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Cumulative hazard: The case of nuisance flooding

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Key Points:
- The cumulative cost of frequent events over time may exceed the costs of the extreme events
- Nuisance coastal flooding could have property value exposure comparable to, or larger than, record extreme floods
- A Cumulative Hazard Index is proposed that is a useful tool for framing the future cumulative impacts of low cost incidents

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Abstract The cumulative cost of frequent events (e.g., nuisance floods) over time may exceed the costs of the extreme but infrequent events for which societies typically prepare. Here we analyze the likelihood of exceedances above mean higher high water and the corresponding property value exposure for minor, major, and extreme coastal floods. Our results suggest that, in response to sea level rise, nuisance flooding (NF) could generate property value exposure comparable to, or larger than, extreme events. Determining whether (and when) low cost, nuisance incidents aggregate into high cost impacts and deciding when to invest in preventive measures are among the most difficult decisions for policymakers. It would be unfortunate if efforts to protect societies from extreme events (e.g., 0.01 annual probability) left them exposed to a cumulative hazard with enormous costs. We propose a Cumulative Hazard Index (CHI) as a tool for framing the future cumulative impact of low cost incidents relative to infrequent extreme events. CHI suggests that in New York, NY, Washington, DC, Miami, FL, San Francisco, CA, and Seattle, WA, a careful consideration of socioeconomic impacts of NF for prioritization is crucial for sustainable coastal flood risk management.

1. Introduction

Climate change is expected to alter the frequency and severity of weather events such as flooding, storm surge, and drought [*Katz and Brown*, 1992; *Easterling*, 2000; *Frich et al.*, 2002; *Schär et al.*, 2004; *Wahl and Chambers*, 2016]. Most previous studies have focused on changes in extreme and infrequent events that typically have substantial impacts [*Easterling*, 2000; *Meehl et al.*, 2000b; *Starkel*, 2002; *Diffenbaugh et al.*, 2005; *Tessler et al.*, 2015; *Muis et al.*, 2016]. However, relatively little attention has focused on how climate change affects minor and more frequent events that, when aggregated over time, may have similar cumulative social and economic impacts.

For example, flood events may be categorized into three types: (1) minor (e.g., exceedance probability greater than 0.50), often called nuisance flooding (NF), with relatively small public impacts, (2) major (e.g., exceedance probability between 0.05 and 0.50) that can cause considerable infrastructure inundation/damage, and even loss of lives, and (3) extreme (e.g., exceedance probability less than 0.05) with extensive property damage, structural failure, injury, and death [*National Weather Services (NWS)*, 2012]. Although nondestructive in an immediate sense, NF is indeed capable of causing substantial negative socioeconomic impacts [*Gornitz et al.*, 2001], compromising infrastructure such as surface transportation [*Suarez et al.*, 2005] and sewer systems [*Flood and Cahoon*, 2011; *Cherqui et al.*, 2015], and posing public health risks [*ten Veldhuis et al.*, 2010].

The potential impacts of climate change on extreme floods have been extensively discussed in academic literature [*Mirza*, 2003; *Lehner et al.*, 2006; *Dankers and Feyen*, 2008; *Hirabayashi et al.*, 2008, 2013; *Wilby et al.*, 2008; *Guhathakurta et al.*, 2011; *Intergovernmental Panel on Climate Change (IPCC)*, 2012; *Wahl et al.*, 2015; *McInnes et al.*, 2016]. In contrast, far less attention has been given to the potential costs of NF [*Rowling*, 2016] even though there is considerable evidence that NF is on the rise in coastal regions as a result of sea level rise (SLR) [*Sweet and Park*, 2014; *Moftakhari et al.*, 2015; *Ray and Foster*, 2016; *Vandenberg-Rodes et al.*, 2016]. An increase in the frequency of NF arises from the reduced gap between tidal datum and flood stage with SLR [*Sweet and Park*, 2014; *Moftakhari et al.*, 2015].

Anthropogenic SLR over the next century and beyond [*Church and White*, 2006, 2011; *IPCC*, 2013; *Hamlington et al.*, 2014; *Kopp et al.*, 2014; *Dangendorf et al.*, 2015; *Slangen et al.*, 2016] would inundate assets located in highly populated low-lying coastal areas around the world and poses safety and health risk issues to the communities located in these regions [*Rahmstorf*, 2007; *Nicholls and Cazenave*, 2010; *Lyu et al.*, 2014; *Bierkandt et al.*, 2015; *Hauer et al.*, 2016]. The United States is especially threatened by SLR [*Strauss et al.*, 2015], with over half of the population living in coastal regions [*Scavia et al.*, 2002], and with 8 out of the world's 20 most vulnerable cities in terms of average annual losses due to flooding [*Hallegatte et al.*, 2013]. The State of Florida alone is expected to have 1.22 ± 0.24 million people placed at risk due to 0.9 m of SLR by 2100 [*Hauer et al.*, 2016]. Financially, a 0.68 m of rise in mean sea level by 2100 yields more than $230 billion of undiscounted cost across the continental United States [*Neumann et al.*, 2011]. This is a serious threat given that the projections of SLR over the 21st century, based on the current trajectories of anthropogenic activities and greenhouse gases emissions [*Lyu et al.*, 2014], cannot rule out an increase greater than 1 m [*Rahmstorf*, 2007; *Milne et al.*, 2009; *Nicholls and Cazenave*, 2010; *Cazenave et al.*, 2014; *Kopp et al.*, 2014]. However, the evaluation of such impacts by taking static SLR into account may not be sufficient and dynamic coastal response and the impacts of adaptation measures must be considered to avoid overprediction of inundation likelihood [*Hinkel et al.*, 2013, 2014; *Bordbar et al.*, 2015; *Bisaro and Hinkel*, 2016; *Lentz et al.*, 2016].

An analysis [*Kousky and Michel-Kerjan*, 2015] of flood insurance claims in the United States during the period 1978–2012 provides a valuable insight into the important challenge confronting managers, planners, and policymakers. Results show that the total value of insured properties has increased over time from $178 billion in 1978 to approximately $1.28 trillion in 2012 (all in 2012 dollars) [*Kousky and Michel-Kerjan*, 2015]. The U.S. Government Accountability Office (GAO) has reported that repetitive loss properties, which constitute just 1% of policies-in-force, accounted for around 38% of National Flood Insurance Program (NFIP) claims between 1978 and 2004 [*U.S. Government Accountability Office (GAO)*, 2004]. Repetitive loss properties are defined by the Federal Emergency Management Agency (FEMA) as those having two or more losses of at least $1000 within a 10-year period [*Federal Emergency Management Agency (FEMA)*, 2015]. The data show that half of the claims are for less than 10% of the value of the building [*Kousky and Michel-Kerjan*, 2015]. Using the vulnerability (V) estimation function [*Hinkel et al.*, 2014]:

$$V(h) = \frac{h}{h+1}, \tag{1}$$

where h is the depth of flood; we can estimate that half of the claims were associated with floods of depth approximately 0.11 m or less, that are by definition minor events or NF. This highlights the fact that cumulative cost of NF is staggering, and could even exceed the cost of infrequent events that are typically the basis of flood risk management programs.

In this study, we analyze hourly water level (WL) data and property exposure data for 11 coastal cities and counties along the coasts of United States. We then estimate the expected exposure of coastal communities to minor, major, and extreme flood events. Finally, we compute a Cumulative Hazard Index (CHI) which represents a relative measure of coastal community exposure to NF versus infrequent floods. Because policymakers are often aware of the grave consequences of extreme flooding events, for example, Katrina and Sandy, CHI provides a way for policymakers to more easily grasp the potential impacts of NF at the community level.

2. Data and Methodology

We use two sets of data in this study to implement coastal property exposure analysis for the current climate and flood defense infrastructure: (1) unprotected (i.e., connected to the ocean) property values associated with an incident WL exceedence above mean higher high water (MHHW) for 11 coastal cities and counties along the coasts of United States, and (2) hourly WL observed at the nearest tide gauges to the chosen cities and counties with relatively long records (i.e., >60 years). The data for property values (in 2012 dollars) on land below sea level for different SLR scenarios are obtained from the risk finder tool provided by Climate Central (http://sealevel.climatecentral.org/) [*Tebaldi et al.*, 2012]. The methodology assumes that property values are evenly distributed across land within each census block group [*Neumann et al.*, 2011]. The hourly WL data for all tide gauges used in this study (Figure 1) are provided by National Oceanic and Atmospheric Association (NOAA; http://tidesandcurrents.noaa.gov/).

The cumulative exposure or cost of flooding C is calculated based on the cost of flooding (or exposure to flooding) as a function of WL, $c_{(Z)}$, and the WL probability density, $p_{(Z)}$. Because, $c_{(Z)}$ is very difficult

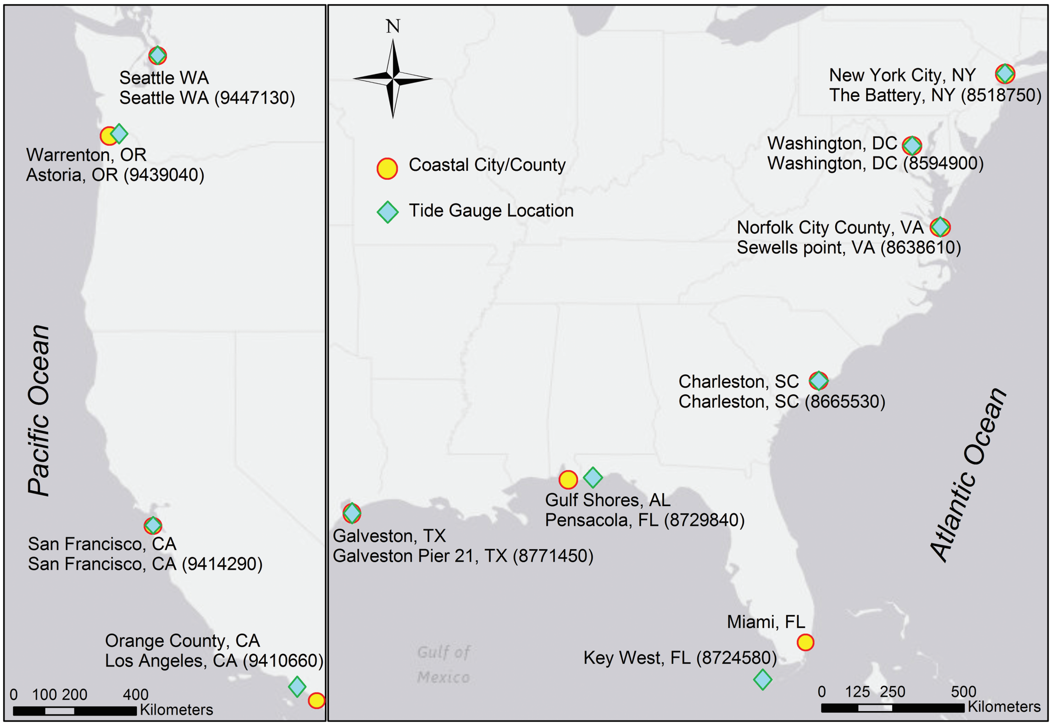

Figure 1. Location of coastal cities/counties (circle) and the nearby tide gauges (diamond) used in this study. The numbers mentioned inside the parenthesis in front of the tide gauge name represent the National Oceanic and Atmospheric Administration (NOAA) ID number of the tide gauge.

to estimate across different types of flooding, especially considering indirect impacts, in this study we use property exposure as a proxy. Property exposure is relatively easily calculated for most coastal communities threatened by SLR and thus represents a pragmatic first-order approach. We should, however, acknowledge that estimating the true cost is far more complex and deserves consideration of many factors:

1. Structural stability of coastal properties and the potential expenses for repair or reconstruction.
2. Extreme events often lead to more intangible losses (i.e., loss of life) than major events [*IPCC*, 2012], which are extremely difficult to be estimated [*Jonkman et al.*, 2003, 2008, 2010] and weighted against other types of loss [*Vrijling*, 1995; *Vrijling et al.*, 1998; *Jonkman et al.*, 2003].
3. Minor events usually trigger adaptation measures and spontaneous learning processes at the individual or community level [*Sivapalan et al.*, 2012; *Buchecker et al.*, 2013; *Di Baldassarre et al.*, 2013], which make the estimated function $c_{(Z)}$ nonstationary [*Lopez et al.*, 2016]. Thus, no single time-invariant function could perfectly characterize the relationships between frequency and potential impacts, and evaluate the dynamic response of the threatened community [*Di Baldassarre et al.*, 2015; *Mechler and Bouwer*, 2015].
4. Owing to the nature of extreme events (that are rare, by definition) the epistemic uncertainty (lack of knowledge) can play a bigger role than aleatory uncertainty [*Di Baldassarre et al.*, 2016] and consequently the real impacts of these events are more uncertain compared to frequent floods.

Given complexities in estimating the true cost of extreme and minor events, in this study we use property exposure as a proxy. The cumulative exposures are subsequently estimated for each flood category (i.e., minor, major, and extreme) by integrating over the respective range of probabilities:

$$\begin{cases} C_{\text{minor}} = \int_{Z=0}^{Z_{0.50}} c_{(Z)\times} p_{(Z)} \mathrm{d}z \\ C_{\text{major}} = \int_{Z_{0.50}}^{Z_{0.95}} c_{(Z)\times} p_{(Z)} \mathrm{d}z \\ C_{\text{major}} = \int_{Z_{0.95}}^{Z\to\infty} c_{(Z)\times} p_{(Z)} \mathrm{d}z \end{cases}, \quad (2)$$

where $Z = 0$ is equal to the MHHW level, $Z \to \infty$ refers to the highest observed WL over the analysis period, and $Z_{0.50}$ and $Z_{0.95}$ are the 50th and 95th quantiles of the observed hourly WL at the tide gauge, respectively (Figure 2). The ratio of estimated C for each flood category to the total cost or exposure (C_{total}), which is obtained by integrating over all probabilities as follows,

$$C_{\text{total}} = \int_{Z=0}^{Z\to\infty} c_{(Z)\times} p_{(Z)} \mathrm{d}z \tag{3}$$

represents the relative contribution of each flood category in total flood exposure/cost likelihood.

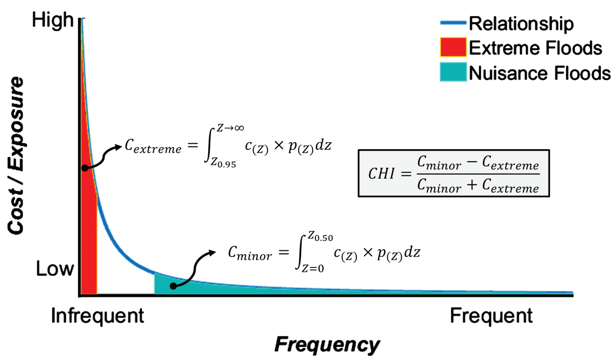

Figure 2. Conceptual representation of the relationship between cost/exposure and frequency of climate/oceanic events. Cumulative Hazard Index (CHI) is defined as the normalized difference between cumulative exposure or cost (C) of minor and extreme events.

Finally, a CHI is computed as an indicator of relative exposure to NF versus infrequent events. This index compares the C of minor and extreme events within a given coastal community (Figure 2), as:

$$\text{CHI} = \frac{C_{\text{minor}} - C_{\text{extreme}}}{C_{\text{minor}} + C_{\text{extreme}}}. \tag{4}$$

CHI, varying between −1 and +1, is a measure of exposure to NF, where CHI ≅ −1 means the cumulative costs or exposure associated with NF are negligible relative to the ones by extreme events, whereas CHI ≅ +1 means the cumulative costs or exposure to NF over time are considerably higher than those of rare extreme events. CHI ≅ 0 can be considered a tipping point below which planning for preventive measures against low frequency hazards should be prioritized. In areas with CHI > 1 (exceeding the tipping point threshold), the cumulative cost of NF with minor impacts should be taken into account for planning, risk assessment, and management.

3. Results

Climate Central data reports property exposure under 10 different SLR values (i.e., 1 through 10 ft above MHHW), and for integrating across WLs we need to interpolate between exposure estimates. We found out that a single nonlinear curve of the form

$$c_{(Z)} = \alpha + \beta Z^{\gamma} \tag{5}$$

is a good fit of the cost or exposure ($c_{(Z)}$; here property exposure) for $Z > 2$ ft, where α, β, and γ are parameters to be calibrated through nonlinear regression analysis. However, the fitted nonlinear curve poorly represents the property exposure for Z less than 2 ft (~0.61 m above MHHW). Therefore, we decided to linearly interpolate between exposure estimates associated with $Z \leq 2$ ft (Figure 3).

The bars on Figure 3 represent the empirical probability density (p) of exceedance above MHHW for the analyzed tide gauges. The bars in green, grey, and red represent the frequency density of events with exceedance probability greater than 0.50, between 0.05 and 0.50, and less than 0.05, respectively. The green curves in Figure 3 show the expected property exposure associated with each WL above MHHW ($c_{(Z)\times} p_{(Z)}$).

In Figure 4, the upper panel summarizes the contribution of each coastal flood category in total property exposure to flooding. Major floods are responsible for approximately 60%–70% of the total exposure to coastal flooding. This is because of their higher associated property value relative to minor events, and significantly higher frequency relative to extreme events, that has made the product much larger than the other two categories. The lower panel presents the estimated CHI for all the studies gauges, under their current settings. As explained before, CHI is a simple ratio for framing the impacts of NF versus extreme events whose impacts are often better understood by decision makers.

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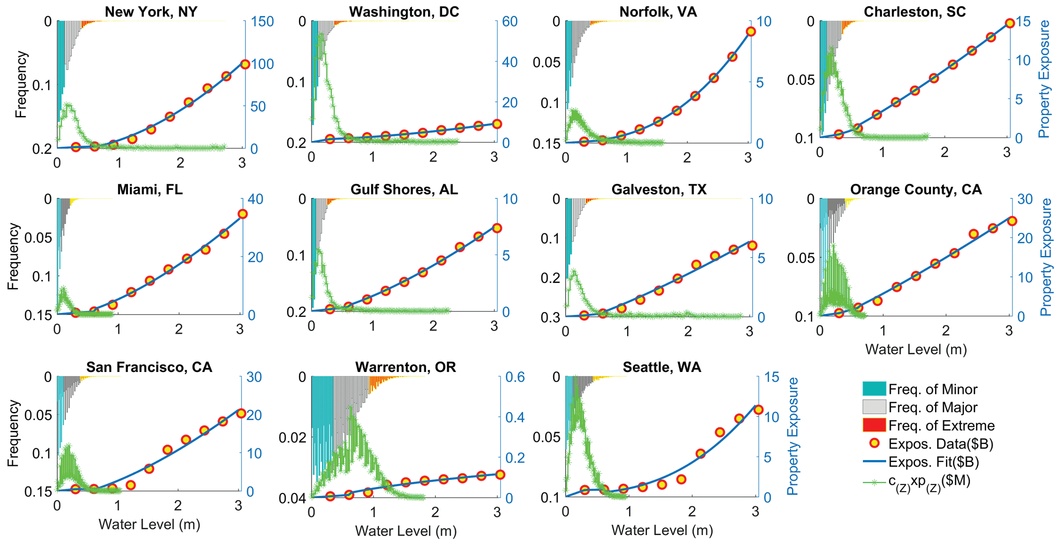

Figure 3. Bars represent the empirical probability density ($p_{(Z)}$) of exceedance above MHHW at the nearby tide gauge. The circle and the fitted blue line show the incident exposure ($c_{(Z)}$) to the WL above the MHHW. The green curve shows the expected exposure or cost (here property exposure), associated with each WL above MHHW.

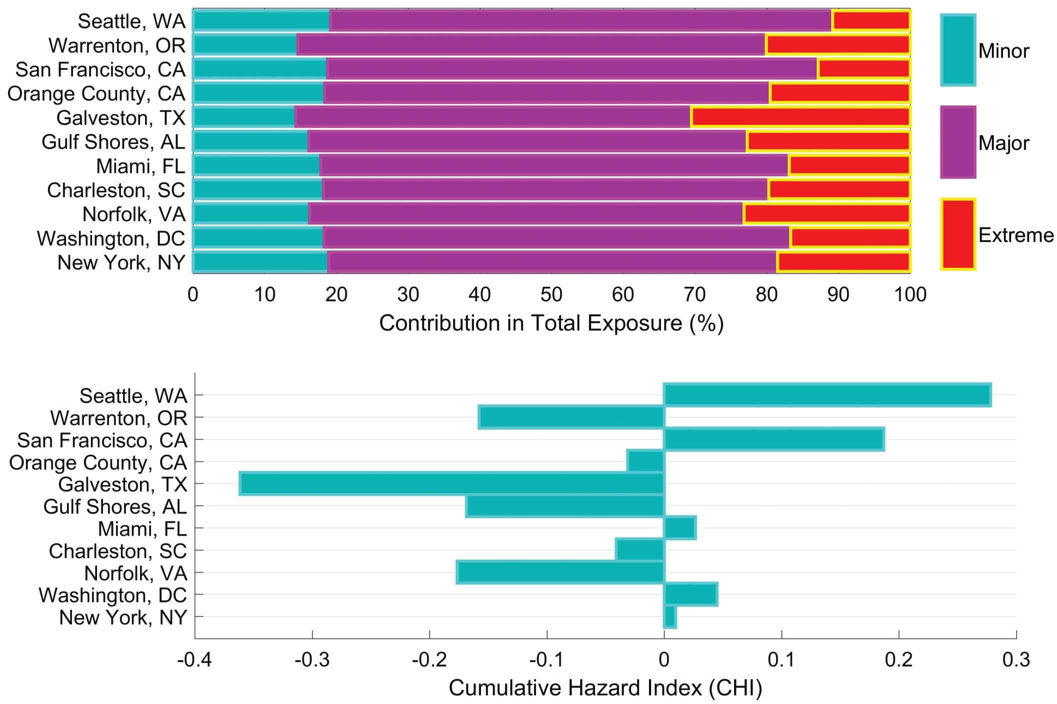

Figure 4. (Upper) relative contribution of different flood types in the total property value exposure in current settings; (lower) Cumulative Hazard Index (CHI) in the current system.

In three of the East Coast case studies, viz., New York, NY, Washington, DC, and Miami, FL, and two of the West Coast case studies, viz., San Francisco, CA, and Seattle, WA the estimated CHI is positive. This means the cumulative exposures of these coastal communities to minor floods are of the same order of magnitude/larger than extreme events, and this finding calls for further study of potential socioeconomic impacts here and development of interventions.

Washington, DC serves as a good example of a major metropolitan area facing serious challenges posed by the increased frequency of NF over the last few decades. The number of hours this region experiences

NF each year has increased considerably over time from an average of 19 h between 1930 and 1970 to 94 h during the last two decades [*Sweet and Park*, 2014]. But a recent projection suggests that by 2050 the region could experience (with 90% confidence) 100–700 h of NF annually [*Moftakhari et al.*, 2015] as a result of 0.22–0.54 m of projected SLR [*Kopp et al.*, 2014]. This poses concerns on many fronts. For example, NF could affect 17.8 km of streets, 4.2 km of railroads, 3.8 km of metrolines, and 15 bridges that are located less than 0.4 m above the current mean sea level [*Ayyub et al.*, 2012]. More frequent NF could also affect tourism by interrupting businesses and temporarily closing attractions located in flood-prone zones, such as two markets, five monuments and museums, and six marinas and parks that would be affected by 0.4 m of SLR [*Ayyub et al.*, 2012]. Business interruptions and public inconveniences impacting tourism and possibly dropping real estate values over one or two decades would be comparable to the damage of record extreme events like Hurricane Irene. Additionally, five hazardous waste sites and three wastewater sites would be exposed to NF by a rise of 0.3 m above MHHW [*Climate Central*, 2016].

Making coastal infrastructure resilient to the increased risk of flooding is indeed costly [*Neumann et al.*, 2011; *Aerts et al.*, 2014; *Temmerman and Kirwan*, 2015]. For example, in Washington, DC, in which 98% of the land located below 1 ft of SLR is connected to the ocean and not protected by appropriate flood defense structures [*Climate Central*, 2016], the construction of a reliable levee system to prevent the region from Potomac River overflows would cost approximately 9.4 million USD [*U.S. Army Corps of Engineers*, 2014]. This issue is not unique to Washington; New York City has more than 2.6 billion USD of property on land below 1 ft above MHHW, approximately 50% of which is connected to the ocean [*Climate Central*, 2016]. The massive exposure of New York City to coastal flooding has resulted in plans for a 20 billion USD mix of defense and adaptation measures—most notably, construction of "The Big U," a 10-mile (16-km) fortress of berms and movable walls around lower Manhattan [*Nelson and Wilson*, 2014]. Another example would be Miami Beach, FL with more than 11 billion USD of properties on land less than 3 ft above MHHW, 94% of which is connected to the ocean [*Climate Central*, 2016]. But how and when to implement protection measures to avoid negative impacts of more frequent NF are questions that are still unanswered.

4. Discussion

The possibility that diffuse, low-cost incidents will aggregate over time into extremely high-cost outcomes (Figure 2) is a daunting challenge for policymakers and politicians in many domains. Remote, highly local outbreaks of disease may remain isolated but can aggregate into national hazards and also become platforms for global pandemics (e.g., Zika, Ebola, severe acute respiratory syndrome (SARS)). Small-scale Internet crimes involving credit and debit cards may not cause significant direct hardship at the individual level but can accumulate to affect national economies. Minor snowstorms and fires are also examples of nuisance events that have the potential to become cumulative hazards when their frequency increases. In these and many other cases, responding too soon can mean that scarce resources are wasted and hence public trust—which is critical to the success of disaster risk reduction policies and programs—may be reduced. Responding too late, on the other hand, can result in costly losses that might have been avoided—and again public trust in government may suffer.

Many observers contend that the impacts of current trends in areas such as biodiversity loss, Internet crime, infectious disease, and natural hazards could cross critical thresholds and subsequently have systemic impacts, including large-scale breakdowns [*Meehl et al.*, 2000a; *Wall*, 2001; *Adger et al.*, 2003; *Fidler*, 2003; *Klein et al.*, 2003; *Chen et al.*, 2004; *Patz et al.*, 2005; *Cutter and Finch*, 2008; *Butchart et al.*, 2010; *Choo*, 2011; *Gall et al.*, 2011; *Bisaro and Hinkel*, 2016; *Hicks et al.*, 2016]. Through better understandings of what we have termed "cumulative hazards," frameworks can be developed for systematically exploring: investments that may make sense for both minor and major events, the risks of preparing for major events in ways that leave societies exposed to the cumulative impacts of minor events, the possibility that trends in minor events might be a predictor of major events, and the extent to which focused adaptation catalyzed by a concern for cumulative hazards might build fungible resilience in a community.

Recent studies on NF suggest how difficult it can be to decide at which point to invest heavily in prevention or response [*Sweet and Park*, 2014; *Moftakhari et al.*, 2015]. There is thus a clear need for tools that help policymakers determine whether (and when) low-cost incidents are likely to aggregate into high-cost impacts. Scientists are well positioned to provide tools that make scientific knowledge actionable and thus able to support and shape responses to these daunting policy challenges [*Landström et al.*, 2011; *Lane et al.*, 2011; *Rahmstorf*, 2012; *Viglione et al.*, 2014; *Wong-Parodi et al.*, 2014; *Spiekermann et al.*, 2015; *Alfonso et al.*, 2016; *Burke et al.*, 2016; *Hallegatte et al.*, 2016].

Today's century WLs may become decadal or more frequent events and the majority of coastal communities are likely to experience substantially higher frequency of previously rare water heights in the future [*Tebaldi et al.*, 2012]. In this context, we believe that potential of NF to impose extremely high costs is significant. But, how can policymakers and politicians make the best decisions about whether and when to invest in aggressive protective infrastructure and adaptation measures?

We propose a category of policy activity called Cumulative Hazard Policy Challenges (CHPCs). Cumulative hazards are situations in which relatively low cost incidents have the potential to increase in frequency rapidly enough to impose significant social and economic costs, but their actual trajectory cannot be predicted. Faced with these cases, policymakers would like two sorts of guidance:

1. What is the probability that these incidents will achieve a critical mass that imposes significant social and economic costs?
2. What are our policy options at different points along this anticipated trajectory?

In very general terms, policymakers can at any time take one of three courses of action: (a) defer policy action, (b) take incremental policy action, and (c) take transformative policy action. Absent clear answers to 1 and 2 above, there is an overwhelming bias toward deferring action and taking incremental steps—even though politicians often campaign on the promise of taking transformative action. But clearly, this bias toward deferring action and taking incremental steps runs the risk of pushing truly enormous costs into the future. *What, then, can scientists provide to decision-makers that can help them to choose the optimal course of action under conditions of complexity and uncertainty?*

The emerging ability to harness big data provides an unprecedented opportunity for scientists to analyze the complex systems from which these CHPCs emerge and improve understanding of important trends such as the nature and potential drivers of flood claims [*Kousky and Michel-Kerjan*, 2015] and impacts on the frequency of nuisance coastal floods [*Sweet and Park*, 2014; *Moftakhari et al.*, 2015]. Policymakers are growing accustomed to informing decision-making with simple indices based on vast amounts of environmental data. CHI offers a "what if" scenario analysis tool for framing the cumulative impacts of frequent and low cost incidents relative to infrequent extreme events that politicians understand quite well. Furthermore, CHI can be used to assess how a system will respond to building levees and sea walls (i.e., reducing exposure or expected costs) or rising sea levels (i.e., increased exposure or expected costs). As such, harnessing big data to monitor CHI nationally and internationally could help to identify the locations where high-frequency, low-impact problems are expected to be most severe, and promote greater awareness among the public. Indeed, with these inputs and the perspective of local experts for critical community context, this information might help policymakers decide to move beyond the convenient but potentially very costly strategies of deferral and incrementalism, and promote more transformative policies where these make sense.

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