AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2015GL066072

Key Points:
- Nuisance flooding substantially increases in a warming climate
- An ~80% increase in sea level by 2050 increases nuisance flooding by ~55%
- Increased nuisance flooding leads to socio-economic and public health impacts

Supporting Information:
- Supporting Information S1

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

Received 4 SEP 2015
Accepted 22 OCT 2015
Accepted article online 26 OCT 2015
Published online 19 NOV 2015

Increased nuisance flooding along the coasts of the United States due to sea level rise: Past and future

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Abstract Mean sea level has risen tenfold in recent decades compared to the most recent millennia, posing a serious threat for population and assets in flood-prone coastal zones over the next century. An increase in the frequency of nuisance (minor) flooding has also been reported due to the reduced gap between high tidal datums and flood stage, and the rate of sea level rise (SLR) is expected to increase based on current trajectories of anthropogenic activities and greenhouse gases emissions. Nuisance flooding (NF), however nondestructive, causes public inconvenience, business interruption, and substantial economic losses due to impacts such as road closures and degradation of infrastructure. It also portends an increased risk in severe floods. Here we report substantial increases in NF along the coasts of United States due to SLR over the past decades. We then take projected near-term (2030) and midterm (2050) SLR under two representative concentration pathways (RCPs), 2.6 and 8.5, to estimate the increase in NF. The results suggest that on average, - 80 ± 10% local SLR causes the median of the NF distribution to increase by 55 ± 35% in 2050 under RCP8.5. The projected increase in NF will have significant socio-economic impacts and pose public health risks in coastal regions.

1. Introduction

Sea level rise (SLR) is a well-documented and urgent aspect of anthropogenic global warming [*Church et al.*, 2013; *Hansen*, 2007; *Syvitski et al.*, 2009; *Hamlington et al.*, 2014; *Dangendorf et al.*, 2015; *Karl and Trenberth*, 2003; *Bordbar et al.*, 2015; *Wallace et al.*, 2014] that by 2050 could cause one trillion USD or more of damage to assets around the world lying less than 1 m above the current sea level [*Milne et al.*, 2009]. By 2050, 25% of the world's population will live in flood-prone coastal zones [*Aerts et al.*, 2014]. The United States is particularly vulnerable with three of the 10 top at-risk cities in terms of assets exposed to flooding [*Nicholls et al.*, 2008; *Hallegatte et al.*, 2013], and with over half of its population living in ~17% of - land area- considered as coastal regions [*Scavia et al.*, 2002; *Culliton*, 1998]. New York City alone is projected to experience 174 million USD/year losses due to flooding if no further flood management measures are implemented [*Aerts et al.*, 2014].

High-quality sea surface water level (WL) data, recorded at tide gauges all around the world over the last 100+ years, document a significant globally averaged acceleration in mean SLR of 0.009 mm yr^{-2} since 1880 and a globally averaged mean SLR of ~2.8 mm yr^{-1} between 1993 and 2009 [*Church and White*, 2011; *Church and White*, 2006; *Church et al.*, 2013; *Domingues et al.*, 2008; *Merrifield et al.*, 2013; *Watson et al.*, 2015], while altimetry records suggest an SLR rate of 3.3 ± 0.4 mm yr^{-1} between 1993 and 2014 [*Cazenave et al.*, 2014]. The rate of SLR over the past decades is an order of magnitude larger than SLR over the past millennia [*Milne et al.*, 2009] and projections of SLR over the 21st century, based on current trajectories of anthropogenic activities and greenhouse gases emissions [*Lyu et al.*, 2014], cannot rule out an increase greater than 1 m [*Milne et al.*, 2009; *Rahmstorf*, 2007; *Nicholls and Cazenave*, 2010; *Kopp et al.*, 2014].

The global SLR is spatially distributed by climate-driven dynamic processes (e.g., coastal/oceanic circulation) [*Sallenger et al.*, 2012], vertical land motions (e.g., tectonics) [*Kopp et al.*, 2014; *Wahl et al.*, 2013], and static equilibrium processes (e.g., melting land ice) [*Mitrovica et al.*, 2001]. Such processes have caused, for example, between 1950–1979 and 1980–2009, SLR in the northeast U.S. to be ~3–4 times higher than the global average [*Sallenger et al.*, 2012]. Increases in local mean sea level (MSL) (measured relative to land) reduce the gap between high tidal datums and flood stage [*Sweet et al.*, 2013; *Kriebel and Geiman*, 2014] and increase the frequency of nuisance (minor) tidal-related flooding and more damaging levels [*Kemp and Horton*, 2013], such that today's century level floods might become decadal by 2050 [*Tebaldi et al.*, 2012; *Wahl and Chambers*, 2015]. As an example, a shift toward storm surge weather patterns [*Wahl et al.*, 2015] has caused three of the nine highest recorded WLs in the last 170 years in the New York Harbor region to occur since 2010 [*Talke et al.*, 2014].

Nuisance flooding is a relatively new term that describes nondestructive flooding and is nonetheless capable of causing substantial negative socio-economic impacts [*Gornitz et al.*, 2002], compromising infrastructure such as surface transportation [*Suarez et al.*, 2005] and sewer systems [*Cherqui et al.*, 2015; *Flood and Lawrence*, 2011], and posing public health risks [*Ten Veldhuis et al.*, 2010]. Previous studies on socio-economic impacts of future coastal flooding have primarily focused on extreme flood heights and therefore the least frequent flood events [*Hallegatte et al.*, 2013; *Hinkel et al.*, 2014], and in contrast nuisance flooding is typically measured in hours and is therefore strongly affected by the most frequent flooding events. Indeed, even high tides and minor surges now cause nuisance flooding in coastal regions, while in the past it would require a major surge or hurricane to have the same impact [*Sweet and Park*, 2014]. In the past 50 years, nuisance flooding has increased along the coasts of United States between 300% to over 900%, and the majority of locations are expected to experience even more NF as "tipping points" for inundation will be surpassed by 2050 under the local median SLR projections [*Sweet and Park*, 2014]. This poses the question: *How does NF in the United States increase with local MSL rise*, and *can local MSL be used as a proxy to project NF in a changing climate?*

In this study, we first describe the relationship between the observed local annually averaged MSL and NF since 1920 through nonlinear regression analysis and Monte Carlo simulation (see section 2 for details) of 12 tide gauges located along the coasts of United States. Then, we use Monte Carlo analysis to project the 90% confidence interval of NF under near-term (2030) and midterm (2050) future SLR [*Tebaldi et al.*, 2012]. In this study, the mean SLR is from the spatially redistributed local MSL estimations based on the Coupled Model Inter-Comparison Project, Phase 5 (CMIP5 [*Taylor et al.*, 2012]) projections, under two different representative concentration pathways (RCPs) 2.6 and 8.5 [*Kopp et al.*, 2014].

2. Methods

2.1. Tide Gauge Data and SLR Projections

We use three sets of data here to calibrate our model and project NF in the future. Hourly WL data for all tide gauges used in this study (Figure 1) is provided by the National Oceanic and Atmospheric Association (NOAA; http://tidesandcurrents.noaa.gov/). The hourly WL record is yearly averaged and subtracted by the long-term mean (e.g., over the whole record) to produce a time series of mean sea level anomaly (ΔMSL). The cumulative hours that observed WL exceed a certain threshold, in each meteorological year (MY; May to April), represent the NF at any given tide gauge. This NF threshold (listed in *Sweet and Park* [2014]), determined by local Weather Forecasting Offices of NOAA's National Weather Service, has been historically associated with minor flooding impacts. It is worth mentioning that not necessarily every WL exceedance above this threshold results in noticeable coastal flooding [*Sweet and Park*, 2014]. *Sweet and Park* [2014] provided NF records prior to MY 2012 (May 2012 to April 2013), and here we extended the records to MY 2013. The probability distribution of local SLR projections under CMIP5 scenarios (RCP 2.6 and RCP 8.5) are provided by *Kopp et al.* [2014]. We use quantiles 0.05 and 0.95 as representatives of 90% confidence limits of projected SLR for years 2030 and 2050.

2.2. Model Calibration

We use nonlinear regression analysis (Figure S1 in the supporting information) to model the correlation between ΔMSL and NF and estimate NF in the future. The analysis suggests that NF over the East and West Coast of U.S. on average increases with ΔMSL following a polynomial function of the form -$NF = \alpha + \beta(\Delta MSL)^{\theta}$- with $\theta = 3.58$ (±1.43; within 90% confidence interval). The estimated parameters α, β, and θ (along with their 90% confidence intervals) for each gauge are shown in Table S1 in the supporting information. However, NF in most of the gauges show a relatively minor sensitivity to variation in MSL for $\Delta MSL < 0$; as ΔMSL further rises, the rise in NF accelerates.

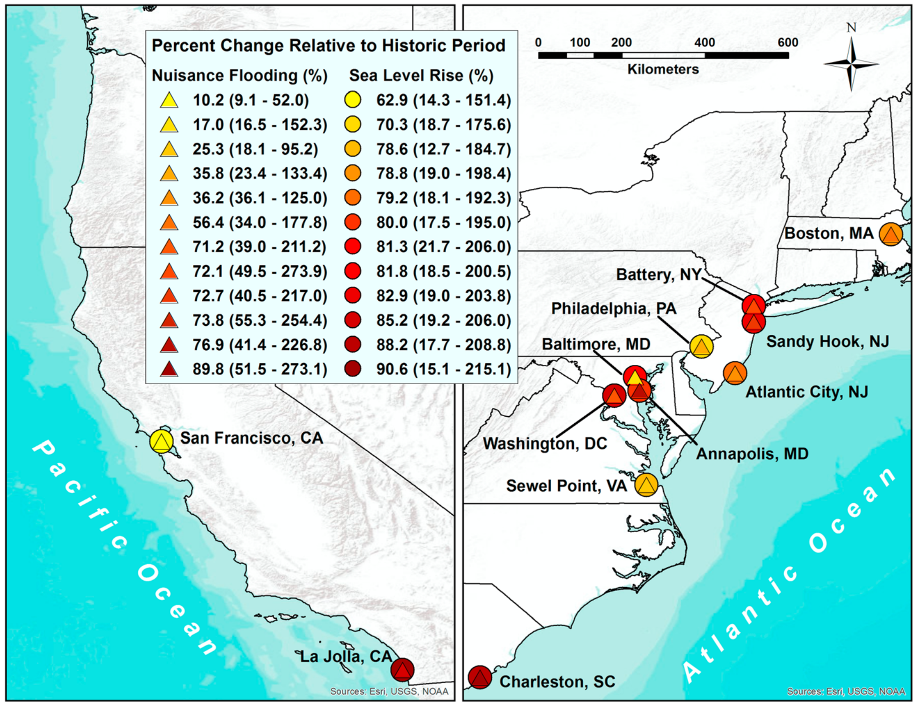

Figure 1. Percent change in SLR and NF relative to the historic period. Percent changes calculated using the 50th quantile of 2050 projections (RCP 8.5) are represented in the color scale, while percent changes calculated using the 25th and 75th quantile of 2050 projections are shown in parentheses. *Brown* represents a higher percent change in SLR/NF, while *yellow* represents a lower percent change in SLR/NF relative to the other gauges shown.

2.3. Uncertainty Estimation

In this study we use Monte Carlo analysis to define the 90% confidence interval of the estimated future NF. For this purpose we propagate the uncertainty of regression parameters and sea level projections by randomly generating one-million ensembles using values between the quantiles 0.05 and 0.95 of the estimated parameters α, β, and θ (estimated via nonlinear regression analysis) and the projected MSL [*Kopp et al.*, 2014] for years 2030 and 2050. The resulting 0.05 and 0.95 quantiles of the estimated NF distribution for years 2030 and 2050 represent the 90% confidence limits of estimation.

3. Results

Figure 2 shows the time variation of annually averaged sea level anomaly (ΔMSL; see section 2) and its associated cumulative hours of NF for each MY in six selected U.S. tidal gauges since 1920s. The gauges are chosen such that there would be at least one representative gauge with a long ($>$80 years) and relatively complete ($>$80%) record for each region in the east and west coast of United States. These gauges on-average have experienced 35 ± 15 cm MSL rise (since 1920s) and are expected on-average to experience a MSL rise of ~34 ± 17 cm by 2050, under RCP 8.5 (assuming 90% confidence interval). This means that almost the same SLR that U.S. coastal gauges have observed over the last 80+ years is estimated to occur in the following 35 years. This accelerated SLR, for example, in Washington, DC, in which NF has not exceeded 200 h/yr, may cause NF to be between 60 and 700 h/yr by 2050, under RCP 8.5. Almost the same rate of rise in MSL may cause the gauges located in Boston, Battery, Charleston, La Jolla, and San Francisco (Figure 1) to experience up to 75, 435, 315, 125, and 120 h of NF per year by 2050, under RCP 8.5.

Figure 1 shows the change in local SLR and NF by 2050 under RCP 8.5, relative to historic records. In each gauge, the triangle and circle represent the change (in percent) in NF and SLR assuming the 50th quantile of SLR projections, relative to the observed range of sea level variation and NF, respectively, over the last 80+ years. To calculate the percent change, quantiles are divided by the historic range of variability (the maximum observed MSL/NF subtracted by lowest observed MSL/NF). The results

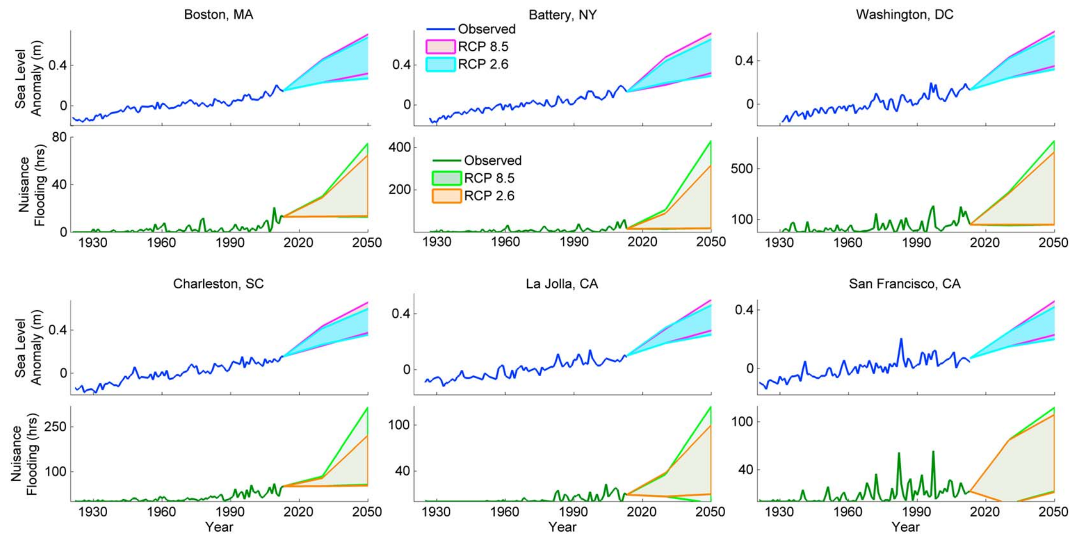

Figure 2. Observed and projected MSL and NF between 1920 and 2050; MSL anomaly (blue curve) and NF (green curve) since 1920 (where available), and projected MSL anomaly (blue and pink envelopes) and NF (brown and green envelopes) for the next 35 years are presented in this figure. The annually averaged MSL is subtracted by the long-term mean (e.g., over the whole record) to calculate the anomalies.

suggest that on average an 80 ± 10% increase in local MSL median may yield a 55 ± 35% increased NF median by 2050 over all coasts of United States. The distribution of estimated NF is negatively skewed (e.g., toward the lower quantiles), and the 25th quantile is only ~20 ± 25% below the median, while the 75th quantile is ~130 ± 95% larger than the median.

Among the studied gauges, some are more vulnerable to the same rate of increase in MSL compared to others. Figure 3 compares the relative vulnerability of the studied gauges to the unified 3, 6, and 15 cm local SLR associated with 10, 20, and 50 years of suggested Global SLR [*Merrifield et al.*, 2013] in which all the gauges experience the same SLR. San Francisco and Washington are the most and the least sensitive gauges to a unified SLR, in which a 15 cm rise in MSL may cause NF to become 8.1 and 3.8 times larger, respectively. Results suggest a spatial pattern in relative sensitivity of the studied gauges, such that the gauges with lowest sensitivity to a unified SLR are all located in midlatitude (between 36 and 41°) East Coast. The gauges located on West Coast with a narrow and shallow continental shelf and affected by no significant storm surge [*Tebaldi et al.*, 2012] are among the most sensitive gauges to the unified SLR scenarios. These results are compatible with previous studies [e.g., *Tebaldi et al.*, 2012], which implies that the NF in less sensitive gauges to a unified SLR is relatively more affected by coastal processes (e.g., wind waves), compared to the other gauges.

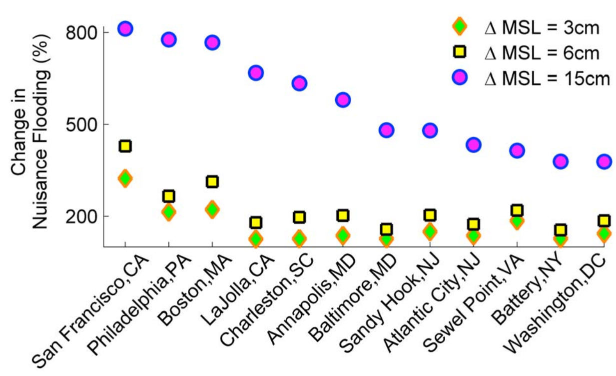

Figure 3. Relative vulnerability of gauges along U.S. coast to a unified MSL rise.

4. Discussion and Conclusions

This study shows substantial increases in nuisance flooding (NF) along the coasts of United States due to SLR over the past decades. Based on the relationship between the observed historical NF and sea level information, and projected near-term (2030) and midterm (2050) SLR under two representative concentration pathways (RCPs) 2.6 and 8.5, we estimate future NF response to SLR. The results indicate that on average, an $80 \pm 10\%$ local SLR causes the median of the NF distribution to increase by $55 \pm 35\%$ in 2050 under RCP8.5.

By current definition, coastal NF is primarily dominated by sea surface water levels. In fact, NF can be independent of local hydrometeorological characteristics and can occur even during a severe drought [*Cherqui et al.*, 2015]. For example, on average, La Jolla, CA, has been experiencing eight NF event per year since 2000. In MYs 2012 and 2013, while Southern California has been experiencing a severe drought [*Shukla et al.*, 2015], La Jolla experienced 11 and 9 NF events, respectively.

The morphologic/hydrodynamic characteristics of the coast and the gauge location (i.e., whether if it is located in a harbor, an estuary, or an open coast) can affect the number of hours of NF. For cases like San Francisco Bay, in which the fluvial inflow strongly modulates the tides, and the interaction between oceanic tides/waves and freshwater discharge to the estuary determines the observed WL at the gauge [*Moftakhari et al.*, 2013, 2015], observed NF depends on both WL and local hydrometeorlogical conditions. In cases like La Jolla, where the tide gauge is located in the open coast (i.e., not disturbed by fluvial plumes), the observed WL at the gauge is solely affected by coastal processes, and it may not necessarily reflect the contribution of other flood drivers (e.g., river flow and local precipitation). More efforts are needed to develop a generalized definition for NF.

Evaluating the significance of our estimates requires understanding the magnitude of likely systematic (due to bias) and random errors. The mean of random errors such as digitization errors are assumed to be close to zero when averaged over the whole data. Systematic errors are likely to be the most important limitation to the accuracy of our results. Part of systematic errors may stem from the assumption that the relationship established between ΔMSL and NF over the last 80+ years (Figure S1) may remain the same for the following ~35 years. To address this issue, we have only provided projections for near-term and midterm SRL conditions. Future morphologic/bathymetric changes due to human activities (i.e., dredging) and infrastructural enhancements can alter the relationship between ΔMSL and NF. Another possible source of error is the extrapolation of ΔMSL-NF relationship beyond the observed dynamic range of MSL for future predictions. As ΔMSL increases beyond the observed range, a larger percentage of the cumulative distribution of hourly data will more frequently exceed the NF threshold and our model will likely become an underestimate in the longer term. This type of error, which stems from the "evolution in exceedance probabilities" [*Sweet and Park*, 2014], is statistically addressed in terms of confidence intervals (see Figures 1 and 2) through Monte Carlo analysis (see section 2). Estimates of future NF are subject to high uncertainties due to error sources mentioned above. Therefore, the results should be considered as indicative estimates of how NF can respond to future SLR. While uncertainties in estimating the actual future NF would be very high, considering the observed increases in NF events recent years, they will likely increase even further primarily because of the expected increase in SLR.

Socio-economic impacts of coastal flooding include the immediate impacts to coastal populations and their personal and real estate property, as well as longer-term effects on crucial infrastructure, including that which is designed to avert, mitigate, or reduce the hazards of future flooding, and public health—an area that is understudied. Generally, socio-economic impacts may be categorized as falling into a fourfold typology: (1) impacts to vulnerable populations who are likely to suffer the highest and most irreplaceable losses due to factors such as social vulnerability, (2) the ability of a coastal community to recover due to effects upon important infrastructure (e.g., water supply and sewer systems, transportation, power, communications, hospitals, schools, seaports, and bridges), (3) impacts upon social capital —meaning, the ability of a community to recover through investing in the rebuilding and recovery from loss (e.g., such factors as governance capacity, financial structures, and workforce availability), and (4) long-term impacts upon coastal community resources expended to mitigate or avert future flood damages (e.g., elevating or flood-proofing structures, or acquiring and relocating those in areas too hazardous for habitation, and the construction of levees, dikes, and seawalls).

Addressing these issues requires not only attention to the height of flood events [*Hallegatte et al.*, 2013; *Hinkel et al.*, 2014] but also duration (e.g., number of hours) of NF because many socio-economic impacts of NF (e.g., closure of a business district) are proportional to the number of hours a region is affected. The results of this study show that in a warming climate, the NF hours may significantly increase in coastal regions, which points to a substantial increase in NF impacts. To maintain the current level of nuisance flooding in the future climate, the level of protection offered by flood defense infrastructure should increase (e.g., higher sea walls, more storm barriers). In addition to engineering solutions, forward thinking land use management, urban development policies, and flood mitigation and adaptation plans are critical to reduce the adverse impacts of nuisance flooding.

Acknowledgments
This study is supported by the National Science Foundation Award No. DMS 1331611. We acknowledge the constructive comments and suggestions which led to substantial improvements in the revised version of the manuscript. Hourly water level data used in this study are available from the National Oceanic and Atmospheric Administration (NOAA; http://tidesandcurrents.noaa.gov/). The local sea level projections are provided by *Kopp et al.* [2014]. The authors will provide nuisance flooding data to interested readers upon request.

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