise through 2016 since the most recent (1983-2001) datum epoch at a tide gauge location (Figure 3a) and the variance of the daily highest water levels in 2016 (Figure 3b) at a tide gauge location. Together with the elevation threshold, this additional factor (mean \* variance) largely explains ( $R^2=0.90$  of bivariate regression significant above the 99% level, not shown) the fitted curve in Figure 2a. Thus, where RSL in 2016 was higher (e.g., Southeast Atlantic and Western Gulf Coasts) and/or where daily highest water levels during 2016 were more energetic (from larger tide range or more *stormy* conditions) as found along the mid-Atlantic, daily water levels more often exceeded a specific elevation threshold.



**Figure 3.** a) RSL rise through 2016 relative to local MSL datum and b) variance of 2016 daily highest water levels.

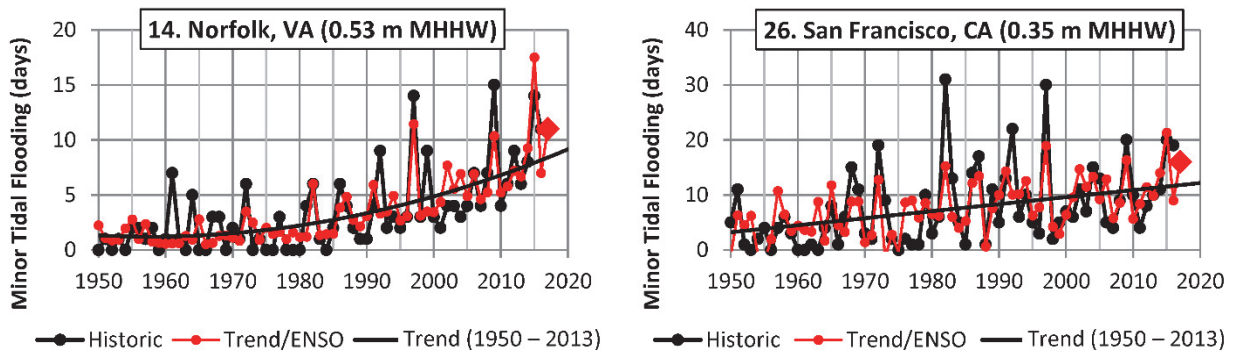
Historical Comparison. Due to continued RSL rise, which decreases the remaining ‘freeboard’ or height between the typical high tides and the elevation threshold for minor flooding, flood frequencies are rapidly increasing (Sweet and Park, 2014). In fact, annual flood frequencies are accelerating in over 25 of 45 locations with hourly tide gauge observations since 1980 (Sweet et al., 2014), though not all are examined in this report. Comparing 2016 flood frequency trend values (based upon regression fits of historical annual exceedances) to those for 1995, the rates have increased locally by 130% on average (ranging from 30% to 270%) since 1995 (Table 1). Changes in annual flood frequencies since 1950 are shown in Figure 4.



**Figure 4.** Annual tidal flood frequencies from 1950 – 2016 (meteorological year: May – April) above the local minor flood elevation threshold for 28 NOAA tide gauges (location number listed in Table 1 and shown in Figure 1).

**2017 High Tide Flood ‘Outlook’**

We provide next-year flood-frequency “outlooks” by projecting the historic trends into 2017, and where applicable, considering the predicted strength of the El Niño Southern Oscillation (ENSO; Table 1) following methods of Sweet and Park (2014). The ensemble average of a group of international ENSO predictions (<http://iri.columbia.edu/our-expertise/climate/enso>) suggests the development of a relatively mild El Niño (average Oceanic Niño Index [ONI] value of 0.64). Tidal flood frequencies are typically higher along the mid-Atlantic and West Coasts during El Niño (Sweet and Park, 2014) from changes in regional sea surface heights and/or high-water variances from a combination of oceanic forcing along the West Coast and altered prevailing winds and storm tracks along the East Coast (e.g., Sweet and Zervas, 2011; Thompson et al., 2013; Hamlington et al., 2015). Historic annual flood frequencies are shown for Norfolk, VA and San Francisco, CA in Figure 5 showing this relationship and the 2017 outlook (red diamond). Considering the projected strength of ENSO (ONI), flood frequencies during 2017 may be about 25% (15-40%) higher than the historical trends not considering ENSO effects in several West and East Coast locations (Table 1) based upon historical relationships (significant above the 90% level).



**Figure 5.** Annual flood frequencies (black circles) reaching or exceeding the local flood elevation threshold (shown for each location) for minor impacts from 1950 to 2016 (black line-dots) with 1950-2013 quadratic trends in Norfolk and a linear trend fit in San Francisco and bivariate regressions (red line-dot) including ENSO effects (ONI) and 2017 Outlooks (red diamond). Update to Sweet and Park (2014).

**Table 1.** Location number and name and NOAA-defined minor (nuisance) flood level as shown in Figure 1, historic maximum number of days per year with a minor tidal flood, the number of minor tidal flood days for 1995 estimated by trend analysis, the number of flood days occurring in 2016 and Outlooks for 2017 based upon trend continuation and bivariate regression based upon inclusion of the 2017 ONI prediction. Trends shown are significant above the 90% level (p values < 0.1). Numbers in bold represent a tied or broken all-time record.

Location Name	Minor Flooding	Historic Record	1995 Floods --- 2016 Flood Days ---			--- 2017 Outlook ---	
	(above MHHW)	Yearly Floods	Trend <sup>1</sup>	Trend <sup>1</sup>	Observed	Trend <sup>1</sup>	w/ El Nino <sup>1,2</sup>
1 Boston, MA	0.68	14	2	7	9	8	---
2 Providence, RI	0.66	5	1	2	1	3	---
3 New London, CT	0.60	6	---	---	2	---	---
4 Montauk, NY	0.60	7	1	3	2	3	4
5 Kings Point, NY	0.52	29	8	18	10	19	---
6 Battery (NYC), NY	0.65	9	2	5	5	5	---
7 Sandy Hook, NJ	0.45	37	11	28	28	29	35
8 Atlantic City, NJ	0.43	37	11	28	27	29	33
9 Philadelphia, PA	0.49	30	6	14	4	14	---
10 Lewes, DE	0.41	39	10	25	23	26	32
11 Baltimore, MD	0.41	24	6	15	9	16	18
12 Annapolis, MD	0.29	66	20	47	42	48	---
13 Washington D.C.	0.31	48	18	33	33	34	42
14 Norfolk, VA	0.53	15	4	8	11	8	11
15 Wilmington, NC	0.25	90	17	44	84	46	52
16 Charleston, SC	0.38	38	14	27	<b>50</b>	28	---
17 Savannah, GA	0.46	34	9	18	<b>38</b>	19	---
18 Fernandina Beach, FL	0.59	7	1	2	3	2	---
19 Mayport, FL	0.44	19	2	6	9	7	---
20 Virginia Key (Miami), FL	0.40	18	*0	4*	17	4	---
21 Key West, FL	0.33	14	1	3	<b>14</b>	4	---
22 St. Petersburg, FL	0.84	1	---	---	0	---	---
23 Galveston, TX	0.79	4	---	---	0	---	---
24 Port Isabel, TX	0.34	36	6	17	31	18	---
25 La Jolla, CA	0.51	14	4	6	3	6	8
26 San Francisco, CA	0.35	31	9	12	19	12	16
27 Seattle, WA	0.65	10	---	---	1	---	---
28 Honolulu, HI	0.22	57	12	17	45	18	---

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

<sup>(2)</sup> El Nino (ONI) strength = 0.64 during 2017 (iri.columbia.edu: May 18, 2017 plume)

\* based upon 1994-2013 linear fit

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