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## ADDENDUM

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## Addendum to ‘Understanding risks in the light of uncertainty: low-probability, high-impact coastal events in cities’

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### Abstract

This addendum adds to the analysis presented in ‘Understanding risks in the light of uncertainty: low-probability, high-impact coastal events in cities’ Abadie *et al* (2017 *Environ. Res. Lett.* **12** 014017). We propose to use the framework developed earlier to enhance communication and understanding of risks, with the aim of bridging the gap between highly technical risk management discussion to the public risk aversion debate. We also propose that the framework could be used for stress-testing resilience.

Uncertainty about climate change risks represents a great challenge to design effective adaptation policies. These need to assess which climate risks can be reduced, how they should be reduced and when (Refsgaard *et al* 2013). Understanding these risks and defining an acceptable level of risk (ALR) therefore becomes an essential part of the policy discussion. The discussion with regard to climate risks, however, is rather technical and is dominated by highly specialized expert judgments (Akerlof *et al* 2016). While public participation is necessary to this process (Few *et al* 2007, Dietz 2013) and critical to build trust, it is very difficult to involve non-specialized stakeholders in the decision-making process. Finding ways of enhancing understanding and communicating of these risks is thus an important challenge.

We also know that special attention should be paid to socio-economic impacts of major but unlikely climatic events due to their very significant potential damage (Pindyck 2011). This has been argued at length in the economic literature (Weitzman 2009, 2013, Nordhaus 2011). Hurricane Harvey has tragically reminded us how important these catastrophic events can be. Yet, the IPCC scenarios, which are the basis of most modelling in this area, have focused mainly on central distributions (i.e. median damages) paying very little attention to the so-called tail events. Including estimates of damages under low confidence situations

is critical for decision-making, particularly in coastal areas (Hinkel *et al* 2015).

In a recent research paper (Abadie *et al* 2017), we presented a risk-based approach to focus on the combined risk of sea-level rise and coastal extremes in major coastal cities around the world. It included consideration of extreme case events at the high-risk tail of the probability distribution of damages; i.e. the likelihood of rare, adverse events from which one wishes to be protected. Hurricane Harvey in Houston was exactly such an event. This approach enables one to deal with high-damage, low-probability events, improves comprehension of these risks and provides the grounds to involve decision-makers and other relevant stakeholders in the definition of ALR<sup>4</sup>. Hence it makes an important step forward in risk governance.

Coastal areas represent only 2% of the world’s land but concentrate 13% of its urban population and

<sup>4</sup> It is not the scope of this paper to analyse in detail which stakeholder could take part on this process. Some tentative suggestions could be: (a) city managers and their representatives, (b) representatives of vulnerable household groups within the city, (c) representatives of businesses within the city, (d) representatives from regional and central government, on the grounds that they have an interest in the choices made because they are liable to finance either part of the protective measures and bear some of the costs of recovery after an event. And perhaps other groups such as representatives of local citizens and NGOs.



**Figure 1.** Risk in major US coastal cities in the middle of the road sea-level rise scenario (RCP4.5) in 2050. Circles represent the risk measured as the average damage of 5% worst cases.

generate 10% of global GDP; around 600 million people currently live within 10 m of present-day sea level (McGranahan *et al* 2007). Sixty percent of cities with a population over 5 million are located within 100 km of the coast and population densities in coastal areas in 2000 were five-fold larger than the average (Small and Nicholls 2003, Neumann *et al* 2015). Risk exposure in coastal areas is expected to increase during the following decades due to sea-level rise and extreme events, but also as a result of population growth and associated urbanization processes (Neumann *et al* 2015).

The most common approach when assessing flood impacts is to estimate annual average losses (AAL). As several authors have argued before (Weitzman 2009, Nordhaus 2011, Hinkel *et al* 2015), focusing on average damages leads to an important underestimation of potential impacts. As an alternative, we propose to use two risk measures: the value at risk (VaR(95%)) and the expected shortfall (ES(95%)). The first represents the damage at the 95th percentile of the distribution and the latter the average damages of the 5% worst cases. These measures are well-known in financial economics and have been extensively and successfully used to account for the uncertainty of many different economic variables. As far as we know, we are the first to apply the measures for coastal risks. VaR is most commonly used, but it has less desirable properties as a risk measure than ES (Hull 2012, Abadie *et al* 2017)<sup>5</sup>. When addressing the impacts of sea-level rise

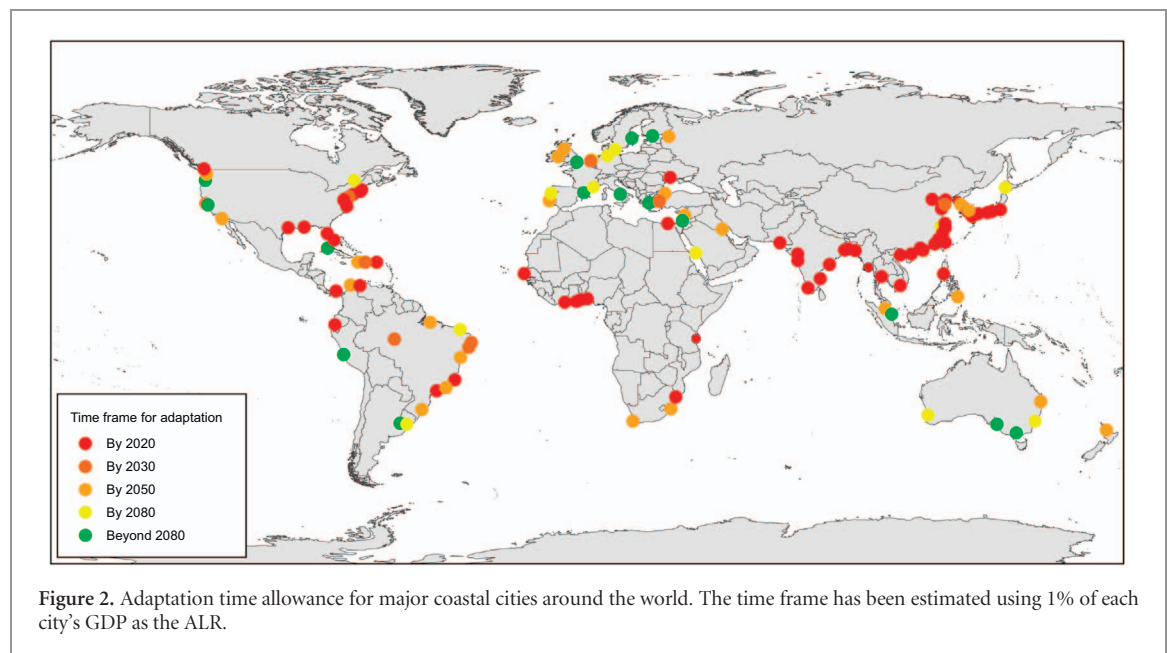
and extreme events, both risk measures provide very relevant information for coastal planners about the so-called tail events: even if the probability of occurrence is small (5%), their consequences could be catastrophic, intolerable from an economic, social or environmental perspective. Therefore, this information is very relevant for risk adverse planners (Hinkel *et al* 2015).

When we look at the impacts of the 5% worst cases under several IPCC scenarios, a global review shows that five US cities are among the top 30 with the greatest potential damages in the world. Houston is one of these cities. The average damages in the 5% of worst cases (and depending on IPCC scenarios) ranged from US\$31–36 billion in 2050, from US\$44 to 54 billion in 2070 and from US\$67–86 billion in 2100. The other American cities included in the analysis that are under a high risk by 2050 are New Orleans (from US\$809–934 billion), Boston (from US\$68–85 billion), New York (from US\$65 to 82 billion) and Miami (from US\$48–58 billion) (figure 1). These numbers more than double by 2100.

Taking account of these flood related low probability catastrophic events raises estimated expected damages in main US coastal cities by as much as 641%, and at least by 139% relative to previously estimated annual average damages.

The two risk measures proposed in this article can be used in conjunction with the concept of ALR to decide on appropriate adaptation. Indeed, these measures are very appropriate for stress testing in an analogous way to the tests done in the financing and banking system to assess resilience (Kupiec 1998). These tests consist of assessing whether a system can

<sup>5</sup> As stated in Abadie *et al* (2017), 'ES gives more information on expected losses in less favorable situations than just a level of a critical threshold represented by VaR. Additionally, ES provides optimization short-cuts which, through linear programming techniques, make many large scale calculations practical that would otherwise be out of reach'.



or cannot recover (or how much effort will require to recover) from certain negative events occurring. In other words, what is the level of risk the system will not recover from in the case of the unlikely and unexpected situation happening.

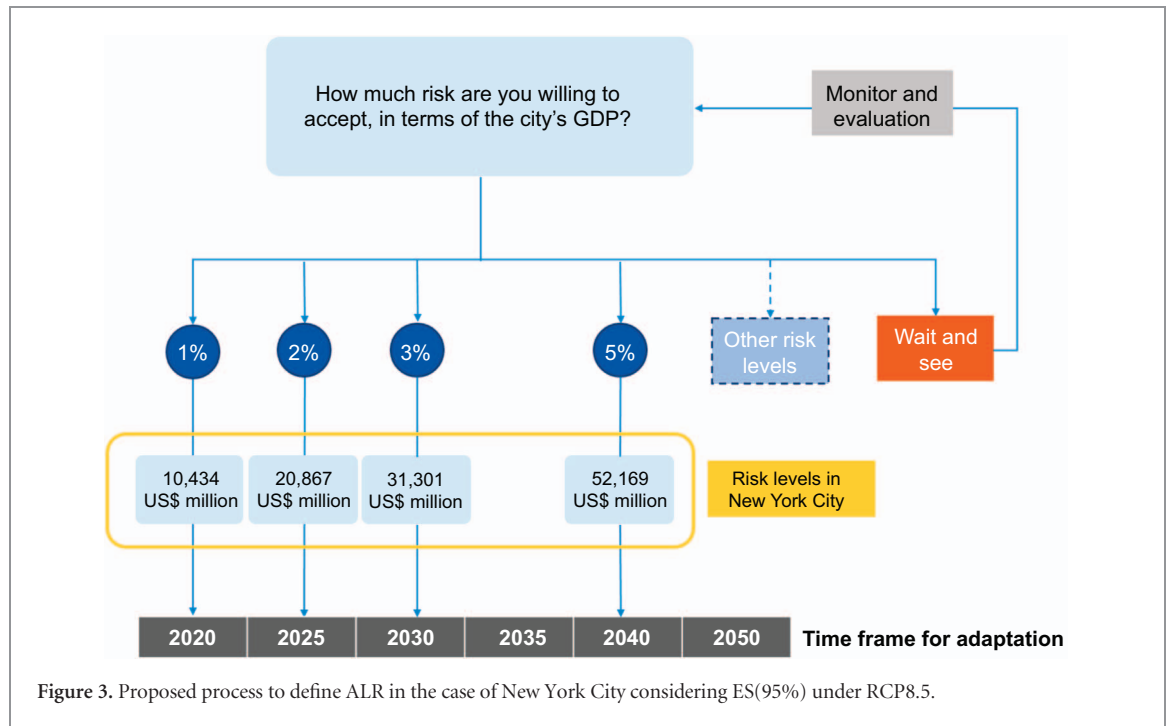
We have applied this approach to 120 coastal cities with a population over one million (Abadie *et al* 2017). For illustrative purposes, ALRs were set at 1% and 2% of local gross domestic product (GDP) for each city, with damages measured as ES(95%). Given the available continuous probability distribution of damage over time, we can obtain the year in which the acceptable risk level is expected to be exceeded in each city. This will depend on the climate scenario (RCP2.6, 4.5 and 8.5). In other words, we are providing the year at which adaptation policies and measures need to be effectively in place in order to avoid exceedance of such ALR. To have these adaptation measures in place will typically involve several years preparation before they are fully operative. Figure 2 shows an illustration of this approach for the cities in our database under sea-level rise scenario RCP8.5. When ALR is defined at 1% of GDP, we see that many cities in South and South East Asia, Western Africa and the West Coast of the US would need to implement adaptation by 2020. Most Latin American cities in the east coast could extend this deadline up to 2030, with a couple of exceptions in Brazil (Sao Paulo and Grande Vitoria). European cities have the longest time before they need to act, but some exceptions can also be found. Rotterdam, for example, would need to implement adaptation by 2030 in order to avoid a risk equivalent to 1% of its GDP.

We suggest that this indicator of acceptable risk to tail events (i.e. damage in terms of GDP of the city or region) can be used (together with VaR and ES) in consultation processes with stakeholders to define ALRs for each city, region or country. Once the ALR

is agreed—that is, once stakeholders have decided how much damage they are willing to accept as a percentage of GDP—the method allows the adaptation needs for each city to be assessed, including the timing of the adaptation measures. These are very relevant policy questions.

This proposal represents an important step forward towards the governance of climate change related risks. It bridges the divide from the very technical risk management discussion to the risk aversion debate by enhancing understanding of the risks.

For illustrative purposes, consider the case of New York (USA) depicted in figure 3. To frame the case recall that losses due to hurricane Sandy in New York in 2012, only in terms of repair and response costs, reached US\$36.9 billion (US Department of Commerce 2013). No reliable estimates are available yet for the losses of hurricane Harvey but the same exercise could be run for a city like Houston, also analyzed in our earlier paper (Abadie *et al* 2017). Stakeholders in New York could decide on an ALR measured in terms of local GDP: if they were willing to accept a risk level of 1% of the local GDP (2015), they would be assuming a coastal risk of US\$10.4 billion if the worst case occurs—measuring risk in terms of the average losses of the 5% worst cases. In order to avoid the risk of having greater losses, adaptation measures would need to be implemented (and be effectively working) by 2020. However, New York stakeholders might be willing to accept higher or lower risks. For example, a risk of 2% of the city's GDP accounts for US\$20.9 billion, delaying the need for having adaptation in place until 2025. And, logically, the higher the ALR the later they could postpone adaptation. In other words, the lower the risk they are willing to accept the sooner they should have adaptation measures implemented. When the time frame for adaptation extends for a few decades may be advisable to wait.



Numbers differ significantly from city to city. For example, with a city such as Shanghai, an ALR of 1% of city GDP in 2015 (US\$3.4 billion) means that adaptation should be in place before 2020. However, the risk increases so fast in this city that this would still be the deadline for adaptation when considering acceptable risk levels of 2%, 3% or 5% of the city's GDP.

We have proposed a decision-making framework with strong scientific grounds that responds to several challenges: first, the stochastic modelling approach enables uncertainty to be accounted for in a scientifically sound manner, providing a probability distribution of annual average damages, but also looking at low-probability, high-damage tail events; second, it creates a space for policy makers and stakeholders to contribute to decisions about climate risk that often occur in highly technical contexts; third, it provides an indicative time frame for adaptation, based on the level of risk that stakeholders are willing to accept.

Of course, a number of issues remain to be solved such as the dynamic nature of risks or issues around how to elicit acceptable risk and to effectively integrate different views of stakeholders. However, the framework proposed here offers considerable promise to enhance communication and understanding of climate risks as well as a planning tool.

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