Future Nuisance Flooding in Norfolk, VA, From Astronomical Tides and Annual to Decadal Internal Climate Variability

A. G. Burgos
Old Dominion University, aburg002@odu.edu

B. D. Hamlington

P. R. Thompson

R. D. Ray

Original Publication Citation

Burgos, A. G., Hamlington, B. D., Thompson, P. R., & Ray, R. D. (2018). Future nuisance flooding in Norfolk, VA, from astronomical tides and annual to decadal internal climate variability. *Geophysical Research Letters, 45*(22), 12432-12439. doi:10.1029/2018gl079572

Geophysical Research Letters

RESEARCH LETTER
10.1029/2018GL079572

Key Points:
- Nuisance flooding can occur from high tides alone in Norfolk starting in the year 2030 with a sea level rise of 18 cm
- Internal climate variability can increase nuisance flooding by 126% compared to tides alone in Norfolk with a medium sea level rise of 40 cm

Correspondence to:
A. G. Burgos,
aburg002@odu.edu

Citation:
Burgos, A. G., Hamlington, B. D., Thompson, P. R., & Ray, R. D. (2018). Future nuisance flooding in Norfolk, VA, from astronomical tides and annual to decadal internal climate variability. *Geophysical Research Letters*, *45*, 12,432–12,439. https://doi.org/10.1029/2018GL079572

Received 10 JUL 2018
Accepted 17 NOV 2018
Accepted article online 21 NOV 2018
Published online 28 NOV 2018

Future Nuisance Flooding in Norfolk, VA, From Astronomical Tides and Annual to Decadal Internal Climate Variability

A. G. Burgos[1], B. D. Hamlington[2], P. R. Thompson[3], and R. D. Ray[4]

[1]Department of Ocean, Earth and Atmospheric Sciences, Old Dominion University, Norfolk, VA, USA, [2]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA, USA, [3]Department of Oceanography, University of Hawai'i at Mānoa, Honolulu, HI, USA, [4]Laboratory for Geodesy and Geophysics, NASA Goddard Space Flight Center, Greenbelt, MD, USA

Abstract Increasing sea level rise will lead to more instances of nuisance flooding along the Virginia coastline in the coming decades, causing road closures and deteriorating infrastructure. These minor flood events can be caused by astronomical tides alone, in addition to internal climate variability on annual to decadal timescales. An assessment of nuisance flooding from these two effects is presented up until the year 2050 for Norfolk, Virginia. The analysis of water levels indicates that nuisance flooding from tides alone in conjunction with a medium-high sea level scenario will result in flooding beginning in 2030 with frequency increasing thereafter. The addition of climate variability, by use of an empirical mode decomposition, leads to a substantial increase of flooding relative to the tides-alone analysis and shows flood events beginning as soon as 2020. High tides in the future will produce nuisance flooding without the need of other drivers such as coastal storms.

Plain Language Summary As sea level continues to rise, coastal cities are going to start to see increases in nuisance flooding. This minor flooding is generally caused by tides and wind events, leading to inundation that over time deteriorates roads and infrastructure. Nuisance flooding in Norfolk, Virginia, has increased 325% since 1960 and is becoming more prominent. By combining sea level estimates, tidal estimates, and natural internal climate variability contributions to sea level rise, we have determined how nuisance flooding will increase in the future for Norfolk up until the year 2050. Our analyses show that this flooding will continue to increase in frequency with time, with a potential for well over 200 flood events in the year 2049.

1. Introduction

As sea level rise (SLR) continues, many coastal cities around the world will experience more frequent and severe flooding. Adaptation and mitigation plans are crucial for these coastal cities, and how well a city can plan for coastal change relies heavily on accurate flood assessments for the future. Although large disaster flooding from coastal storms such as hurricanes receives the majority of attention in news outlets, SLR is contributing to another significant issue of chronic low-level inundation called nuisance flooding. Although not a major threat, this minor flooding occurs on a local scale during high tide and is often driven by winds, inundating and closing roads, deteriorating infrastructures, and compromising sewer systems (Vandenberg-Rodes et al., 2016). Nuisance flooding is already a concern at many locations around the U.S. coastline, and these flood events are increasing in frequency (Dahl et al., 2017; Ezer & Atkinson, 2014; Moftakhari et al., 2015; Ray & Foster, 2016; Sweet & Park, 2014; Vitousek et al., 2017). There is already evidence that nuisance flooding could cause comparable or even larger, cumulative property damage compared to infrequent extreme events (Moftakhari et al., 2017), and as such, estimates need to be a critical aspect in coastal manager's plans to properly mitigate and adapt to the transportation, property, and public health impacts.

This flooding can also be exacerbated by changes in ocean circulation, such as variations in the Gulf Stream, and from natural internal climate variability, all of which affect sea level (Carson et al., 2015; Ezer, 2016; Ezer & Atkinson, 2017). Natural internal climate variability (IC) on annual to decadal timescales includes signals such as seasonal cycles, El Niño Southern Oscillation, and Pacific Decadal Oscillation, among others. Conceptually, IC acts as a lowering or rising of the sea level baseline, the level upon which higher-frequency variability causes sea level change. There have been a multitude of studies to assess and quantify how specific

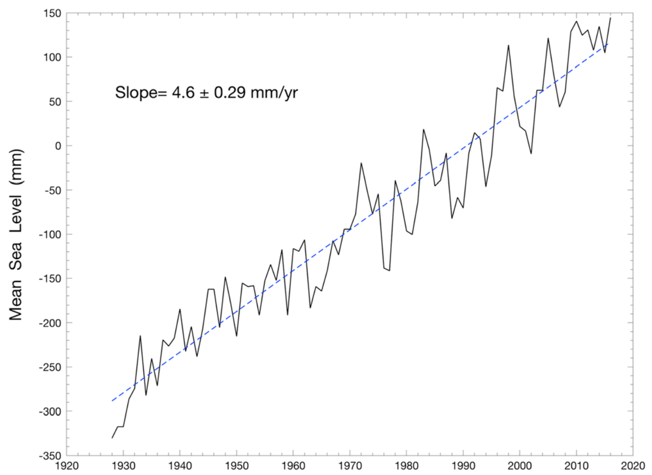

Figure 1. Annual mean sea level at Sewell's Point, VA, from the Permanent Service for Mean Sea Level relative to the 1983–2001 mean sea level datum from the National Oceanic and Atmospheric Administration.

events could influence regional SLR (e.g., Boening et al., 2012; Hamlington et al., 2013, 2015, 2016; Han et al., 2016; Wahl & Chambers, 2016). However, it is the culmination of *all* IC on annual to decadal timescales that impacts sea level height, which will then affect nuisance flooding.

A technical report by the National Oceanic and Atmospheric Administration (NOAA) concluded that nuisance flooding has mainly been occurring with high tide due to climate-related SLR, land subsidence, and loss of natural barriers in locations such as Baltimore, Maryland; San Francisco, California; and Norfolk, Virginia (NOAA, 2017). In Norfolk alone, there has been a 325% increase in nuisance flooding since 1960, which ranks in the top 10 U.S. cities with an increase in high-tide flooding (NOAA, 2017). This flooding is only going to be exacerbated in the future due to regional SLR and may be enhanced or suppressed by IC (Sweet & Park, 2014). As flooding intensifies, coastal populations need accurate assessments of future nuisance flooding to help shape adaptation plans. This study focuses on the Hampton Roads region in southeast Virginia, which covers approximately 7,500 km^2 of low-lying coastal land surrounded on three sides by water (Kleinosky et al., 2007). More than 1.5 million people live in this area, which is home to the largest naval base in the world, making this a crucial area to study (Kleinosky et al., 2007). Popular belief in Norfolk is that these nuisance flood events are caused by large wind events, which leads this study to look in detail how nuisance flooding may change in the future due to rising seas coupled with tides and internal climate variability alone. The first analysis for Norfolk is modeled after Ray and Foster (2016) who looked at nuisance flooding in Boston, MA, from tides alone through the year 2050. While other high-frequency events are important, this analysis focuses on when astronomical tides alone may cause nuisance flooding in Norfolk. A second analysis looks at the coupled effects from tides and IC on annual to decadal timescales.

2. Data

2.1. Tide Gauge Data

The Sewell's Point tide gauge is located at a naval port north of downtown Norfolk (36.947, −76.330). The record spans from 1927 to 2016 and is 99% complete. The annual sea level height data at Sewell's point was taken from the Permanent Service for Mean Sea Level (PSMSL), and had the mean during the epoch (1983–2001) removed to provide Figure 1. Taking a least squares linear fit yields a relative SLR of 4.6 ± 0.29 mm/year. The nuisance flood level is determined by NOAA's Weather Forecast Office (NFO) at 53 cm above mean higher high water (MHHW), of 217.6 cm (relative to Sewell's point station datum; Sweet et al., 2014). It is important to realize that this nuisance flood level is an empirical threshold and is designated based on NOAA's Weather Forecast Office's minor flooding level, which describes water levels that have minimal or no property damage, with some public threat (Moftakhari et al., 2018). The threshold does vary from city to city depending on how the flood waters affect the respective area. Flooding may still occur in select locations in and around Norfolk with a water level below the 53 cm above MHHW threshold. This empirical level is necessary, however, to be able to provide a quantitative basis for describing when nuisance flood events occur. By using this threshold, we can determine when predicted high waters may exceed this level leading to nuisance flood events in Norfolk.

2.2. SLR Scenarios

To create future scenarios of SLR, three projections were established: low, medium, and high scenarios with the observed annual record from PSMSL preceding the three projections The annual instead of monthly mean sea level data was used to smooth out daily or monthly extrema, such as daily flood events, to isolate the contribution of tides alone to nuisance flood events. For the projections, the medium projection follows the intermediate-high scenario as discussed in Tebaldi et al. (2012) for Sewell's Point. Tebaldi et al. (2012) created SLR projections using a semiempirical approach following Vermeer and Rahmstorf (2009). This method uses observations and model simulations in a linear relationship between SLR, global warming during a reference period, and an instantaneous global warming rate (Tebaldi et al., 2012). These data were then applied to climate model simulations to determine global sea level projections and adjusted for local variations including vertical land motion, thermal expansion, changing ocean dynamics, and gravitational changes (Tebaldi et al., 2012). For Sewell's Point, there is an expected 18-cm increase by 2030, and by 2050 a 40 cm increase all relative to the 2008 sea level height (Tebaldi et al., 2012). The next two scenarios are taken as a high and low end of this projection. The low scenario follows a 30-cm rise, and the high scenario follows a 50-cm rise by the year 2050, again relative to the 2008 sea level height. These scenarios are not meant to follow any specific representative concentration pathway (RCP), but the low, medium, and high projections are within the bounds of the RCP 2.6, RCP 4.5, and RCP 8.5 climate projections, respectively, as further discussed in Kopp et al. (2014). The ranges presented (between 30- and 50-cm rise by 2050) are also in line with the upper and lower bounds of projected SLR at Sewell's Point from other studies (Boon et al., 2018; Dahl et al., 2017). By using these three scenarios, new time series composed of the historical observations and projected future sea level heights out to the year 2050 were created. The mean sea level found from Sewell's Points datum was added back into each time series.

3. Methods

Relative regional sea level rise (RRSLR) plays an important role in determining how nuisance flooding will increase in the future. RRSLR can be determined from a combination of several factors presented in the following equation:

$$RRSLR = HF + IC + AN + LM, \tag{1}$$

where *HF* refers to high-frequency variability ranging from synoptic to subannual timescales (events like tides and storms), *IC* represents the climactic natural internal variability on annual to decadal timescales, *AN* is the secular trend associated with anthropogenic forcing (thermal expansion and melting ice sheets), and *LM* is the land motion at the coast. The *HF* term is solely represented here by the tidal data. *AN* is represented in the SLR projections along with the *LM* term since Tebaldi et al. (2012) included subsidence rates in the SLR projections. Finally, *IC* is considered as described below.

3.1. Tidal Analysis

The first analysis determines the predicted nuisance flooding events in Norfolk from the combination of SLR and tides. To predict the tides at Norfolk, we estimated tidal harmonic constants by least squares from hourly data collected over the interval 1983–2015. An initial spectrum of tidal residuals was used to select 88 constituents up through species 10 (i.e., up through frequencies of 10 cpd). Nearly all residual spectral lines could be accounted for by these 88 constituents, although many of these are small and could have been neglected for present purposes. As is typical, the largest constituent is the lunar semidiurnal tide M_2 of amplitude 35.6 cm; it has a small seasonal modulation in both amplitude and phase, accounted for by constituents MA_2 and MB_2. Diurnal constituents are small, the largest being K_1 with amplitude 5.1 cm. It is known (Flick et al., 2003) that the tidal range at Norfolk has slowly decreased over the course of the twentieth century. We have therefore also done a second analysis of historical hourly data back to 1927 by computing annual time series of harmonic constants, and we find a secular decrease in M_2 amplitude of -1.3 ± 0.2 cm per century. A similar decrease is observed in mean tidal range: -2.8 ± 0.3 cm per century, which is slightly greater in magnitude than twice the tidal amplitude. A corresponding decrease in phase lag is even larger: $-4.7° \pm 0.6°$ per century. However, the phase time series (not shown) indicates that this large change occurred mainly between years 1950 and 1985 and the phase has not significantly changed since then. (See Hill, 2016, for a review of possible mechanisms that can induce such changes.) Partly owing to their somewhat erratic nature and partly to the relatively small amplitude change, we have decided to ignore these secular changes when predicting tidal water levels into the future.

The seasonal cycle in water level is appreciable at Norfolk, with mean amplitudes of the annual and semiannual constituents (over the 1983–2015 interval) being 6.5 and 5.0 cm, respectively. The two terms combine to produce highest water levels in late September and lowest in mid-January. These terms are included in our time series of predicted tidal high water. At the latitude of Norfolk, the 18.6-year node tide is very small, 2 mm at most (Woodworth, 2012), and can be ignored.

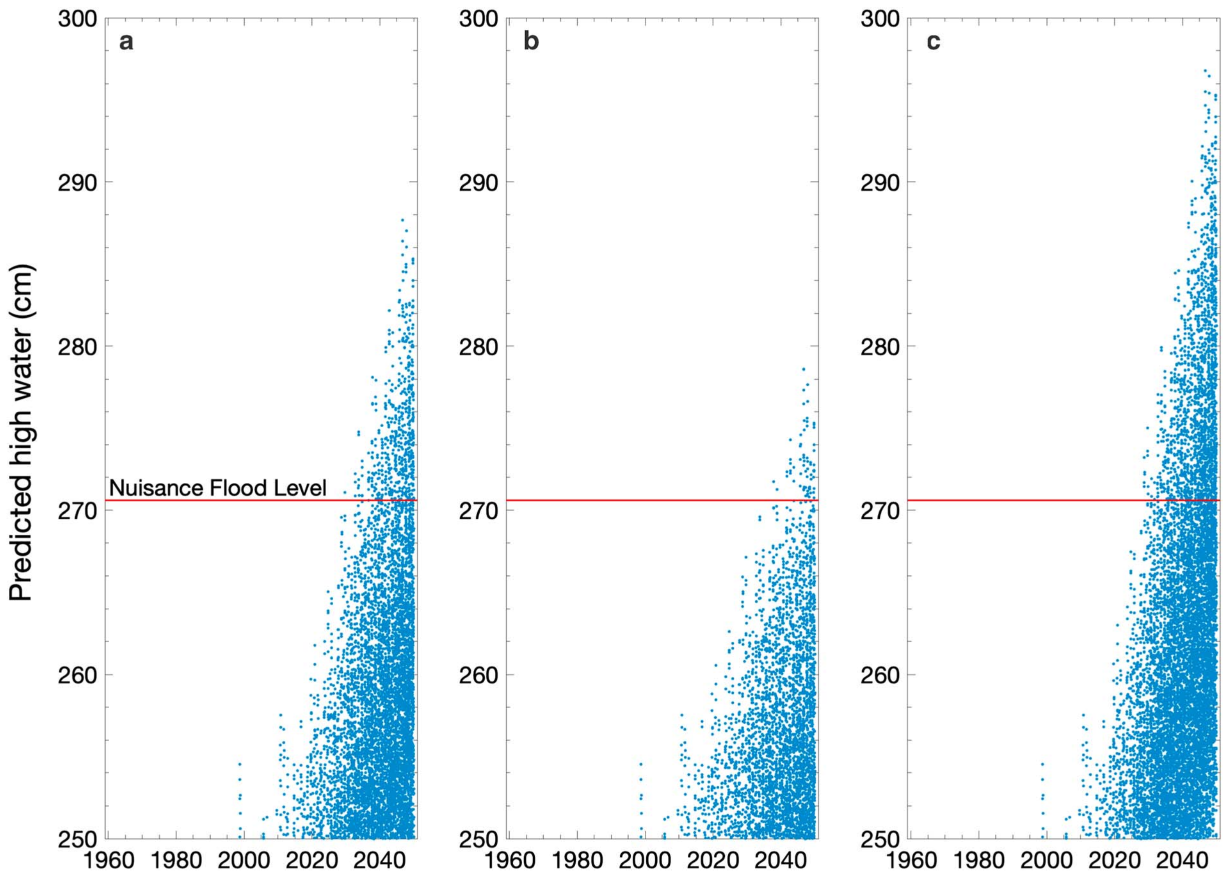

Figure 2. Predicted high tides exceeding the nuisance flood level of 53 cm above mean higher high water. (a) shows the medium scenario, (b) the low scenario, and (c) the high scenario. Heights are relative to the station datum of the Sewell's Point tide gauge.

The tidal predictions (January 1960 to December 2049) for Sewell's Point were used to compute times and elevations of high and low water. The high tides were isolated, and the annual data from the SLR scenarios starting at 1960 were added to the tidal elevations. This was done for all three scenarios, creating nuisance flood estimates from 1960 to 2050 (Figure 2). Once the predicted high water (including SLR) exceeds the nuisance flood level, this is defined as a nuisance flood event.

3.2. Internal Climate Variability

To determine future IC, first the natural climate signals are isolated using past observations. To do this, an empirical mode decomposition (EMD) was performed on the observed monthly sea level height data at Sewell's Point after the seasonal (both annual and semiannual) signal in the tide gauge data was removed. This was done with a harmonic fit of sines and cosines with periods of 1 and 0.5 years. This was done to prevent overlap with the tidal predictions, which included seasonal cycles. The EMD acts as a suite of band-pass filters that separates the natural climate signals into intrinsic mode functions (IMFs)—each with its own intrinsic timescale—without leaving the time domain. The assumption is that the data must be composed of simple intrinsic modes of oscillations (Molla et al., 2005), where the EMD will separate these oscillatory patterns into high and low frequencies. This nonlinear nonstationary method has proven useful for extracting natural climate signals and allows for annual and decadal modes to be isolated (Ezer, 2013; Ezer et al., 2016). Figure 3 shows the eight IMFs extracted from the data. These IMFs do not represent or show individual IC modes, like El Niño Southern Oscillation, but instead show the individual components of IC on the order of specific timescales. Figure 3 shows the dominant frequencies that range from high to low frequency. We are interested in the IMFs that cover the range from annual to multidecadal variability (subplots 2–7), which will be referenced hereafter as A, B, C, D, E, and F. The first and last IMF were not used because the first one shows a frequency too high on the order of less than 1 year and may be influenced by short term wind events, and the last IMF was not used since it represents SLR and would overlap with the SLR projections.

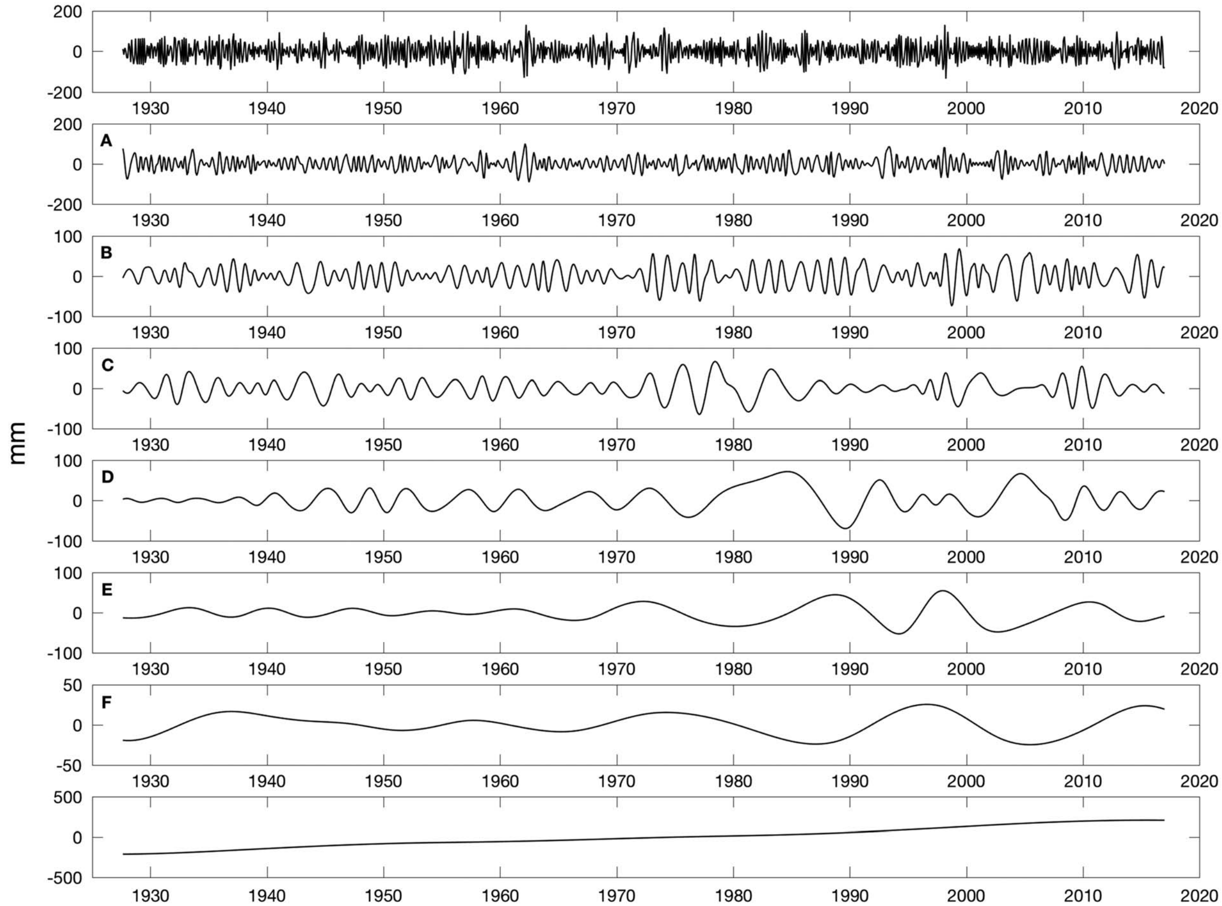

Figure 3. Intrinsic mode functions from the empirical mode decomposition analysis on Sewell's Point monthly sea level data. Top three plots indicate signals on the order of annual variability. The next two show annual variability, with the two plots following on decadal timescales. The last subplot indicates multidecadal timescales.

To use the selected IMFs, we assume that IC will occur in the future, as it has been occurring in the past. Because we cannot conclude that the variability will repeat itself exactly, we introduce a randomization procedure to provide different possibilities of how these internal variabilities could be combined and applied in the future. We are only interested in creating a new time series of IC to apply to the future years, from January 2017 to December 2049. By determining possibilities of future IC, we can have a better idea of how nuisance flooding will progress in Norfolk from more than the combination of tides and SLR.

We extracted randomized years from the selected IMFs (A–F) to create a synthetic time series of 33 years, which were added directly to the projected years from the three SLR scenarios plus the tidal predictions. To capture potential phasing of the signals in the IMFs, different window lengths were extracted from each mode. More specifically, in IMF A, B, and C, random 5-year segments were taken out of the IMF's to create new 33-year long time series. The remaining IMFs had a similar process done with 10-, 15-, and 20-year segments pulled out of D, E, and F respectively. These 5- to 20-year time segments were chosen based on the IMF frequencies occurring on those timescales as seen in Figure 3. The new randomized time segments from all six IMFs were added together, smoothed to remove discontinuities, and the mean subtracted. The mean was subtracted to ensure that the randomization process created IC values within a reasonable amplitude, by mediating the high and low peaks. This time series now represents possible natural internal sea level height variability on the order of annual to decadal timescales. Of this process, 10,000 randomizations were created, then each one was added on to the future years of the low, medium, and high sea level projections with the tides. This gives us 10,000 iterations of potential nuisance flooding scenarios for each SLR case, which included the tidal and IC influences.

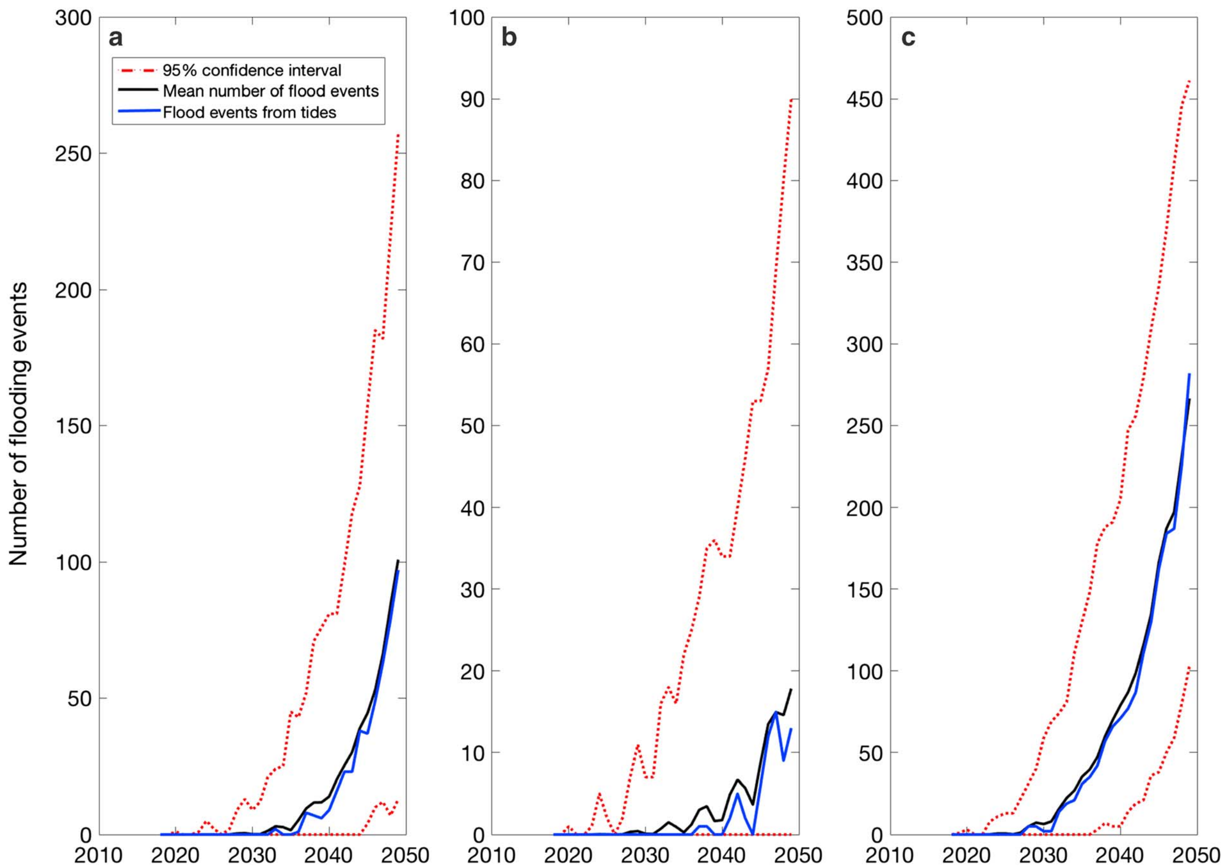

Figure 4. Average number of flood events each year across the 10,000 iterations combining tides, internal climate, and sea level rise scenarios in black. On this mean, 95% confidence estimates are in dashed red. The number of nuisance flood events from tidal influences alone are in blue. (a) shows the medium scenario, (b) the low scenario, and (c) the high scenario.

4. Results and Discussion

Figure 2 shows the flooding events for the three different SLR cases plus tides. Each event will be relatively short, on the order of minutes (if the predicted high water barely exceeds the nuisance flood level) to a few hours (Ray & Foster, 2016). This is because low tide will occur roughly 6 hr after high tide and soon brings the water level back down under the nuisance flooding threshold. From this analysis, no nuisance flood events are expected from tides alone until around 2030 for all three scenarios. This is the case because although nuisance flood events have been occurring in Norfolk, they happen on a daily timescale in conjunction with other high-frequency events like storms or high wind events, which were removed by using the annual sea level data as discussed previously. Figure 2 shows the medium scenario with a total of 458 events throughout the time period, with the first event occurring in 2030. On the low and high end, these scenarios show 66 and 1,816 total events, respectively. It is clear that the number of events relies heavily on how SLR will progress in the future, and the number of flood events for each scenario is still likely to change due to wind driven events. Also, IC can temporarily increase or decrease RRSLR, shifting that baseline for high-frequency events to act upon. It is important to realize that IC can either increase or decrease the number of flood events, as it lowers or rises sea level.

The results from combining the three different SLR scenarios plus the tides and different combinations of potential IC are depicted in Figure 4. Averaging the number of flood events across all 10,000 iterations (black line) provides an estimate of how many events could be expected per year. This is very close to the tides alone analysis (blue line) due to IC essentially being averaged out when looking at the mean events. The medium scenario gave an average total of 579 events across the time frame (2018–2050), the low scenario yielded an average of 140 events, and the high scenario showed 1992 events. By using a randomization procedure to include IC in the flood estimates, the average number of flood events for each scenario changes slightly with each new iteration. However, the average number of events stays within a few events of the numbers presented here each time. Compared to the flooding with tides alone, including IC into the analysis increased the number of events in the low scenario by 212%, medium scenario by 126%, and high scenario by 110%. In addition, for the medium scenario, several iterations showed nuisance flood events from tides and IC to begin occurring as soon as 2020. Furthermore, and importantly for planning, each scenario in Figure 4 shows a relatively large confidence interval resulting from the possible range of IC. For example, the low scenario has a potential to have zero nuisance flood events by 2050 or upward of 60 events within the 95% confidence interval. Similarly, the upper end of the high scenario confidence interval is over 400 events per year by 2050. While the exact timing is unknown, at some point in the future, periods of elevated sea level due to IC will occur, leading to Norfolk experiencing the number of flood events at the higher end of the confidence bound.

5. Conclusions

Nuisance flooding will increase along coastal towns as sea level continues to rise. Norfolk in the Hampton roads region is particularly prone to flooding due to its low elevation, with over a million people and the world's largest navy base at risk. The frequency and severity of future flooding will be heavily influenced by how much SLR occurs in the future. There has yet to be seen a purely tide-induced nuisance flood event in Norfolk, with that expecting to change around 2030 across all scenarios. Tides are not going to be the only factor to consider, and it is important to keep in mind that these flooding events generally occur when several processes converge together, such as SLR combined with wind-driven events like coastal storms. These are virtually impossible to spatially and temporally predict, even though we know that they will occur at some point in the future. IC is also difficult to predict, and although we cannot forecast exact phasing, we can describe how it might impact flood events in the future based on past observations. With internal climate variability added in, the time frame shifts such that nuisance flood events occur earlier than 2030 from the combination of SLR, tides, and IC.

These results show that nuisance flooding will continually increase in the future without the occurrence of wind-driven events. This has large implications for the future, where at periods of some high tide, there will be minor flooding without any extra forcing needed, solely from SLR, tides, and IC. The flooding events presented here, especially in the medium- to high-end SLR scenarios, should be taken as a baseline for coastal planners looking into the future, as other high-frequency events will increase the severity and number of flood days beyond what is presented here. Overall, nuisance flooding presents an increasing problem for coastal towns and can cause considerable harm over time by adding stress to infrastructure, storm sewers, and transportation if no action is taken. These estimates are essential for decision makers and coastal managers, who need to develop and implement adaption plans in the coming years to reduce the impacts of nuisance flooding. These estimates can also allow managers to better inform residents on how flooding will be increasing in the future, and the actions they can take to protect themselves and property.

Acknowledgments
The tide gauge data are available from the Permanent Service for Mean Sea Level (PSMSL), 2018, retrieved 3 January 2018 from http://www.psmsl.org/data/obtaining/. A. G. B and B. D. H acknowledge support from NASA Grants NNX16AH56G and 80NSSC17K0564. P. R. T. acknowledges support from the NOAA Research Global Ocean Monitoring and Observing Program in support of the University of Hawaii Sea Level Center (NA16NMF4320058).

References

Boening, C., Willis, J., Landerer, F., Nerem, S., & Fasullo, J. (2012). The 2011 La Niña: So strong, the oceans fell. *Geophysical Research Letters*, *39*, L19602. https://doi.org/10.1029/2012GL053055

Boon, J. D., Mitchell, M., Loftis, J. D., & Malmquist, D. M. (2018). Anthropocene sea level change: A history of recent trends in the U.S. East, Gulf, and West coast regions. Special report in Applied Marine Science and Ocean Engineering (SRAMSOE) No. 467. Virginia Institute of Marine Science, College of William and Mary. https://doi.org/10.21220/V5T17T

Carson, M., Köhl, A., & Stammer, D. (2015). The impact of regional multidecadal and century-scale internal climate variability on sea level trends in CMIP5 models. *Journal of Climate*, *28*(2), 853–861. https://doi.org/10.1175/JCLI-D-14-00359.1

Dahl, K., Fitzpatrick, M., & Spanger-Siegfried, E. (2017). Sea level rise drives increased tidal flooding frequency at tide gauges along the U.S. East and Gulf Coasts: Projections for 2030 and 2045. *PLoS One*, *12*(2), E0170949. https://doi.org/10.1371/journal.pone.0170949

Ezer, T. (2013). Sea level rise, spatially uneven and temporally unsteady: Why the U.S. East Coast, the global tide gauge record, and the global altimeter data show different trends. *Geophysical Research Letters*, *40*, 5439–5444. https://doi.org/10.1002/2013GL057952

Ezer, T. (2016). Can the Gulf Stream induce coherent short-term fluctuations in sea level along the U.S. East Coast?: A modeling study. *Ocean Dynamics*, *66*(2), 207–220. https://doi.org/10.1007/s10236-016-0928-0

Ezer, T., & Atkinson, L. P. (2014). Accelerated flooding along the U.S. East Coast: On the impact of sea-level rise, tides, storms, the Gulf Stream, and the North Atlantic Oscillations. *Earth's Future*, *2*(8), 362–382. https://doi.org/10.1002/2014EF000252

Ezer, T., & Atkinson, L. P. (2017). On the predictability of high water level along the U.S. East Coast: Can the Florida current measurement be an indicator for flooding caused by remote forcing? *Ocean Dynamics*, *67*(6), 751–766. https://doi.org/10.1007/s10236-017-1057-0

Ezer, T., Haigh, I. D., & Woodworth, P. L. (2016). Nonlinear sea-level trends and long-term variability on western European coasts. *Journal of Coastal Research*, *320*(4), 744–755. https://doi.org/10.2112/JCOASTRES-D-15-00165.1

Flick, R. E., Murray, J., & Ewing, L. (2003). Trends in United States tidal datum statistics and tide range. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, *129*(4), 155–164. https://doi.org/10.1061/(ASCE)0733-950X(2003)129:4(155)

Hamlington, B. D., Cheon, S. H., Thompson, P. R., Merrifield, M. A., Nerem, R. S., Leben, R. R., & Kim, K.-Y. (2016). An ongoing shift in Pacific Ocean sea level. *Journal of Geophysical Research: Oceans*, *121*, 5084–5097. https://doi.org/10.1002/2016JC011815

Hamlington, B. D., Lebel, R., Strassburg, M., Merem, R., & Kim, K. (2013). Contribution of the Pacific decadal oscillation to global mean sea level trends. *Geophysical Research Letters*, *40*, 5171–5175. https://doi.org/10.1002/grl.50950

Hamlington, B. D., Leben, R. R., Kim, K.-Y., Nerem, R. S., Atkinson, L. P., & Thompson, P. R. (2015). The effect of the El Niño-Southern Oscillation on U.S. regional and coastal sea level. *Journal of Geophysical Research: Oceans*, *120*, 3970–3986. https://doi.org/10.1002/2014JC010602

Han, W., Meehl, G., Stammer, D., Hu, A., Hamlington, B., Kenisgon, J., Palanisamy, H., et al. (2016). Spatial patterns of sea level variability associated with natural internal climate modes. *Surveys in Geophysics*, *38*(1), 217–250. https://doi.org/10.1007/s10712-016-9386-y

Hill, D. F. (2016). Spatial and temporal variability in tidal range: Evidence, causes, and effects. *Current Climate Change Reports*, *2*(4), 232–241. https://doi.org/10.1007/s40641-016-0044-8

Kleinosky, L. R., Yarnal, B., & Fisher, A. (2007). Vulnerability of Hampton Roads, Virginia to storm-surge flooding and sea level rise. *Natural Hazards*, *40*(1), 43–70. https://doi.org/10.1007/s11069-006-0004-z

Kopp, R. E., Horton, R. M., Little, C. M., Mitrovica, J. X., Oppenheimer, M., Rasmussen, D. J., Strauss, B. H., et al. (2014). Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's Future*, *2*(8), 383–406. https://doi.org/10.1002/2014EF000239

Moftakhari, H. R., AghaKouchak, A., Sanders, B. F., Allaire, M., & Matthew, R. A. (2018). What is nuisance flooding? Defining and monitoring an emerging challenge. *Water Resources Research*, *54*, 4218–4227. https://doi.org/10.1029/2018WR022828

Moftakhari, H. R., AghaKouchak, A., Sanders, B. F., Feldman, D. L., Sweet, W., Matthew, R. A., & Luke, A. (2015). Increased nuisance flooding along the coasts of the United States due to sea level rise: Past and future. *Geophysical Research Letters*, *42*, 9846–9852. https://doi.org/10.1002/2015GL066072

Moftakhari, H. R., AghaKouchak, A., Sanders, B. F., & Matthew, R. A. (2017). Cumulative hazard: The case of nuisance flooding. *Earth's Future*, *5*(2), 214–223. https://doi.org/10.1002/2016EF000494

Molla, K. I., Rahman, S. M., Sumi, A., & Banik, P. (2005). Empirical mode decomposition analysis of climate changes with special reference to rainfall data. *Discrete Dynamics in Nature and Society*, *2006*, 1–17. https://doi.org/10.1155/DDNS/2006/45348

NOAA. (2017). *Shallow coastal flooding (nuisance flooding)*. U.S. climate resilience toolkit. Retrieved from https://toolkit.climate.gov/topics/coastal-flood-risk/shallow-coastal-flooding-nuisance-flooding

Ray, R. D., & Foster, G. (2016). Future nuisance flooding at Boston caused by astronomical tides alone. *Earth's Future*, *4*(12), 578–587. https://doi.org/10.1002/2016EF000423

Sweet, W., & Park, J. (2014). From the extreme to the mean: Acceleration and tipping points of coastal inundation from sea level rise. *Earth's Future*, *2*(12), 579–600. https://doi.org/10.1002/2014EF000272

Sweet, W., Park, J., Marra, J., Zervas, C., & Gill, S. (2014). Sea level rise and nuisance flood frequency changes around the United States. NOAA Technical Report NOS CO-OPS 073.

Tebaldi, C., Strauss, B. H., & Zervas, C. E. (2012). Modelling sea level rise impacts on storms surges along US coasts. *Environmental Research Letters*, *7*(1). https://doi.org/10.1088/1748-9326/7/1/014032

Vandenberg-Rodes, A., Moftakhari, H. R., AghaKouchak, A., Shahbaba, B., Sanders, B. F., & Matthew, R. A. (2016). Projecting nuisance flooding in a warming climate using generalized linear models and Gaussian processes. *Journal of Geophysical Research: Oceans*, *121*, 8008–8020. https://doi.org/10.1002/2016JC012084

Vermeer, M., & Rahmstorf, S. (2009). Global sea level linked to global temperature. *Proceedings of the National Academy of Sciences of the United States of America*, *106*(51), 21,527–21,532. https://doi.org/10.1073/pnas.0907765106

Vitousek, S., Barnard, P. L., Fletcher, C. H., Frazer, N., Erikson, L., & Storlazzi, C. D. (2017). Doubling of coastal flooding frequency within decades due to sea-level rise. *Nature Scientific Reports*, *7*(1), 1399. https://doi.org/10.1038/s41598-017-01362-7

Wahl, T., & Chambers, D. P. (2016). Climate controls multidecadal variability in U.S. extreme sea level records. *Journal of Geophysical Research: Oceans*, *121*, 1274–1290. https://doi.org/10.1002/2015JC011057

Woodworth, P. L. (2012). A note on the nodal tide in sea level records. *Journal of Coastal Research*, *280*, 316–323. https://doi.org/10.2112/JCOASTRES-D-11A-00023.1