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LETTER

Risk measures and the distribution of damage curves for 600 European coastal cities

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Abstract

A good understanding of climate change damages is vital to design effective adaptation policies and measures. Using a dataset of probabilistic sea-level rise and other of flood damages and protection cost curves for the 600 largest European coastal cities we generate stochastic damage curves and their distributions with and without adaptation. We apply the Generalized Extreme Value distribution to characterize the distributions and calculate two risk measures: the Value at Risk and the Expected Shortfall, which contribute to understanding the magnitude and probability of high-end sea-level rise represented by the upper tail of the distribution. This allows the costs of sea-level rise to be estimated (that is, in addition to other costs related to coastal extreme events) and supports decision-makers in integrating the high uncertainty related to future projections. This knowledge is necessary for an adequate risk management that does not underestimate risk. Furthermore, it allows city planners to tailor their risk tolerance. A great number of cities in Europe are currently undertaking adaptation plans or have already done so. Making these findings available should therefore be of great priority value to inform these processes.

1. Introduction

The rise in sea level is one of the main threats of climate change (IPCC 2013, Kopp *et al* 2014). Globally, sea level has risen by more than 20 cm since 1880 (Hardy and Nuse 2016) and since 1993 it is rising at a higher rate, of up to 3 mm per year (Hay *et al* 2015, Watson *et al* 2015). This acceleration is likely to continue in the future (Jackson and Jevrejeva 2016, Wigley 2018) even if the global efforts to reduce GHG emissions are successful, which is not yet certain given the difficulties in the climate negotiations (Rogelj *et al* 2016, Sainz de Murieta *et al* 2018). As 10% of the world's population as well as a substantial proportion of its economic assets and infrastructures are located in low-lying coastal areas, the number of people at risk from extreme coastal events is high and has increased substantially. Climate change is expected to exacerbate this risk (McGranahan *et al* 2007, Wong *et al* 2014).

City planners in Europe, and in many other parts of the world, are currently engaged in defining and/or implementing adaptation plans (Reckien *et al* 2018). In this context, they are in charge of establishing acceptable levels of risk, i.e. defining risk tolerance. Good risk governance requires a profound understanding of the risks and the expected damages; and the scientific community has a crucial role to play in providing this knowledge in an accurate, trustful, comprehensive and understandable manner.

An exhaustive dataset of macroscale flood damage and protection cost curves for the 600 largest European coastal cities was recently published (Prahl *et al* 2018), initiating a more general discussion on the use of cost and damage curves. The authors argue that while 'aggregate cost curves on coastal flooding at city-level are commonly regarded as by-products of impact assessments' this information can be of great use for comparative assessments of costs and benefits of coastal adaptation. Other authors have also highlighted the importance of generating detailed damage curves as well as their distributions with special interest in understanding low-probability, high-damage tail events to guide risk adverse coastal management (Hinkel *et al* 2015, Abadie *et al* 2017). Considering only the probable range (or its median) without analysing what happens at the most severe tail of the distribution of probabilities is tantamount to underestimating risks (Weitzman 2009, Nordhaus 2011, Weitzman 2013). The presence of a wide range of possible outcomes requires the economic analysis to move from one based on scenarios or expected values to one where the full distribution of probabilities is taken into account (Hull 2012), and to pay special attention to tail events (Pindyck 2011, Editorial 2016, Galarraga *et al* 2018). Stochastic models enable analyses to be conducted in the context of uncertainty where the distribution of the results of the model can be determined by implementing a large number of random iterations (Refsgaard *et al* 2007).

Two useful measures of the tail of the distribution are the Value at Risk (VaR) and the Expected Shortfall (ES). The VaR (95%) is a widely used measure of risk that provides information about where the 5% worst cases start. However, it does not provide information about the shape of the upper tail. For this reason, we propose to complement mean damages and VaR (95%) with the ES (95%) which better informs about the shape of the upper tail by showing the average of those 5% worst cases. Both have traditionally been used in financial economics to guide investment decisions, even though several authors have shown that ES is a better indicator of risk than VaR (Artzner *et al* 1999, Hull 2012). These measures can be used to: (i) inform risk adverse coastal planning, (ii) to define acceptable levels of risk (ALR) tailored to the risk tolerance of each city and consequently (iii) time-frame adaptation needs (Abadie *et al* 2017, Galarraga *et al* 2018). In addition, these measures can also be used to stress-test adaptation plans as well as any other urban development for a better understanding of the resilience of a city to the impacts of sea-level rise (SLR) (Galarraga *et al* 2018). As will be shown later, using ES is much more effective as it offers a complete picture of what is happening in the tail of the distribution and thus complements very well the rest of the indicators.

2. Modelling risk measures

Aiming to contribute to the discussion initiated by Prahl *et al* (2018), we have combined deterministic damage curves for coastal flooding with relative probabilistic SLR for three emission scenarios (Kopp *et al* 2014). This gives us the probabilistic distribution of the additional damages due to SLR for each scenario and point in time for 600 European cities, which are necessary to obtain the damage distributions, understand the shape of its tail and calculate the ES (95%). Note that we are only accounting for future SLR and not storm surges.

This process has been completed as follows.

We use a Generalized Extreme Value (GEV) distribution model which is particularly suitable and widely used for modelling extreme values in probability distributions.

The GEV cumulative distribution function $F(x)$ can be described as follows:

$$F(x) = e^{\left(-(1+\xi\frac{x-\mu}{\sigma})^{-\frac{1}{\xi}}\right)},\ 1 + \xi\frac{x-\mu}{\sigma} > 0 \qquad (1)$$

where $\mu \in R$ represents the location, $\sigma > 0$ the scale and $\xi \in R$ the shape. Thus, the probability density function $f(x)$ is as shown in equations (2) or (3), depending on whether ξ is zero or not:

$$f(x) = \frac{1}{\sigma}\left(1 + \xi\frac{x-\mu}{\sigma}\right)^{-\frac{\xi+1}{\xi}} e^{\left(-(1+\xi\frac{x-\mu}{\sigma})^{-\frac{1}{\xi}}\right)},\ \xi \neq 0 \qquad (2)$$

$$f(x) = \frac{1}{\sigma}(e^{[-\frac{x-\mu}{\sigma} - e^{-\frac{x-\mu}{\sigma}}]}),\ \xi = 0. \qquad (3)$$

The mean of the distribution of probabilities $E(x)$ can be estimated as shown below:

$$E(x) = \mu + \sigma(\Gamma(1-\xi) - 1)/\xi,\ \text{if}\ \xi \neq 0,\ \xi < 1 \qquad (4)$$

$$E(x) = \mu + \sigma\gamma,\ \text{if}\ \xi \neq 0,\ \xi = 0 \qquad (5)$$

$$E(x) = \infty,\ \text{if}\ \xi \geqslant 1 \qquad (6)$$

where Γ is the gamma function and γ is Euler's constant. The distribution has three parameters and combines the extreme value distributions of Gumbel, Fréchet & Weibull.

The starting point is the relative SLR percentiles estimated by Kopp *et al* (2014). While these are a key input to be able to model probabilistic damages due to SLR, they alone do not fully explain the shape of the tail of the distribution of probabilities, which is the focus of this paper. The percentiles in Kopp *et al* (2014) show that SLR has a non-symmetric distribution due to the positive skewness in the data and, therefore, these data cannot be used directly to calculate the mean of the distribution, nor the ES (95%).

For this reason, the first step in our methodological proposal is to calibrate the GEV model described in equations (1) to (6) using the 50, 95 and 99.5 percentiles for SLR given by Kopp *et al* (2014), as described in figure 1. Because we are interested in the shape of the upper tail, we have selected the median and two percentiles corresponding to the right tail, instead of using all the percentiles provided by Kopp *et al* (2014). An analysis of the goodness of fit of the SLR distribution's upper tail based on the 50th, 95th and 99.5th percentiles versus an alternative using all Kopp *et al* (2014) percentiles is included as supplementary material, available online at stacks.iop.org/ERL/14/064021/mmedia. It shows that the first alternative is better when the objective is to calculate the risks linked to the upper tail of the distribution.

The estimates by Kopp *et al* (2014) are calculated for a large set of tide gauges around the globe. In this case, we have selected the projections from 224 tide gauges that

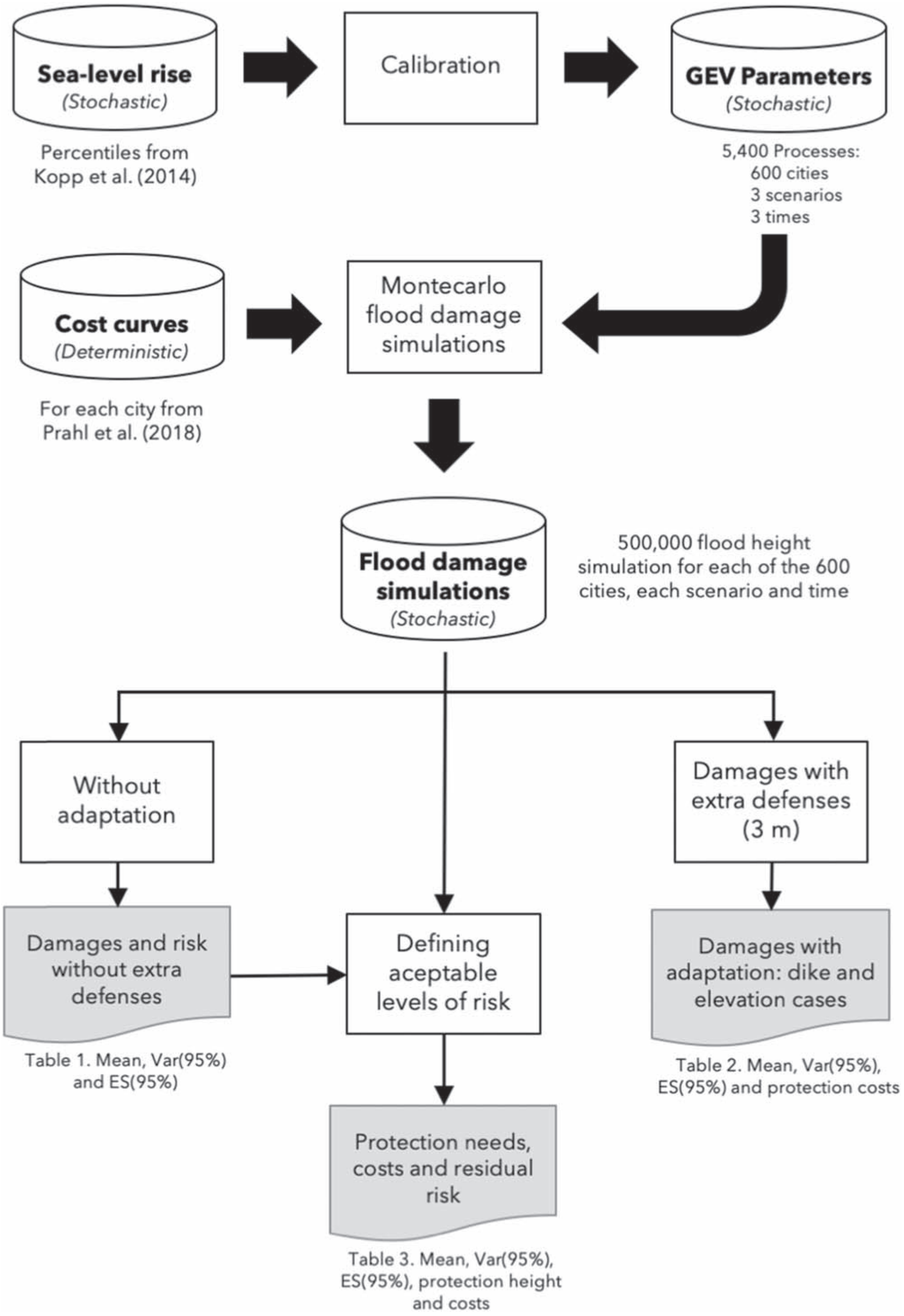

Figure 1. Diagram explaining the modelling process, including input data and output products.

are located in Europe to generate 2016 GEV distributions for SLR. The tide gauge closest to each city was obtained using the haversine formula, commonly used to estimate the distance between two points from latitude and longitude data (Song and Lee 2015).

In the second step, the GEV parameters for SLR obtained in the calibration process and the damage curves (Prahl *et al* 2018) are processed using Monte Carlo methods to obtain the additional flood damages due to SLR for each city, scenario and time considered. Results for the three SLR scenarios and all 600 cities are provided in supplementary tables S1 to S3.

Up to 500 000 Monte Carlo simulations were run through 5400 processes (i.e. 600 cities for years 2030, 2050 and 2100; and for RCP 2.6, 4.5 and 8.5). This way one can generate the full distribution of probabilities for each city. The whole process of estimation is illustrated in figure 1.

Note that at first sight, including more optimistic scenarios such as RCP2.6 and RCP4.5 when stating that from a pure risk perspective we should focus on low-probability, high-damage may not seem necessary. However, analysing the three scenarios is appropriate as outcomes will depend on the probability

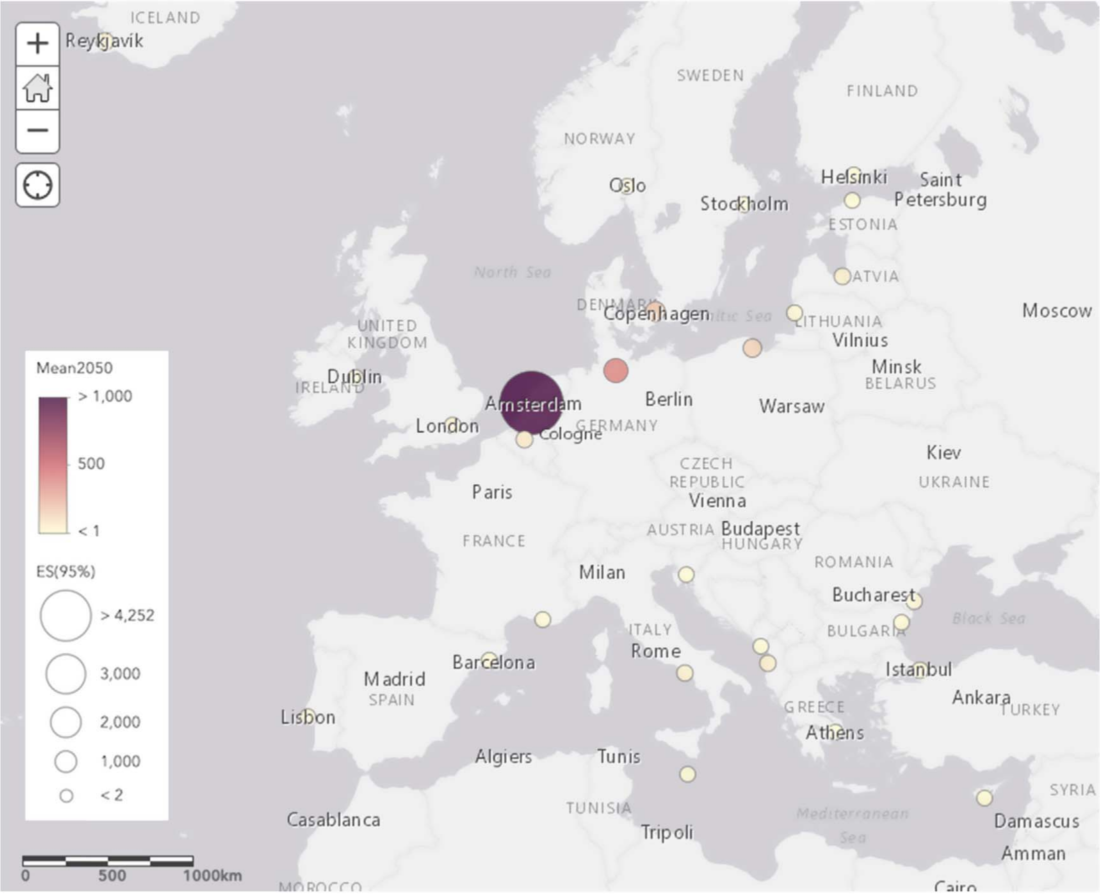

Figure 2. Expected damages and risk of SLR, measured as ES (95%) for main European coastal cities. Damages are shown in millions of euros (2016), under RCP4.5 in 2050.

assigned to each emission pathway. That is, if a high probability of reaching RCP8.5 is expected, then risk will be determined by the upper tail of this scenario. Per contra , if the chances of reaching this scenario were low, then it makes good sense to analyse what happens on more optimistic scenarios such as, RCP 2.6 or RCP 4.5. In this paper we do not assess the probability of each RCP (as was done, for example, in Abadie 2018) and therefore investigate the impacts under all three of them.

From these distributions we have estimated the expected damages (mean), as well as the two risk measures, VaR (95%) and the ES (95%), which represent the additional damages of high-end SLR. Using only expected damages means ignoring what happens in the upper tail distribution of probabilities.

3. Estimating additional damage risks due to sea-level rise in main European coastal cities

Damages in each city, as well as the difference between average and extreme SLR, increase with time. Amsterdam is, by far, the city with the highest risk in every scenario and year, followed by Hamburg, Copenhagen and Gdansk. Figure 2 presents mean damages and the average of the 5% worst SLR cases. Full data for all cities and RCPs is available in table S4.

When expected damages in the low-probability-high-impact zone are considered, the losses can be significantly higher, and in some cases more than double the mean values. This has also been demonstrated in earlier studies (Abadie *et al* 2017). Understanding the size of the risk in the upper tail of the distribution can be a critical information for city planners in order to avoid underestimating the potential impacts of climate change and accordingly to design effective adaptation policies (Hinkel *et al* 2015).

In 2030, 16 of the main cities presented in table 1 show damage risks below 40 million euro, as measured as ES (95%). Four cities show risks between 40 and 50 million euro and seven cities' risk ranges between 65 million euro (in the case of Riga) to more than 2500 million euro (for Amsterdam). By the end of the century, the top five cities present an ES (95%) over 500 million euro, with Hamburg, Copenhagen and Amsterdam exceeding 1.1 billion euros. Seven cities show risks between 100 and 500 million euros, while the remaining 15 cities' risk stays below 100 million euros. The results for Amsterdam look disproportionate compared to the rest in all cases, but this might

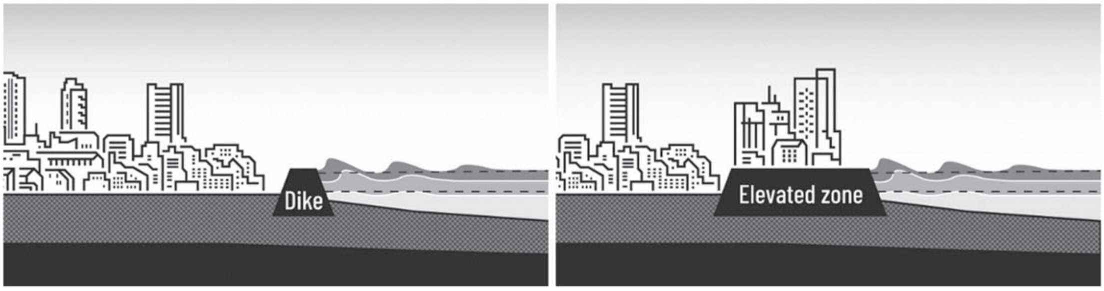

Figure 3. Illustration of defence-failure scenarios. Left: dike case: illustration of a consolidated area in which only dikes can be built to adapt to SLR. Right: Elevation case: illustration of a new construction area in which the zone can be elevated to adapt to SLR.

Table 1. Protection costs (3 m) and residual expected damages and risk, measured as ES (95%) of main European coastal cities in 2100. Damages are shown in millions of euros (2016), under RCP4.5.

			Protection costs (3 m)		Dike		Elevation	
ID	City	Country	Low	High	Mean	ES (95%)	Mean	ES (95%)
1	Amsterdam	Netherlands	45 939	66 393	11.8	235.2	2.8	56.9
2	Antwerp	Belgium	10 958	15 839	4.6	91.6	0.6	12.5
3	Athens	Greece	1668	2411	—	0.6	—	0.1
4	Bar	Montenegro	71	103	—	0.1	—	—
5	Barcelona	Spain	1434	2072	0.1	1.8	—	0.2
6	Constanta	Romania	1505	2175	0.0	0.1	—	—
7	Copenhagen	Denmark	7198	10 403	1.3	25.4	0.1	2.3
8	Dublin	Ireland	2170	3136	0.4	8.4	0.1	1.4
9	Durrës	Albania	843	1218	0.1	2.3	—	0.5
10	Gdansk, Gdynia	Poland	3350	4842	0.3	6.8	—	0.8
11	Hamburg	Germany	16 164	23 369	2.0	40.8	0.3	6.2
12	Helsinki	Finland	1467	2120	—	0.1	—	—
13	Istanbul	Turkey	4091	5913	—	0.2	—	—
14	Klaipeda	Lithuania	839	1212	0.1	1.4	—	0.1
15	Limassol	Cyprus	300	434	—	0.3	—	—
16	Lisbon	Portugal	947	1369	0.1	1.1	—	0.1
17	London	United Kingdom	1648	2381	1.5	30.9	0.2	4.1
18	Marseille	France	1165	1683	0.1	1.6	—	0.4
19	Naples	Italy	3039	4392	0.3	6.3	0.1	1.4
20	Oslo	Norway	1413	2043	—	0.7	—	0.1
21	Reykjavik	Iceland	4388	6348	0.2	3.6	—	0.7
22	Riga	Latvia	3627	5242	0.1	2.2	—	0.1
23	Rijeka	Croatia	197	285	—	0.1	—	—
24	Stockholm	Sweden	1605	2319	—	0.1	—	—
25	Tallinn	Estonia	517	748	—	—	—	—
26	Valletta	Malta	420	607	—	0.3	—	0.1
27	Varna	Bulgaria	434	628	—	0.0	—	—

be due to a limitation of the cost curve acknowledged by Prahl *et al* (2018), which underrepresent the role of current defences.

We use these data to compare the damage estimates with the costs of building a certain protective infrastructure (Prahl *et al* 2018). That is, we are proposing a probabilistic design model for adaptation measures. For illustrative purposes we have chosen two protection models, both 3 meters high: assuming two defence-failure scenarios in line with other studies (Hallegatte *et al* 2013):

1. Dike Case: a consolidated area in which the only possible protection is to build a barrier-type defence (figure 3, left).
2. Elevation Case: a new area for development that can be elevated aboveground, according to a certain ALR (figure 3, right). Note that these calculations are provided for illustrative purposes only. It cannot be applied to areas that are already consolidated because it is unlikely that a whole city could be elevated.

We now consider two defence-failure scenarios, in line with other studies (Hallegatte *et al* 2013). For the dike case, if SLR is higher than 3 meters we assume that water levels overtop the defence and damages correspond to the full water height. There is no damage, however, if the SLR is equal to or lower than 3 meters. In this case, the damage is obtained directly from the stochastic damage function estimated in this paper. That is, for the dike case and protection of 3 meters when SLR $>$ 3, damage is a function of SLR only, written as Damage $=$ f(SLR). Damage is equal to zero when SLR is lower or equal to 3 meters.

For the elevation case, if SLR is higher than 3 meters, damages will correspond to a water height that is the difference between sea level and the height of the protection (elevation). There is of course no damage if the SLR is equal or lower than 3 meters. That is, for the elevation case and protection of 3 meters, when SLR $>$ 3, the damage is equal to the function of SLR minus 3 meters. That is Damage $=$ f(SLR-3). Damage will be equal to zero when SLR is lower or equal to 3 meters.

Expected damages, costs of the infrastructure as well as risk measures for both cases under RCP4.5 are shown in table 1 (and table S5 for the rest of the cities and scenarios). Again, note the significant differences between the averages expected damages and the tail events. Only data for 2100 are displayed in table 1 because after implementing protection measures the residual damages and risk in 2030 and 2050 would be zero. Of course, this situation assumes that the defence is built before 2030. This is a simplification for illustrative purposes, but more discussion is warranted to understand as to when it is optimal to start the construction works.

Note that while the VaR (95%) would be zero for all cities (see table S5), the ES (95%) shows a significant residual risk that should not be ignored, that is, in some cases important damages occur in higher percentiles, demonstrating that ES is a better measure of risk (Losada *et al* 2013), as was also stated earlier. This is a very important attribute of the ES. Indeed, it illustrates the interest in understanding the shape of the distribution of damages as well as the tail (Heal and Millner 2014, Weaver *et al* 2017, Etkin *et al* 2018). In this case, the 3-meter defences will protect the cities for a SLR of this level but will not eliminate all the residual risk as represented by ES. We do not suggest that VaR be discarded, rather that it complements the information offered by the ES.

4. Defining acceptable levels of risk

For either protection model (dike or elevation), one could now use this information to design the infrastructure based on the level of risk a city chooses to protect itself from. This is the so-called ALR (Galarraga *et al* 2018) and can be defined considering tail events, i.e. the value for VaR (95%) or ES (95%), rather than just expected damages. The ALR can be easily translated into different indicators such as a percentage of a city's public budget, its GDP or similar (Abadie *et al* 2017, Galarraga *et al* 2018).

For illustrative purposes, let us consider cities that are very risk adverse and aim at protecting themselves for the 99.5th percentile, that is, the ALR is set at a value that in 2100 is only exceeded in 0.5% of cases in each city. In other words, with this ALR in the year 2100, 90% of cases included in ES (95%) will take the value zero. In order to achieve this level of protection, defences of certain height, different for each city, would need to be built. Then calculations are done by assuming that when SLR is greater than the corresponding height then Damage $=$ f(SLR) and Damage $=$ 0 in the contrary. Figure 4 presents the level of protection needed in the cities previously considered under scenario RCP4.5, including protection costs and residual damages (full data, including residual damages, are available in table S6). For example, in the case of Antwerp or Barcelona the required protection height would be 1.5 meters, while for Oslo a 1 meter protection could be enough. The ALR illustrated here can be tailored to each city's preferences, calculating both risk measures VaR (95%) and ES (95%) so that the design of defences guarantees this predefined level of protection. The calculations can be replicated with the methodology provided in this paper.

Note that while VAR (95%) can be reduced to zero thanks to the protection, there is still a residual risk represented by ES (95%) that remains (table S6). This again illustrates why the ES is a much better measure of risk; it provides an alternative approach to account for low-probability, high-damage events in a context of high uncertainty, which is due to the volatility in the SLR distribution that is less relevant early in time but increases with time. This approach could prove to be useful to stress-test adaptation measures and could be the basis for defining ALRs by each city, measured as a certain value for VaR or ES for any given year.

5. Time-framing adaptation

In addition to calculating the level of protection required, defining ALRs can also be used to time-frame the adaptation: knowing the tolerable risk threshold allows one to estimate the year in which this damage threshold will be exceeded. This means that whatever the adaptation options are, these should be fully operative by a certain date if the aim is to keep the risk at the given level (Abadie *et al* 2017, Galarraga *et al* 2018). We illustrate this for the case of Barcelona.

Assume that Barcelona decides on an ALR of 50 million euro by 2100, or more specifically, that the city wishes to be protected from the average damage not being higher than 50 million euro in the 5% worst cases. This means that the city is setting the ALR at ES

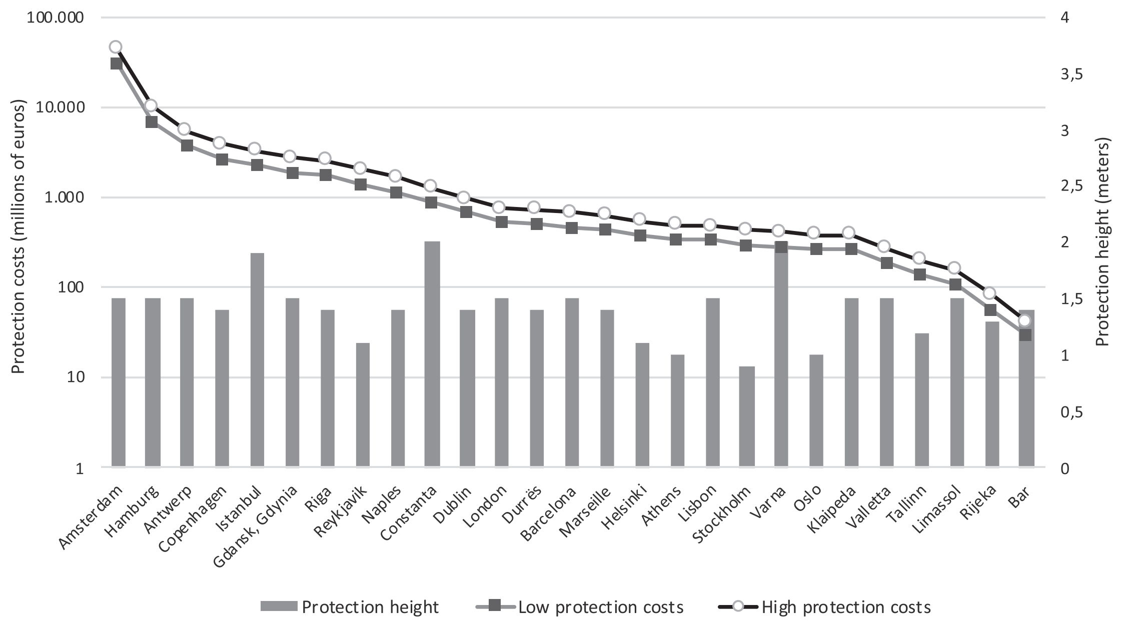

Figure 4. Protection need (height), in the dike case, and protection costs for an ALR equivalent to 99.5% percentile in 2100. Protection costs are shown in millions of euros (2016), under RCP4.5.

Table 2. City of Barcelona with ALR in terms of ES (95%) in 2100 under RCP 2.6, 4.5 and 8.5. Protection costs and ES (95%) are shown millions of euros (2016).

	RCP 2.6			RCP4.5			RCP8.5		
ES (95%) Objective	H	Cost range		H	Cost range		H	Cost range	
10	1.78	636	919	1.76	625	903	2.02	773	1117
20	1.58	520	751	1.42	442	638	1.72	600	867
30	1.45	456	659	1.26	372	537	1.57	514	743
40	1.36	416	602	1.15	326	472	1.46	460	665
50	1.29	386	558	1.07	294	424	1.38	427	617
60	1.23	361	521	1.02	269	389	1.32	401	579
70	1.18	339	491	0.97	253	365	1.27	379	548
80	1.14	320	463	0.93	241	348	1.23	362	523

(95%) = 50 M€. We then estimate that the protection height for such ALR in the city of Barcelona should be 1.38 meters (RCP 8.5), 1.07 meters (RCP 4.5) and 1.29 meters (RCP 2.6). And the cost under RCP 8.5 will range from 427 million euro to 617 million euro. Observe that risk is an annual value, in this case in 2100, while protection costs represent an investment made with a long lifetime. Note that protection height under RCP4.5 is smaller than in RCP2.6. While the median SLR value is higher in RCP4.5, the percentiles from Kopp *et al* (2014) that shape the tail (95th and 99.5th) in 2100 are larger in RCP2.6. This is the reason for risk in Barcelona being higher under RCP2.6. See tables 2 and S7 for more detail.

For this case we have used a cubic spline method, a standard technique for interpolation, to obtain the percentiles for intermediate years (de Boor 2001). The cubic splines interpolation method uses third-order polynomials which pass through the points with known values. Then, applying the same procedures as before, we have calculated the damage distributions for these intermediate years. Based on that an estimate has been made of the time frame for adaptation needs considering that ES (95%) = 50 million euro (see table S7).

Looking at the values for the city of Barcelona presented in table S3 (further developed in table S7 to account for every decade), it is possible to assess when the threshold of ES (95%) = 50 M€ will be exceeded. Thus, one can show that protection measures should be fully operative by the year 2060 under RCP 8.5. Many other calculations are possible with the data and method presented in this paper such as those to assess progressive adaptation measures versus more rigid ones.

6. Conclusions

Uncertainty is critical in climate projections and therefore needs to be adequately addressed when making decisions on adaptation and risk management. This is especially important so as not to underestimate risks. In this paper we show that stochastic modelling is more adequate than deterministic modelling in contexts of significant uncertainty or risk. We provide the distributions for additional damages due to sea-level rise (SLR) in 600 cities in Europe together with a method on how to use these functions for the following: first, understand what happens in the tail of the distribution of damages due to SLR, going beyond the most conventional use of expected damages that can lead to underestimating climate risks; second, inform on the costs and benefits of adaptation measures tailoring them to satisfy the risk tolerance of each city; and finally, estimate the time by which the adaptation needs to be implemented. We conclude that understanding what happens in the tail of the distribution as well as its shape is extremely relevant for coastal managers and city planners as it allows the calculation of the distribution of damages and the residual risk once an adaptation measure is implemented.

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Author contributions

Galarraga, I and Abadie, L M designed the research; Abadie, L M performed the modelling; all authors contributed to the discussion of the research idea, analysing the results and writing up.

Conflict of interest

The authors declare that they have no competing interests.

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