water

MDPI

Article

The Costs of Sea-Level Rise: Coastal Adaptation Investments vs Inaction in Iberian Coastal Cities

Luis M. Abadie [1], Elisa Sainz de Murieta [1,2,*] and Ibon Galarraga [1]

[1] BC3 Basque Centre for Climate Change, Sede Building 1, 1st floor, Scientific Campus of the University of the Basque Country, 48940 Leioa, Spain; lm.abadie@bc3research.org (L.M.A.); ibon.galarraga@bc3research.org (I.G.)

[2] Grantham Research Institute, London School of Economics and Political Science (LSE), London WC2A 2AZ, UK

* Correspondence: elisa.sainzdemurieta@bc3research.org; Tel.: +34 944 014 690

Received: 3 March 2020; Accepted: 21 April 2020; Published: 24 April 2020

Abstract: Iberian coastal cities are subject to significant risks in the next decades due to climate change-induced sea-level rise. These risks are quite uncertain depending on several factors. In this article, we estimate potential economic damage in 62 Iberian coastal cities from 2020 to 2100 using regional relative sea-level rise data under three representative concentration pathways (RCP 8.5, RCP 4.5 and RCP 2.6). We analyze the expected accumulated damage costs if no adaptation actions take place and compare this scenario to the investment cost of some adaptation strategies being implemented. The results show that some adaptation strategies are less costly than the potential damage under inaction. In other words, it is economically rational to invest in adaptation even in a context of high uncertainty. These calculations are very relevant to inform climate change adaptation decisions and to better manage the risk posed by sea-level rise. Moreover, our findings show the importance of a good understanding of the shape of the sea-level rise and damage cost distributions to calculate the expected damage. We show that using the 50th percentile for these calculations is not adequate as it leads to a serious underestimation of expected damage and coastal risk.

Keywords: climate change; adaptation costs; investment decision; Spain and Portugal coastal cities; uncertainty; stochastic model

---

1. Introduction

Sea-level rise is one of the main consequences of anthropogenic climate change [1]. Sea level worldwide was stable from approximately 7000 years before present until the end of the 19th century, but since then the geological and tide gauge record presents signs of acceleration [2]. During the 20th century, a significant acceleration of sea-level rise has occurred, quantified at about 1.2 millimetres per year from 1901 to 1990 [3,4]. The same analysis applied to the period 1993–2010 revealed a much larger acceleration, of about three millimetres per year [4]. Other calculations [5] show an increasing sea-level rise since 2010 of up to 4.4 ± 0.5 mm yr^{-1}, so since the 1880s, the global sea level has increased more than 20 cm and continues rising at more than 4 mm yr^{-1} [6]. Nonetheless, sea-level rise can vary significantly in magnitude and rate of change regionally and these differences can be of up to four times larger in some areas [7].

The global sea-level rise projections by the Intergovernmental Panel for Climate Change (IPCC) [1], as well as the regionalized assessments for each emission scenario (representative concentration pathways, RCP), foresee an acceleration in sea-level rise over the course of the present century [8–11]. Sea-level rise will accelerate in the future and over the next centuries even if emissions stabilize [12]. The magnitude of change, however, remains uncertain because it depends on the ambition of mitigation efforts, as well as the location and the time considered. Let us illustrate this point: if the global average temperature is stabilized at 2 °C above preindustrial levels, by 2100 global sea-level rise could reach 26 cm at the median of the distribution and 81 cm at the 95th percentile. In a high emission scenario in which global temperatures could reach +5 °C, sea-level rise could reach 51 cm and 178 cm at the median and 95th percentile, respectively. Moreover, sea level could even exceed 2 m in 2100 (95th percentile) if thermal expansion and the contribution of major ice sheets are accounted for [13].

Sea-level rise will also lead to more frequent coastal flooding. The latest global estimations show that, by 2100, extreme sea level events that have occurred once every century are expected to take place annually under all emission scenarios considered [14]. The combination of sea-level rise and extreme events represents a growing risk to coastal areas around the world. In Europe, one-third of the population resides in a 50 km strip of the coast, where many ecosystems, assets and infrastructures are located [15]. Therefore, even if during the 20th century, socioeconomic factors have been the main cause of increased exposure and vulnerability in coastal areas, climate change is expected to aggravate this situation in the future [16].

These changes in sea level and the frequency and magnitude of extreme events may cause severe economic impacts. With no additional investments in adaptation, global damage due to coastal flooding could reach between 93,000 and 961,000 million euros, and the number of people affected would rise to 1.5–3.65 million by 2100, considering three climatic and socio-economic scenario combinations (RCP 4.5-SSP1, RCP 8.5-SSP3 and RCP 8.5-SSP5) [17]. In Europe, coastal flooding and erosion by 2050 could have a cost of between 6500 and 40,000 million euros per year for RCP4.5 and RCP 8.5, respectively, combined with the SSP5 socio-economic development scenario [15]. The same study estimated for the same scenarios that the number of people affected could vary between 460,000 and 740,000 annually. Nonetheless, the differences between RCPs is small until mid-century, when sea-level rise scenarios start to diverge. This situation could lead to a current underestimation of coastal risk and a delay in the definition and implementation of adaptation measures [18].

Just as for future sea-level rise, economic impacts (and adaptation investment costs) depend on the emission scenario, the time considered and location [19]. The use of mean values or probable ranges in the assessments of the impacts of climate change is very frequent, but due to the existing uncertainty, several authors have insisted on the importance of considering the full distribution of probabilities and especially paying attention to the upper tail of the distribution, i.e., the most negative impacts [20–22]. These types of risk approaches that analyse situations of low probability but great impact are not new in disciplines such as financial or energy economics and allow for more informed risk management as well as more risk-averse approaches.

In recent years, these approaches have proved very useful for the analysis of climate change impacts. For example, financial risk measures, despite their complex modelling, can support decision-making with regards to climate change adaptation as they offer a more comprehensive picture of the risks faced. These risk measures can be used to assess the risk of low probability situations whose impacts may have catastrophic consequences [23], to assess the suitability of an investment plan [24] or to perform stress testing for urban planning, adaptation measures, large investments or infrastructure plans [25].

In this study, we aim at determining the costs of adaptation inaction in 62 Iberian coastal cities in the context of sea-level rise and increased climate risks. We define the cost of inaction as the damage due to climate change in the lack of additional adaptation measures. In order to do so, we compare adaptation investment costs with expected damage due to sea-level rise under three scenarios (RCP8.5, RCP 4.5 and RCP 2.6). These estimations are first obtained annually, and in a second step, we calculate accumulated costs in 2030, 2050 and 2100. These accumulated costs of adaptation inaction are then compared to the costs of adaptation investment under different adaptation strategies. This work contributes to the literature by, first, calculating the full distribution of sea-level rise and, second, combining the percentiles of sea-level rise distributions [9] with deterministic damage curves for a large number of European coastal cities [19]. This allows the full distribution of economic damage (or costs) to be estimated.

The rest of the paper is organised as follows: Section 2 presents a summary of the foreseen impacts of sea-level rise in the Iberian coastal areas. Section 3 describes the methods used; the results are presented in Section 4, and the overall discussion is included in Section 5.

2. The Impacts of and Adaptation to Sea-Level Rise in the Iberian Peninsula

Coastal risks have increased in the Iberian Peninsula during the last decades. The urban development model and the overexploitation of some resources have put enormous pressure on these coastal areas, causing biodiversity loss and environmental degradation, while increasing their exposure and vulnerability to climatic events [26]. In some areas of the Basque Coast, habitat and ecosystem destruction induced by sea-level rise could generate losses of up to 2.3 million euros per hectare [27]. The increase in flood exposure in certain areas of the Spanish Mediterranean coast (Murcia and Alicante) has been directly linked to two urban development peaks, between 1978–1982 and 1997–2007 [28]. In fact, the Spanish Mediterranean coast has high or very high vulnerability and exposure values, compared to other areas of the Mediterranean subject to larger hazards. This situation repeats, however, in other densely populated areas such as the French southwest coast and the north Adriatic coast [29].

Assuming that the trend of rising sea levels continues during the first half of the century, flood-risk could increase by 2040 by 8% in the Atlantic and Cantabrian coasts of Spain and the Alboran Sea, 6% in the Canary Islands and between 2% and 3% in the rest of the Mediterranean coast and the Gulf of Cádiz [30]. In some locations, the frequency and intensity of extreme events are expected to increase in the future. For example, in the city of Bilbao, located on the Cantabrian coast, the intensity, measured as the change in the flood level, could increase from 3.85 m in 2010 to 4 m in 2040, and its frequency will increase from once every 50 years (2010) to once every 15 years in 2040 [30]. In Barcelona, however, changes in intensity are not expected and the increase in frequency is expected to be smaller: the return period could vary from once every 50 to once in 40 years [30,31].

In Portugal, sea-level rise and changes in storminess are expected to cause higher coastal flooding and erosion, among other impacts such as coastal wetland inundation and retreat, and have been identified as one of the most important consequences of climate change [32,33]. The coast north of Lisbon and the Algarve were identified as the areas most at risk [32]. Recent studies have addressed these areas of the Portuguese coast in further detail, identifying the areas of Aveiro [34], south of Porto, and the Algarve as hotspots for coastal inundation and erosion [35,36]. Moreover, it has been estimated that 900 km^2 of the Portuguese coast could be subject to flood risk in 2050, considering 50 year return period extreme events and empirical sea-level rise projections. At the end of the century, the areas at risk of coastal flooding could increase by 27%, where Lisbon, Faro and Aveiro are the districts most at risk [37,38].

With regards to coastal protection and adaptation to climate change, Spain was already among those countries in Europe with a larger expenditure in the period between 1998 and 2015 [39]. Projections to 2040 estimate that the population exposed to permanent flooding on the Cantabrian coast could reach 2–3%. If extreme events are also incorporated, the exposed population could range between 4% and 9%. As for the economic impact, at the end of the century, permanent flood damage in the Bay of Biscay could reach between 1 billion euros (0.1% of regional GDP(2008)) under RCP 4.5 and 8 billion euros (0.6% of regional GDP(2008)) under a high-end sea-level rise scenario. Direct average damage could double if extreme weather events are considered [30].

3. Materials and Methods

3.1. Estimating the Costs of Adaptation Inaction

The methodological approach followed in this study to assess the costs due to sea-level rise if adaptation is not implemented is summarised in Figure 1. The first step is to identify the cities for our assessment. A recent study estimated the economic damage due to coastal flood height for 600 European cities, as well as the adaptation costs, obtained as a function of defence height [19]. This is done in a deterministic way. Of all these cities, we focus on those located in the Iberian Peninsula, our target study zone. Our sample includes 62 main coastal cities in Portugal and Spain, as shown in Figure 2. The second step is estimating future sea-level rise in each city using a stochastic method and considering three scenarios (RCP 2.6, 4.5 and 8.5) as described next in subsection 2.1.1. The third step is calculating, also with a stochastic approach, the annual and accumulated expected damage due to sea-level rise in each of our 62 cities. This is explained in subsection 2.1.2.

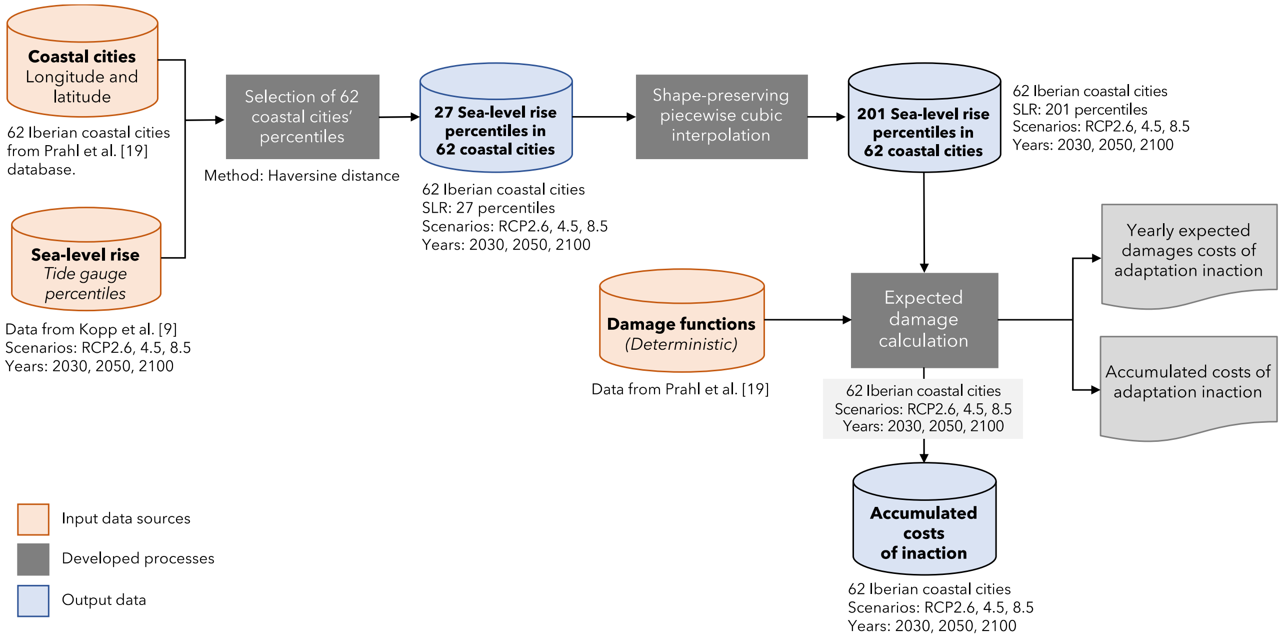
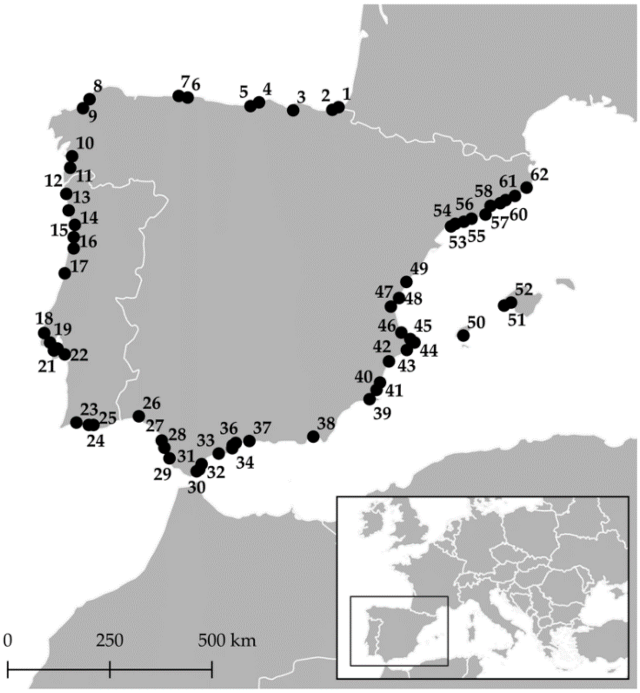


Figure 1. Summary of the methodology followed, including input data and output products.



Id	City	Id	City
1	Hondarribia - Irun	33	Marbella
2	Donostia-San Sebastián	34	Torremolinos
3	Bilbao	35	Malaga (Airport)
4	Santander	36	Málaga
5	Torrelavega	37	Vélez-Málaga, Torre del Mar
6	Gijón	38	Almería
7	Avilés	39	Cartagena
8	Ferrol	40	San Javier
9	La Coruña	41	Torrevieja
10	Pontevedra	42	Alicante
11	Vigo	43	Benidorm, Calp
12	Viana do Castelo	44	Xábia
13	Póvoa de Varzim	45	Denia
14	Porto	46	Gandia
15	Ovar	47	Valencia
16	Aveiro	48	Sagunto
17	Figueira da Foz	49	Castellón de la Plana
18	Ericeira	50	Ibiza
19	Lisbon	51	Santa Ponsa
20	Barreiro	52	Palma de Mallorca
21	Almada	53	Salou
22	Setúbal	54	Tarragona
23	Portimao	55	Port Romá
24	Albufeira	56	Vilanova i la Geltrú
25	Villamoura	57	Castelldefels
26	Huelva	58	Barcelona
27	Sanlúcar de Barrameda	59	Barcelona II
28	El Puerto de Sta María	60	Arenys de Mar
29	Chiclana de la Frontera	61	Blanes
30	Algeciras	62	Sant Feliu de Guixols
31	La Línea de la Concepción		
32	Guadiaro		

Figure 2. Selected 62 Iberian coastal cities in Spain and Portugal. Source: own elaboration.

3.1.1. Modelling Projected Sea-Level Rise in Each City

First, local sea-level rise data for each city is taken from a database that includes the probabilistic distribution of sea-level rise under three emission scenarios (RCP 2.6, 4.5 and 8.5) in 2030, 2050 and 2100, for more than a thousand tide gauges worldwide [9]. With regard to sea-level rise projections, RCP 8.5 represents the highest emission or the business-as-usual scenario where no climate mitigation policies are adopted; RCP 4.5 describes a middle of the road scenario, and RCP 2.6 is the deep-emission reduction scenario, compatible with a 2 °C warming. The database presents a number of sea-level rise percentiles to a large tide gauge dataset worldwide. For every city in our sample, the closest tide gauge is selected using the Haversine distance between the coastal city and the tide gauges [40]. From the dataset, a total of 27 sea-level rise percentiles with values of xx.0th and xx.5th were selected for each city, scenario and selected year, where xx is an integer between zero and 100. Note, however, that the percentiles are irregularly spaced, while regularly spaced percentiles are needed to apply the methodology proposed. For this reason we calculated an additional 174 percentiles using shape-preserving piecewise cubic interpolation. Thus, 201 percentiles of sea-level rise evenly distributed between 0 and 100 were estimated, spaced by 0.5 (see Figure 1).

As the objective is to estimate the expected (average) damage, the average sea-level rise is calculated using these 201 percentiles. The expected sea-level rise for city i at time j is denoted by E(SLRi,j). This average value is greater than the corresponding 50th percentile, which indicates that the tail of the distribution is long, and thus, it is possible that risks are underestimated if median values are used. This again confirms that knowing the full distribution, additionally to estimating average values, may be of great importance for adequate risk management. This process is followed for each city, each year (2030, 2050 and 2100) and the three aforementioned RCPs.

Note that these percentiles are chosen in order to find the best manner to represent the shape of all distributions. An alternative to this approximation is the so-called parametric approach that consists of calibrating a distribution with two or three parameters [40]. However, this method is not recommended in this case as it may cause important calibration errors that lead to differences between the value of the original percentiles and those obtained from the modelled distribution. Consequently, it will negatively impact the calculation of expected values. We thus argue, in this case, in favour of using the percentiles for calibration as explained above.

As an illustration, Figure 3 shows a standard cumulative distribution function for sea-level rise for nine representative Iberian coastal cities in the year 2100 considering the highest emission scenario, RCP 8.5. The ten cities were selected for being those with the largest population based on data from Eurostat (European Commission, Brussels, Belgium).

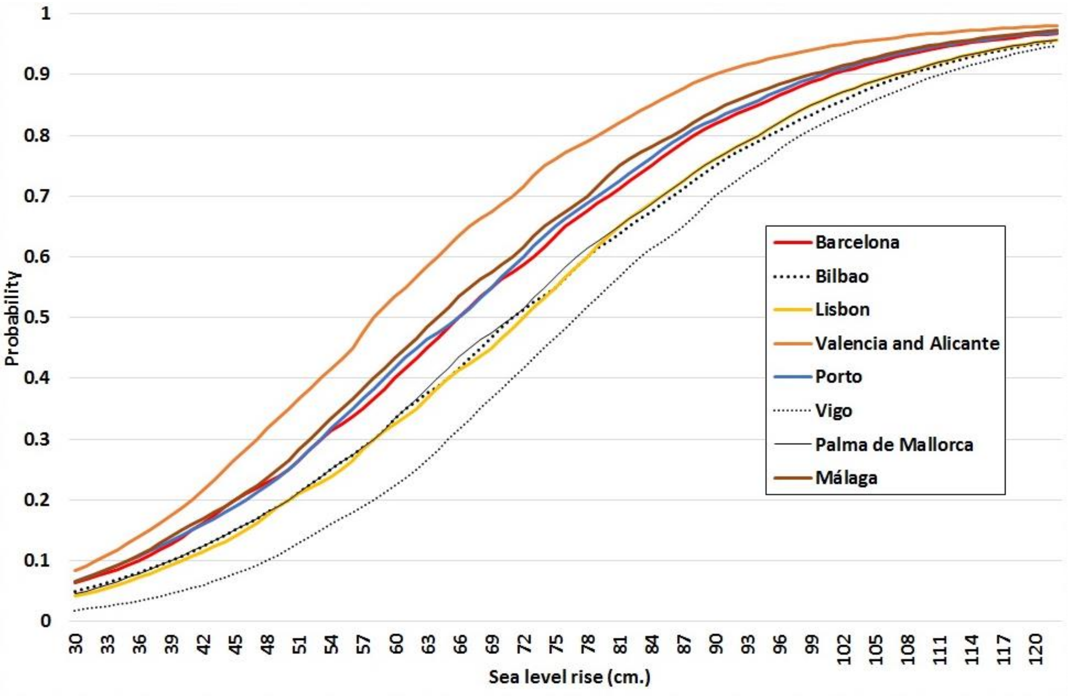


Figure 3. Cumulative distribution function of sea-level rise in 2100 for the nine Iberian cities with largest population under emission scenario RCP 8.5.

Figure 4 shows how cumulative distribution functions may evolve in time, illustrated by the case of Barcelona. One can see that the probabilities of sea-level rise being less than or equal to 50 centimetres in 2100 are 25% under RCP 8.5, 48.25% under RCP 4.5 and 61% in RCP 2.6.

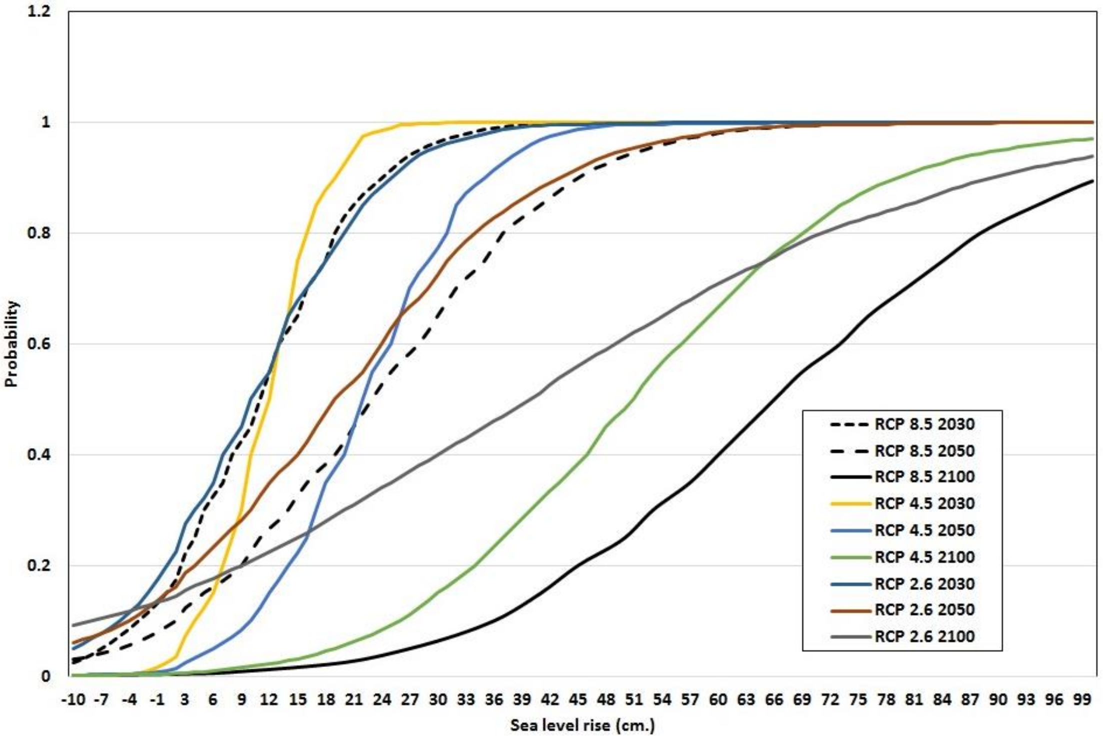


Figure 4. Evolution in time of the cumulative distribution function of sea-level rise in Barcelona under RCP 2.6, 4.5 and 8.5.

3.1.2. Estimation of Economic Damage

A recent study presented the economic damage and adaptation costs as a deterministic function of coastal flood height and height of the defences, respectively, for 600 European coastal cities [19]. The deterministic damage functions used in this work for each of the 62 coastal cities in our sample are taken from the aforementioned study [19]. These functions provide an estimation of damage as a function of sea-level height. The inundation model used to obtain the damage functions used a digital terrain model of 25 m resolution, and hydraulically connected areas were calculated for different coastal flood levels between 0 and 12 metres at intervals of half a metre. The damage cost functions [19] were built based on the economic value of the assets exposed to coastal flooding. This exposure was measured considering the economic value of land use, which in turn is based on country level data from a previous study [41], and then adjusting the monetary estimates to 2016 prices by using inflation rates and consumer price index (see [19](p. 5) for further details).

The cost curves [19] are not linear, that is, at higher levels of sea-level rise (SLR), we might obtain, in some cases, higher than proportional costs (Figure 5). Accordingly, the damage distribution is not a linear transformation of the sea-level rise distribution. We denote using E(Di,j) the expected annual damage value for the city i at the time j. Using the sea-level rise percentiles, we calculate 201 damage values for each city at year j. As these values are equally likely, the expected value is calculated as their average value.

Figure 5 illustrates the annual damage depending on local sea-level rise in nine cities of our sample as taken from the damage function database [19]. Note that these deterministic functions are non-linear and not time-dependent, as damage depend only on flood depth. The time component will be incorporated when combined with the sea-level rise scenarios, which vary with time.

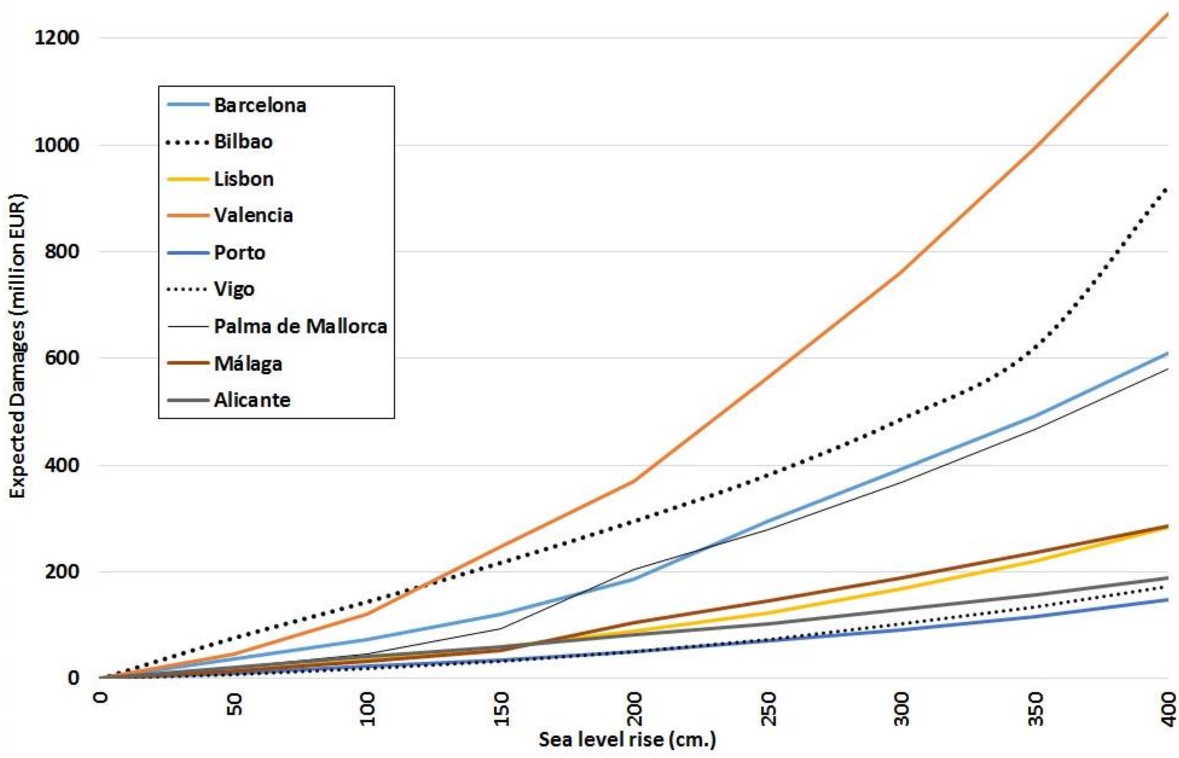


Figure 5. Deterministic damage curves for nine cities based on data by [27].

We define the annual costs of adaptation inaction as the expected damage under three sea-level rise scenarios, which we estimate for the years 2030, 2050 and 2100. Next, we estimate the expected costs for the rest of the years between 2020 and 2100 using shape-preserving piecewise cubic interpolation. Last, we accumulate the calculated damage from 2020 onwards to obtain the accumulated cost of inaction in 2030, 2050 and 2100 [42].

3.2. Measuring the Investment Costs of Adaptation

Adaptation costs for each city were obtained from the study that developed the damage function database [19], which includes the protection needs to be calculated for each city. Adaptation costs are defined based on a theoretical urban protection strategy which consists of a hypothetical defence (adaptation infrastructures, such as dikes or seawalls) that responds to the protection needs in each city. A country-specific dike-construction cost range is used as a proxy for the investment needed for such defences [19]. We acknowledge that this is a rather limited analysis of adaptation options as cities may identify a wide portfolio of both soft and hard adaptation options. However, this is a limitation of the available data but can well illustrate the use of the method proposed in this paper.

A range of adaptation investment costs needed (minimum and maximum cost estimates) are provided in [19]. The average value of this range is also calculated. Based on the available data and for illustrative purposes, two different strategies are assumed to assess adaptation investment needs:

- The first strategy aims at reducing climate change risk, for example by building a defence that can only be overcome in a certain percentage of the cases by a given year under one of the RCP scenarios. In this case we have defined 5% and 0.5% of the cases by the year 2100 under RCP 8.5. In other words, this option requires building an infrastructure to protect from sea-level rise percentiles 95th and 99.5th. We have named this strategy as "risk tailoring".
- The second strategy consists of building defences of standard height (e.g., 2 m or 3 m) and comparing the protection level and costs with the "risk tailoring" strategy.

The costs of adaptation investment for each city and scenario are then compared to the accumulated costs of inaction estimated previously in subsection 3.1.2, to determine in which cases the benefits of adaptation (in terms of avoided damage or costs) exceed its costs. Note that for simplicity it is assumed defences protect the city of coastal flood heights smaller or equal to their height, but we acknowledge that waves could act on adjacent areas or circumvent the defences in some cases.

A summary of the methodological steps followed in this section is described in Figure 6 below.

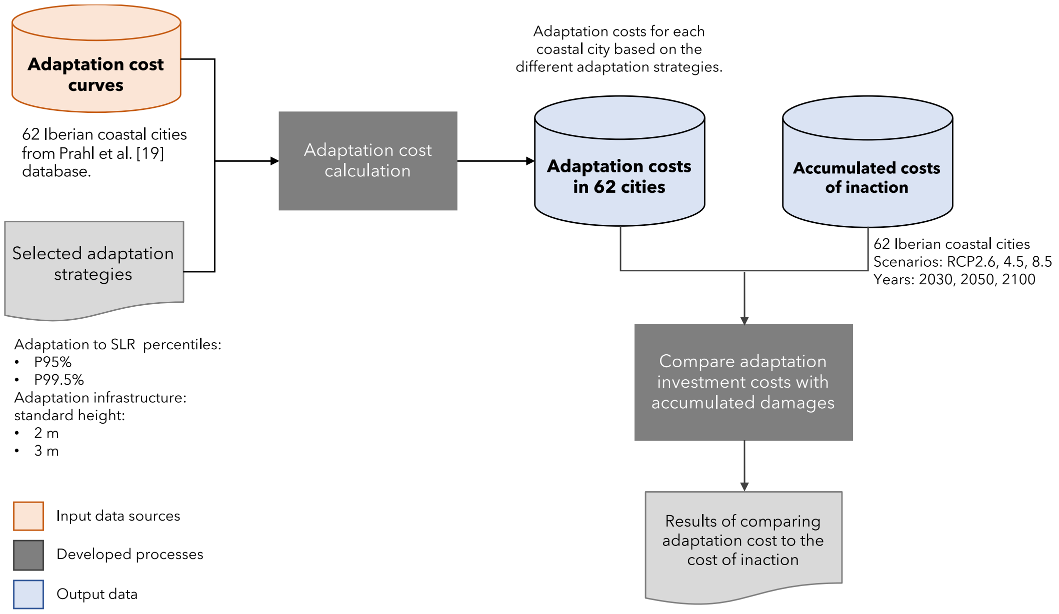


Figure 6. Summary of the methodological approach followed to estimate adaptation investment needs in each city under three sea-level rise scenarios. Investment costs are then compared to the accumulated costs of inaction to assess adaptation benefits.

Discount rates can also be incorporated into the modelling. On this occasion, however, we have decided not to include them for two main reasons. First, setting the appropriate discount factor may become a rather difficult task, especially when such long terms are considered, as fat tails may exist and potential damage (even with very low probability) can be so high [43,44]. There is plenty of literature discussing this issue [45–47] and no clear consensus exists on how to address this (see [48] for a more detailed discussion). Small variations in how the discount rates are applied may have substantial effects on the economic damage and the investment results. Second, in this study we are interested in analysing the decision of inaction and investing in adaptation without the interference of other factors, so we chose to avoid their effect on the calculations. The higher the discount rate the lower the value of the benefit (or costs) will be in the future, but there are other factors that may also substantially affect the results that have not been considered, such as the growth rate in the value of the properties at risk. In fact, one could expect that damage will increase as the value of the properties increase, and therefore, it is the difference between the growth rate and the discount rate that really matters. The impact of discount rates on actual values of investments (or benefits) occurring over long periods of time is always very significant. In any case, with net discunt rates of 1% and 2%, investing in adaptation would still be a good decision in our study (see Table S10 in the Supplementary Material).

4. Results

4.1. Local Sea-Level Rise and the Costs of Inaction

We calculate three sea-level rise percentiles for each city and the accumulated damage in 2030, 2050 and 2100. Table 1 shows the results in 2100 for the 10 coastal cities with the largest population, under RCP 8.5. The results for all cities and scenarios are provided in the supplementary information. We present the RCP 8.5 in Table 1 because of the greater influence of this RCP on the sea-level rise risk [49].

Table 1. Sea-level rise percentiles and accumulated damage costs in 2100 for those cities with the largest number of inhabitants under RCP 8.5.

City	Year	P50 (cm)	P95 (cm)	P99.5 (cm)	Damage (million EUR)
Barcelona	2030	11	28	39	75.8
Lisbon	2030	13	21	26	34.5
Valencia	2030	10	18	24	79.4
Porto	2030	12	20	24	22.1
Bilbao	2030	14	23	29	177.0
Málaga	2030	11	20	25	28.3
Palma de Mallorca	2030	12	30	41	48.0
Alicante	2030	10	18	24	32.3
Vigo	2030	15	23	27	21.3
Gijón	2030	14	23	30	35.4
Barcelona	2050	23	52	71	343.1
Lisbon	2050	26	42	53	150.0
Valencia	2050	21	36	47	365.8
Porto	2050	24	39	51	98.8
Bilbao	2050	27	45	57	806.4
Málaga	2050	23	38	50	132.8
Palma de Mallorca	2050	25	52	70	201.1
Alicante	2050	21	36	47	159.2
Vigo	2050	30	45	56	89.4
Gijón	2050	27	45	58	155.8
Barcelona	2100	66	113	171	2059.5
Lisbon	2100	72	119	181	946.3
Valencia	2100	58	102	161	2504.3
Porto	2100	66	112	174	601.7
Bilbao	2100	71	120	180	4592.3
Málaga	2100	64	111	168	831.9
Palma de Mallorca	2100	71	119	176	1288.4
Alicante	2100	58	102	161	991.2
Vigo	2100	77	123	184	550.9
Gijón	2100	72	122	182	944.9

Note that Bilbao, Valencia and Barcelona are the coastal cities with the largest expected accumulated damage in the case of inaction. Both the sea-level rise percentiles and the damage grow rapidly over time, particularly in the second part of the century, in line with studies for other cities worldwide [49]. An illustration of accumulated expected damage for four cities in the top ranking of damage is shown in Figure 7.

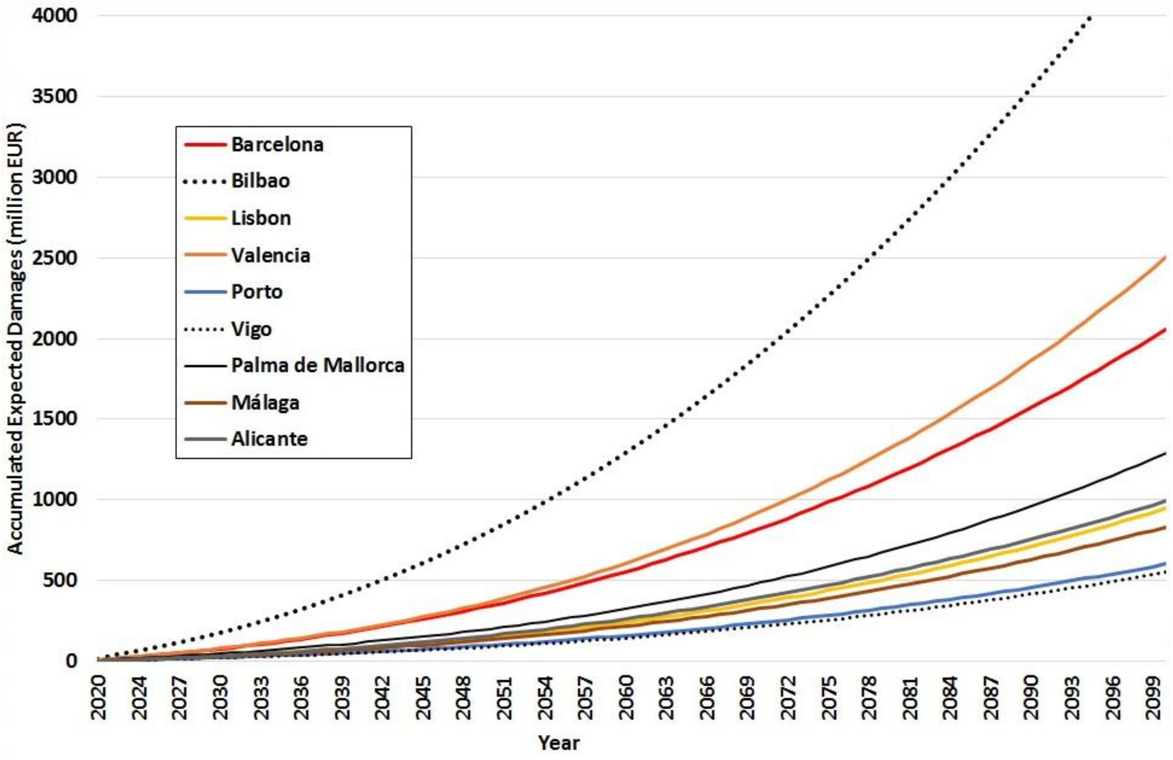


Figure 7. Accumulated expected damage in nine Iberian coastal cities with largest population under RCP 8.5.

To show that averages and median values may differ substantially we present the differences in damage for some cities and years in Table 2. Average damage have been calculated using the full distribution of sea-level rise probabilities, and the damage curves are shown in Figure 5. Damage in Table 2 correspond to the selected years, and they are not accumulated data. As expected, by 2100, differences in mean and average values are very important. This is mainly driven by two effects: 1) the shape of the sea-level rise distribution and 2) the shape of the damage curves. The main and very important conclusion here is that, in the long term, the use and estimation of median values (50th percentile) provide insufficient information and can lead to underestimating coastal risks and consequently to under protection. The methodology proposed in this paper should help overcome this limitation by offering complete information on the risk faced.

In more detail, it can be noted that the shape distribution effect is caused by skewness. Positive skewness is obtained when the distribution has an asymmetric tail extending toward more positive values. In these right-skewed distributions, the mean is greater than the median, and the former is affected by extreme sea-level rise values. The skewness found for Barcelona, Lisbon, Valencia, Porto and Bilbao has also been included in Table 2. Note that skewness increases with time, causing a growing impact of extreme values in the mean values of sea-level rise.

Table 2. Differences in the six largest cities between expected annual damage and damage using the 50th percentile under RCP 8.5. The skewness of the sea-level rise distribution is also presented for each city.

City	Values	2030	2050	2100
Barcelona	Expected damage (A)	8.76	18.00	52.93
	Damage using 50th percentile (B)	8.25	17.24	49.00
	Difference in damage (A−B)	0.52	0.75	3.93
	Skewness	*−0.03*	*0.00*	*3.67*
Lisbon	Expected damage (A)	3.84	7.81	25.36
	Damage using 50th percentile (B)	3.79	7.58	23.23
	Difference in damage (A−B)	0.05	0.23	2.13
	Skewness	*−0.09*	*0.65*	*3.88*
Valencia	Expected damage (A)	9.05	19.94	70.54
	Damage using 50th percentile (B)	9.33	19.58	58.53
	Difference in damage (A−B)	−0.28	0.36	12.01
	Skewness	*−0.06*	*0.62*	*4.41*
Porto	Expected damage (A)	2.53	5.16	15.55
	Damage using 50th percentile (B)	2.54	5.09	14.55
	Difference in damage (A−B)	−0.01	0.07	1.00
	Skewness	*0.01*	*0.73*	*4.05*
Bilbao	Expected damage (A)	20.78	41.82	110.93
	Damage using 50th percentile (B)	21.41	41.28	105.04
	Difference in damage (A−B)	−0.63	0.54	5.89
	Skewness	*−0.18*	*0.38*	*3.47*

Table 3 shows the accumulated damage for a total of 62 Iberian cities and per country for the three scenarios. Damage for RCP 8.5 are very significant, but even in the most favourable scenario (RCP 2.6) important accumulated damage are expected due to sea-level rise.

Table 3. Accumulated damage costs (million EUR) for 64 Iberian coastal cities, aggregated by country.

Country	Scenario	2030	2050	2100
Total Iberian	RCP 8.5	1764	8100	50,476
Spain		1574	7261	45,342
Portugal		189	839	5133
Total Iberian	RCP 4.5	1718	7588	41,261
Spain		1536	6796	37,044
Portugal		183	792	4216
Total Iberian	RCP 2.6	1732	7474	36,895
Spain		1545	6684	33,089
Portugal		188	789	3806

4.2. Adaptation Strategies and Investment Costs

4.2.1. Adapting to the Risk of Sea-Level Rise or “Risk Tailoring”

In this case, we focus on the “risk tailoring” strategy of building protective defences of a height that would only be surpassed in 5% and 0.5% of the cases (under the scenario RCP 8.5 in 2100). These are the heights for the 95th and 99.5th percentiles. Results are shown in Table 4. One can see that inaction is costlier than implementing adaptation in all cases, as expected damage are much greater than the adaptation costs. If defences are to be exceeded only in 5% of the cases, this means that protection height in the top cities with the largest damage would need to be higher than 1 metre, and between 1.61 m and 1.80 m to avoid damage in 99.5% of the cases. Table 4 shows an interval (minimum and maximum values) of infrastructure construction costs taken from [19] for each city, depending on its characteristics and defence height. The average is the mean of these two values.

Table 4. Expected accumulated damage and adaptation strategies linked to sea-level rise percentiles (in million EUR) in 2100 for the 10 Iberian coastal cities with the largest populations under the RCP 8.5 scenario.

City	Accumulated damage	Sea-level rise (cm)		Adaptation costs					
				Minimum		Maximum		Average	
		P95	P99.5	P95	P99.5	P95	P99.5	P95	P99.5
Barcelona	2060	113	171	318	595	459	859	388	727
Lisbon	946	119	181	223	425	323	614	273	520
Valencia	2504	102	161	326	645	472	932	399	788
Porto	602	112	174	87	164	126	236	106	200
Bilbao	4592	120	180	424	702	613	1,015	518	858
Málaga	832	111	168	127	221	184	319	155	270
Palma de Mallorca	1288	119	176	240	531	347	767	293	649
Alicante	991	102	161	164	289	237	417	200	353
Vigo	551	123	184	154	283	223	409	189	346
Gijón	945	122	182	211	348	305	503	258	425

4.2.2. Adapting by Fixing a Certain Height

If defence heights were to be decided exogenously, for instance, at 2 m and 3 m by 2100, the average adaptation costs for the top 10 cities of the ranking would range between 282 and 1225 million euros for a protection infrastructure of 2 m (Table 5). In the case of a 3 m defence, average costs could reach 400–2400 million euros, but even in this case, the investment can be well justified to avoid the accumulated damage. Note that if standard height defences of 2 meters or 3 meters are to be implemented, the probability of damage in the year 2100 is rather small.

Table 5. Expected accumulated damage and adaptation strategies with standard height defences in 2100 (costs shown in million euros) for the 10 largest Iberian coastal cities, under RCP 8.5.

City	Accumulated damage	Adaptation costs					
		Minimum		Maximum		Average	
		2 m	3 m	2 m	3 m	2 m	3 m
Barcelona	2060	758	1434	1096	2072	927	1753
Lisbon	946	491	947	710	1369	601	1158
Valencia	2504	873	1638	1262	2368	1067	2003
Porto	602	201	404	291	584	246	494
Bilbao	4592	799	1343	1156	1942	978	1642
Málaga	832	279	496	404	717	341	607
Palma de Mallorca	1288	712	1342	1029	1940	870	1641
Alicante	991	378	644	547	931	463	787
Vigo	551	319	614	461	888	390	751
Gijón	945	391	660	565	955	478	808

5. Discussion

5.1. The Economic Damage of Sea-Level Rise

In this paper, we propose a model for the calculation of accumulated expected damage under uncertainty. The model uses an expanded version of the projected sea-level rise percentiles [9] and a deterministic function that depends on flood height (in our case, sea-level height) [19]. The combination of both provides a group of stochastic damage distributions that allow us to calculate annual expected damage and, consequently, also the expected accumulated damage. Accumulated average damage in all 62 cities of our sample exceed 1700 million euros in 2030, and the difference between the results under RCP 4.5 and RCP 8.5 is 45 million euros. However, by the end of the century, accumulated damage reach 41,200 million euros under RCP 4.5 and more than 50,400 million euros in the highest emission scenarios (RCP 8.5). Accumulated damage increase by more than 20 times by 2100 and the difference between RCP 4.5 and RCP 8.5 could reach 10 billion euros (Table S8 and S9).

Furthermore, our results show that limiting the assessments to median values (50th percentile) significantly underestimates the potential damage. While differences between median and average values might be small by 2030, they increase considerably by one order of magnitude by the end of the century. For example, in Barcelona the difference between median and average damage is 0.5 million euros in 2030, but increases to almost 4 million euros in 2100 (Table 2). This difference occurs because the shape of the sea-level rise distribution is positively skewed, i.e., the distribution is not symmetrical but has a heavier upper tail The shape of the distribution of the damage is also another cause of important underestimations in the medium term when calculating expected damage. These findings are consistent with previous studies that warned about the larger potential risk of climate-induced impacts.

Damage costs do not account for coastal erosion or ecosystem loss, impacts that are both expected to be relevant in the Iberian Peninsula. Additionally to their intrinsic value, ecosystems provide a number of services to people that can be monetised [50]. The value of services such as storm protection or erosion control provided by salt marshes and mangroves worldwide is estimated to be 194,000 $/ha/year [51], which has not been accounted for in this study. Of course, one should acknowledge that other important factors such as shoreline evolution have to be integrated into a cost-benefit analysis to account for the complexities of coastal defence solutions, as argued earlier by other authors [52]. In this case, we have simplified this part of the analysis to focus on the impact of uncertainty on the economic estimates but by no means do we neglect the need to integrate those factors.

5.2. Comparing the Costs of Inaction to Protection Investment Costs

Two different adaptation options have been explored in this study: the first is based on tailoring the level of risk cities might decide to protect themselves from. This is illustrated through the assumption that coastal or city managers decide to protect each city for 95% or 99.5% of the cases under RCP 8.5 by 2100. In the first case, with protection strategies to face 95% of the cases, investment needs in the largest coastal cities by population would range between 87 (Porto) and 1015 (Bilbao) million euros. Investment costs almost double if a higher protection threshold (99.5%) is considered, and these would vary between 164 (Porto) and 1015 (Bilbao) million euros. The second adaptation option explored the investment costs needed for certain protection heights (2 and 3 metres). In the case of 3 metre protection infrastructures, construction costs range between 404 and 2368 million euros.

An important finding of this analysis is that adaptation costs in the long term are much smaller than the increasingly expensive costs of inaction, and thus, investing in adaptation is a good decision when comparing costs and benefits of the actions, a finding in line with previous research carried out in this area of study [53].

Of course, one should acknowledge that many other adaptation options that have not been considered in this paper may exist, and that many other criteria other than economic costs and benefits may be worth being taken into account when making such decisions. Another clear finding is that adaptation investment needs will be smaller under more favourable scenarios (RCP 2.6 and RCP 4.5). However, even under the most optimistic scenario (RCP 2.6), expected damage will be very important in the second half of the century. In other words, despite strong emission reduction efforts being really effective, adaptation will be inevitable. This is to highlight the importance of the need to implement both mitigation and adaptation policies.

Our findings show that not adapting to climate change is not, by any means, a good strategy in the medium and long term. Note that, even if many types of adaptation options should be considered when protecting coasts from climate risks, the building of defence infrastructures that require strong investments would be justified based on the accumulated damage by 2100, which are much greater than the investment costs of protection. Moreover, the adaptation strategies considered in this paper are shown to be very cost-effective in every city studied and reduce considerably the probability of experiencing high economic damage by the end of the century.

5.3. Policy Implications

In this paper we propose a method to avoid the underestimation of climate risk and estimate what the size of it may be for the case of 62 cities in the Iberian peninsula. We have used two infrastructure-based adaptation options for illustrative purposes. This has been done because the data needed for the analysis is available in these cases, and not because we argue that these solutions should be the ones implemented. Results show that the underestimation of damage can be very important if we consider median values instead of the average (expected) damage. Therefore, we argue that strong efforts should be made to understand the full probability distributions of sea-level rise and the consequent economic damage, for each city, emission scenario and year. Not accounting for all these may lead to investment decisions (and even maladaptation) that underestimate future risks and cannot respond to them.

The method can also be applied to adequately assess the cost effectiveness of other adaptation options when data becomes available. The purpose of the paper has been to propose a methodology and illustrate the case for sea-level rise and hard adaptation measures for which good data was available. Other pieces of research should help us to better consider alternative adaptation options or even other impacts related to the adaptation options considered. Nonetheless, the main message of this paper remains, not accounting for the full distribution of sea level rise as well as damage costs is a clear and very significant underestimation of climate risks that may lead to inadequate policy decisions.

Supplementary Materials: A dataset with additional results for all 62 cities, scenarios and years is available online at www.mdpi.com/2073-4441/12/4/1220/s1.

Author Contributions: conceptualization, L.M.A.; formal analysis, L.M.A. and E.S.M.; methodology, L.M.A.; writing—original draft, L.M.A., E.S.M. and I.G. All authors have read and agreed to the published version of the manuscript.

Funding: This research is supported by the Basque Government through the BERC 2018-2021 program and by the Spanish Ministry of Economy and Competitiveness MINECO through BC3 María de Maeztu excellence accreditation MDM-2017-0714. Additionally, Luis M. Abadie is grateful for financial support from The Spanish Ministry of Science and Innovation (ECO2015-68023). E. Sainz de Murieta acknowledges funding from the Basque Government (Postdoctoral Fellowship grant no. POS_2018_2_0027). Ibon Galarraga received financial support from the European Union's Horizon 2020 research and innovation programme under grant agreement No 776479 for the project CO-designing the Assessment of Climate CHange costs.

Conflicts of Interest: The authors declare no conflicts of interest.

References

1. *IPCC Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Stocker, T.F., Qin, D., Plattner, G.K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P.M., Eds.; Cambridge University Press: Cambridge, UK, 2013.
2. Church, J.A.; White, N.J.; Aarup, T.; Wilson, W.S.; Woodworth, P.L.; Domingues, C.M.; Hunter, J.R.; Lambeck, K. Understanding global sea levels: Past, present and future. *Sustain. Sci.* **2008**, *3*, 9–22, doi:10.1007/s11625-008-0042-4.
3. Church, J.A.; White, N.J. A 20th century acceleration in global sea-level rise. *Geophys. Res. Lett.* **2006**, *33*, doi:10.1029/2005GL024826.
4. Hay, C.C.; Morrow, E.; Kopp, R.E.; Mitrovica, J.X. Probabilistic reanalysis of twentieth-century sea-level rise. *Nature* **2015**, *517*, 481–484, doi:10.1038/nature14093.
5. Yi, S.; Sun, W.; Heki, K.; Qian, A. An increase in the rate of global mean sea level rise since 2010. *Geophys. Res. Lett.* **2015**, *42*, 3998–4006, doi:10.1002/2015GL063902.
6. Hardy, R.D.; Nuse, B.L. Global sea-level rise: Weighing country responsibility and risk. *Clim. Change* **2016**, *137*, 333–345, doi:10.1007/s10584-016-1703-4.

7. Hamlington, B.D.; Fasullo, J.T.; Nerem, R.S.; Kim, K.-Y.; Landerer, F.W. Uncovering the Pattern of Forced Sea Level Rise in the Satellite Altimeter Record. *Geophys. Res. Lett.* **2019**, *46*, 4844–4853, doi:10.1029/2018GL081386.
8. Slangen, A.B.A.; Carson, M.; Katsman, C.A.; Wal, R.S.W. van de; Köhl, A.; Vermeersen, L.L.A.; Stammer, D. Projecting twenty-first century regional sea-level changes. *Clim. Change* **2014**, *124*, 317–332, doi:10.1007/s10584-014-1080-9.
9. Kopp, R.E.; Horton, R.M.; Little, C.M.; Mitrovica, J.X.; Oppenheimer, M.; Rasmussen, D.J.; Strauss, B.H.; Tebaldi, C. Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earths Future* **2014**, *2*, 383–406, doi:10.1002/2014EF000239.
10. Grinsted, A.; Jevrejeva, S.; Riva, R.; Dahl-Jensen, D. Sea level rise projections for northern Europe under RCP8.5. *Clim. Res.* **2015**, *64*, 15–23, doi:10.3354/cr01309.
11. Jackson, L.P.; Jevrejeva, S. A probabilistic approach to 21st century regional sea-level projections using RCP and High-end scenarios. *Glob. Planet. Change* **2016**, *146*, 179–189, doi:10.1016/j.gloplacha.2016.10.006.
12. Nauels, A.; Gütschow, J.; Mengel, M.; Meinshausen, M.; Clark, P.U.; Schleussner, C.-F. Attributing long-term sea-level rise to Paris Agreement emission pledges. *Proc. Natl. Acad. Sci. USA* **2019**, doi:10.1073/pnas.1907461116.
13. Bamber, J.L.; Oppenheimer, M.; Kopp, R.E.; Aspinall, W.P.; Cooke, R.M. Ice sheet contributions to future sea-level rise from structured expert judgment. *Proc. Natl. Acad. Sci. USA* **2019**, *116*, 11195–11200, doi:10.1073/pnas.1817205116.
14. IPCC. *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate*; Pörtner, H.O., Roberts, D.C., Masson-Delmotte, V., Zhai, P., Tignor, M., Mintenbeck, K., Nicolai, M., Okem, A., Petzold, J., Rama, B.; et al, Eds.; IPCC: Geneva, Switzerland, 2019; In press.
15. Ciscar, J.C.; Ibarreta, D.; Soria, A.; Dosio, A.; Toreti, A.; Ceglar, A.; Fumagalli, D.; Dentener, F.; Lecerf, R.; Zucchini, A.; et al. *Climate Impacts in Europe: Final Report of the JRC PESETA III Project*; European Commission: Luxenbourg, 2018; p. 95.
16. Wong, P.P.; Losada, I.J.; Gattuso, J.P.; Hinkel, J.; Khattabi, A.; McInnes, K.L.; Saito, Y.; Sallenger, A. Coastal systems and low-lying areas. In *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*; Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C.; et al, Eds.; Cambridge University Press: Cambridge, UK, 2014; pp. 361–409.
17. Vousdoukas, M.I.; Mentaschi, L.; Voukouvalas, E.; Bianchi, A.; Dottori, F.; Feyen, L. Climatic and socioeconomic controls of future coastal flood risk in Europe. *Nat. Clim. Change* **2018**, *8*, 776–780, doi:10.1038/s41558-018-0260-4.
18. Sánchez-Arcilla, A.; García-León, M.; Gracia, V.; Devoy, R.; Stanica, A.; Gault, J. Managing coastal environments under climate change: Pathways to adaptation. *Sci. Total Environ.* **2016**, *572*, 1336–1352, doi:10.1016/j.scitotenv.2016.01.124.
19. Prahl, B.F.; Boettle, M.; Costa, L.; Kropp, J.P.; Rybski, D. Damage and protection cost curves for coastal floods within the 600 largest European cities. *Sci. Data* **2018**, *5*, 180034, doi:10.1038/sdata.2018.34.
20. Weitzman, M.L. A precautionary tale of uncertain tail fattening. *Environ. Resour. Econ.* **2013**, *55*, 159–173, doi:10.1007/s10640-013-9646-y.
21. Hinkel, J.; Jaeger, C.; Nicholls, R.J.; Lowe, J.; Renn, O.; Peijun, S. Sea-level rise scenarios and coastal risk management. *Nat. Clim. Change* **2015**, *5*, 188–190, doi:10.1038/nclimate2505.
22. Thiéblemont, R.; Le Cozannet, G.; Toimil, A.; Meyssignac, B.; Losada, I.J. Likely and High-End Impacts of Regional Sea-Level Rise on the Shoreline Change of European Sandy Coasts Under a High Greenhouse Gas Emissions Scenario. *Water* **2019**, *11*, 2607, doi:10.3390/w11122607.
23. Abadie, L.M.; Galarraga, I.; Sainz de Murieta, E. Understanding risks in the light of uncertainty: Low-probability, high-impact coastal events in cities. *Environ. Res. Lett.* **2017**, 12, doi:10.1088/1748-9326/aa5254.
24. Abadie, L.M.; Sainz de Murieta, E.; Galarraga, I. Investing in adaptation: Flood risk and real option application to Bilbao. *Environ. Model. Softw.* **2017**, *95*, 76–89, doi:10.1016/j.envsoft.2017.03.038.
25. Galarraga, I.; Sainz de Murieta, E.; Markandya, A.; Abadie, L.M. Addendum to Understanding risks in the light of uncertainty: Low-probability, high-impact coastal events in cities. *Environ. Res. Lett*. **2018**, *13*, 029401, doi:10.1088/1748-9326/aaa513.

26. Losada, I.J.; Toimil, A.; Muñoz, A.; Garcia-Fletcher, A.P.; Diaz-Simal, P. A planning strategy for the adaptation of coastal areas to climate change: The Spanish case. *Ocean. Coast. Manag.* **2019**, 104983, doi:10.1016/j.ocecoaman.2019.104983.
27. Galarraga, I.; Osés, N.; Markandya, A.; Chiabai, A.; Khatun, K. Aportaciones desde la economía de la adaptación a la toma de decisiones sobre Cambio Climático: Un ejemplo para la Comunidad Autónoma del País Vasco. *Econ. Agrar. Recur. Nat.* **2011**, *11*, 113–142.
28. Pérez-Morales, A.; Gil-Guirado, S.; Olcina-Cantos, J. Housing bubbles and the increase of flood exposure. Failures in flood risk management on the Spanish south-eastern coast (1975–2013): Housing bubbles and increase of flood risk in Spain. *J. Flood Risk Manag.* **2015**, 11, S302–S313, doi:10.1111/jfr3.12207.
29. Satta, A.; Puddu, M.; Venturini, S.; Giupponi, C. Assessment of coastal risks to climate change related impacts at the regional scale: The case of the Mediterranean region. *Int. J. Disaster Risk Reduct.* **2017**, *24*, 284–296, doi:10.1016/j.ijdrr.2017.06.018.
30. Losada, I.J.; Izaguirre, C.; Díaz, P. *Cambio Climático en la Costa Española*; Oficina Española de Cambio Climático, Ministerio de Agricultura, Alimentación y Medio Ambiente: Madrid, Spain, 2014; p. 133.
31. Mendoza, E.T.; Jimenez, J.A.; Mateo, J. A coastal storms intensity scale for the Catalan sea (NW Mediterranean). *Nat. Hazards Earth Syst. Sci.* **2011**, *11*, 2453–2462, doi:10.5194/nhess-11-2453-2011.
32. Freitas, M.C.; Andrade, C.; Cachado, C.; Cardoso, A.C.; Monteiro, J.H.; Brito, P.; Rebelo, L. Coastal land-loss associated with sea-level rise assessed by aerial Videotape-Assisted Vulnerability Analysis—The case of mainland Portugal. *J. Coast. Res.* **2006**, 1310–1315.
33. Gornitz, V. Global coastal hazards from future sea level rise. *Glob. Planet. Change* **1991**, *3*, 379–398, doi:10.1016/0921-8181(91)90118-G.
34. Pereira, C.; Coelho, C. Mapping erosion risk under different scenarios of climate change for Aveiro coast, Portugal. *Nat. Hazards* **2013**, *69*, 1033–1050, doi:10.1007/s11069-013-0748-1.
35. Ferreira, O.; Viavattene, C.; Jiménez, J.; Bole, A.; Plomaritis, T.; Costas, S.; Smets, S. CRAF Phase 1, a framework to identify coastal hotspots to storm impacts. *E3S Web Conf.* **2016**, *7*, 11008, doi:10.1051/e3sconf/20160711008.
36. Viavattene, C.; Jiménez, J.A.; Ferreira, O.; Priest, S.; Owen, D.; McCall, R. Selecting coastal hotspots to storm impacts at the regional scale: A Coastal Risk Assessment Framework. *Coast. Eng.* **2018**, *134*, 33–47, doi:10.1016/j.coastaleng.2017.09.002.
37. Rocha, C.; Antunes, C.; Catita, C. Coastal Vulnerability Assessment Due to Sea Level Rise: The Case Study of the Atlantic Coast of Mainland Portugal. *Water* **2020**, *12*, 360, doi:10.3390/w12020360.
38. Antunes, C. Assessment of Sea Level Rise at West Coast of Portugal Mainland and Its Projection for the 21st Century. *J. Mar. Sci. Eng.* **2019**, *7*, 61, doi:10.3390/jmse7030061.
39. Semeoshenkova, V.; Newton, A. Overview of erosion and beach quality issues in three Southern European countries: Portugal, Spain and Italy. *Ocean. Coast. Manag.* **2015**, *118*, 12–21, doi:10.1016/j.ocecoaman.2015.08.013.
40. Abadie, L.M.; Galarraga, I.; Markandya, A.; Sainz de Murieta, E. Risk measures and the distribution of damage curves for 600 European coastal cities. *Environ. Res. Lett.* **2019**, *14*, 064021, doi:10.1088/1748-9326/ab185c.
41. Huizinga, J.; De Moel, H.; Szewczyk, W. *Global Flood Depth-Damage Functions. Methodology and the Database with Guidelines*; European Commission: Luxembourg, 2017; p. 114.
42. Abadie, L.M.; Chamorro, J.M. Income risk of EU coal-fired power plants after Kyoto. *Energy Policy* **2009**, *37*, 5304–5316, doi:10.1016/j.enpol.2009.07.053.
43. Weitzman, M.L. On modeling and interpreting the economics of catastrophic climate change. *Rev. Econ. Stat.* **2009**, *91*, 1–19, doi:10.1162/rest.91.1.1.
44. Stern, N. *The Economics of Climate Change: The Stern Review*; Cambridge University Press: Cambridge, UK, 2007.
45. Gollier, C. *Pricing the Planet's Future: The Economics of Discounting in an Uncertain World*; Princeton University Press: Princeton, NJ, USA, 2012.
46. Groom, B. Discounting. In *Routledge Handbook of the Economics of Climate Change Adaptation*; Markandya, A., Galarraga, I., Sainz de Murieta, E., Eds.; Routledge International Handbooks; Routledge: Oxon, UK; New York, NY, USA, 2014; pp. 138–168. ISBN:978-0-415-63311-6.
47. Drupp, M.A.; Freeman, M.C.; Groom, B.; Nesje, F. Discounting Disentangled. *Am. Econ. J. Econ. Policy* **2018**, *10*, 109–134, doi:10.1257/pol.20160240.

48. Markanday, A.; Galarraga, I.; Chiabai, A.; Sainz de Murieta, E.; Lliso, B.; Markandya, A. Determining discount rates for the evaluation of natural assets in land-use planning: An application of the Equivalency Principle. *J. Clean. Prod.* **2019**, *230*, 672–684, doi:10.1016/j.jclepro.2019.05.107.
49. Abadie, L.M. Sea level damage risk with probabilistic weighting of IPCC scenarios: An application to major coastal cities. *J. Clean. Prod.* **2018**, *175*, 582–598, doi:10.1016/j.jclepro.2017.11.069.
50. TEEB. *The Economics of Ecosystems and Biodiversity: Ecological and Economic Foundations*; Kumar, P., Ed.; Earthscan: London, UK, 2010; ISBN:978-1-84971-212-5.
51. Costanza, R.; de Groot, R.; Sutton, P.; van der Ploeg, S.; Anderson, S.J.; Kubiszewski, I.; Farber, S.; Turner, R.K. Changes in the global value of ecosystem services. *Glob. Environ. Change* **2014**, *26*, 152–158, doi:10.1016/j.gloenvcha.2014.04.002.
52. Lima, M.; Coelho, C.; Veloso-Gomes, F.; Roebeling, P. An integrated physical and cost-benefit approach to assess groins as a coastal erosion mitigation strategy. *Coast. Eng.* **2020**, *156*, 103614, doi:10.1016/j.coastaleng.2019.103614.
53. Coelho, C.; Cruz, T.; Roebeling, P. Longitudinal revetments to mitigate overtopping and flooding: Effectiveness, costs and benefits. *Ocean. Coast. Manag.* **2016**, *134*, 93–102, doi:10.1016/j.ocecoaman.2016.09.022.