The impacts of sea-level rise on European coasts in a 2°C world

Results and analysis of Task 6.5 prepared as part of IMPACT2C: Quantifying project impacts under 2°C warming

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Executive Summary

The European Union is at risk of the adverse effects of rising sea-levels, potentially leading to an increase in number of people affected by flood events and increased damage costs unless adaptation is undertaken. This research answers a question, 'What are the impacts and costs of sea-level rise around Europe in a 2°C world?' A 2°C world could occur rapidly under high emissions, or over much longer periods of time under climate mitigation. Climate mitigation is widely seen a way to reduce adverse risk, but in the coastal zone this is less effective and could only offer potential over very long time periods due to a time lag between atmospheric warming and oceanic response, known as the commitment to sea-level rise. As such, global mean sea-level in a 2°C world is projected to be between 0.11m (under high emissions) and 0.52m (under climate mitigation) higher than 1985-2005 levels under the HadGEM2-ES model. This makes quantifying impacts challenging.

Using the Dynamic Interactive Vulnerability Assessment (DIVA) modelling framework, the number of people at risk from rising sea levels and flood costs have been analysed for scenarios of 2°C and extending up to a 5°C rise compared with pre-industrial levels in European Union coastal regions. Results indicate that following widespread European practices of continued protection, that between 5,300 and 7,000 people per year may be flooded in a 2°C world of climate mitigation – which could double if climate goes unmitigated. In a 5°C world, annual sea flood costs could be up to €1.2 billion per year, but reduce by one third under climate mitigation. The greatest costs occur around many countries surrounding the North Sea, where relatively, the EU's smaller economies and small island states benefit most from climate mitigation.

Adaptation remains particularly important, with sea dikes costing up to €3.9 billion per year in a 5°C world, decreasing by more than one sixth under climate mitigation. To achieve optimum benefits of adaptation and mitigation, it is essential that shoreline management and climate change adaptation are considered over the long time periods in which sea-level rise operates, taking into account multiple factors of coastal change. This includes a range of engineering techniques, including soft adaptation, accommodation and managed retreat, simultaneously considering wider societal needs and social acceptability of coastal change.

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1. Introduction

European coastal zones are economically important, contain high population densities (Small and Nicholls, 2003; McGranahan et al., 2007; Neumann et al. 2015) and vital ecosystems, and are at risk from sea-level rise. Sea-levels have been rising, albeit slowly, around much of the European coast for hundreds of years due to natural variability, and this has been recorded over several millennia by proxy and instrumental records. These records indicate a transition in the late 19th to early 20th century from a time where global mean sea-level rise was relatively low, to faster rates of rise (Church et al. 2013). Whilst a proportion of sea-level rise is due to natural change, scientists are concerned that an increasing proportion of change is attributable to ocean warming due to man-made global warming (Jevrejeva *et al.* 2009). From 1901 to 2010, global mean sea-levels rose 1.7±0.2mm/yr (Church et al. 2013; Church and White 2011) and from 1993 to 2010, global mean sea-level records from tide gauge measurements and satellite altimetry data indicates rises of 2.8±0.8mm/yr and 3.2±0.4mm/yr respectively (Church et al., 2013). Whilst acknowledging the short measurements (i.e. a few decades) of sea-level rise may be misleading, scientists remain concerned that high rates could continue in the future.

In environments where infrastructure has a design life of many decades, it is important to anticipate the magnitude of sea-level so to plan for its occurrence, and how to potentially adapt. However, not until recent decades has sea-level rise been routinely considered in coastal zone planning, leaving pre-existing infrastructure vulnerable to erosion and flooding. Thus, this report aims to assess to damages and costs of sea-level rise around the European Union (EU) coast, focusing on a set temperature rise of 2°C rise since pre-industrial times (1881-1910). Previous research (e.g. Hinkel et al. 2010) suggests that adaptation is an affordable option in coastal zones, and engineering practice indicates that this is largely considered in the design on new structures. Using the Dynamic Interactive Vulnerability Assessment (DIVA) modelling framework (Hinkel 2005; Vafeidis et al., 2008; Hinkel and Klein 2009), particular attention will be paid to people who will be at risk from flooding, as well as damage costs. As EU countries understand the benefits of adapting to coastal change and many places are already heavily engineered, the data produced in this report will assume that as sea-levels rise, the coast will be adapted to cope with changing conditions. In this report, the 23 EU coastal countries will be analysed, which, according to the DIVA database (Vafeidis et al. 2008) have a combined coastal length of 70,466m.

Overseas territories affiliated to a country, but are not part of the EU themselves are not included. EU countries are listed in Table 1 and depicted in Figure 1.

Table 1. Coastal countries in the EU and their coastal length.

Number	Country name	Coastal length (km)
1	Belgium	130
2	Bulgaria	326
3	Croatia	2263
4	Cyprus	671
5	Denmark[1]	4954
6	Estonia	1907
7	Finland	3790
8	France[2]	5890
9	GB and NI[3]	12458
10	Germany	2730
11	Greece	7809
12	Ireland	3435
13	Italy	5767
14	Latvia	655
15	Lithuania	209
16	Malta	76
17	Netherlands	2024
18	Poland	980
19	Portugal	1896
20	Romania	420
21	Slovenia	29
22	Spain	4968
23	Sweden	7077
	TOTAL	**70466**

[1] Excludes Greenland and Faroe Islands.
[2] Comprises mainland France (including Corsica) and overseas departments of Guadeloupe, French Guiana, Martinique, Reunion and Mayotte.
[3] Comprises England, Wales, Scotland and Northern Ireland. Does not include Channel Islands or Isle of Man.

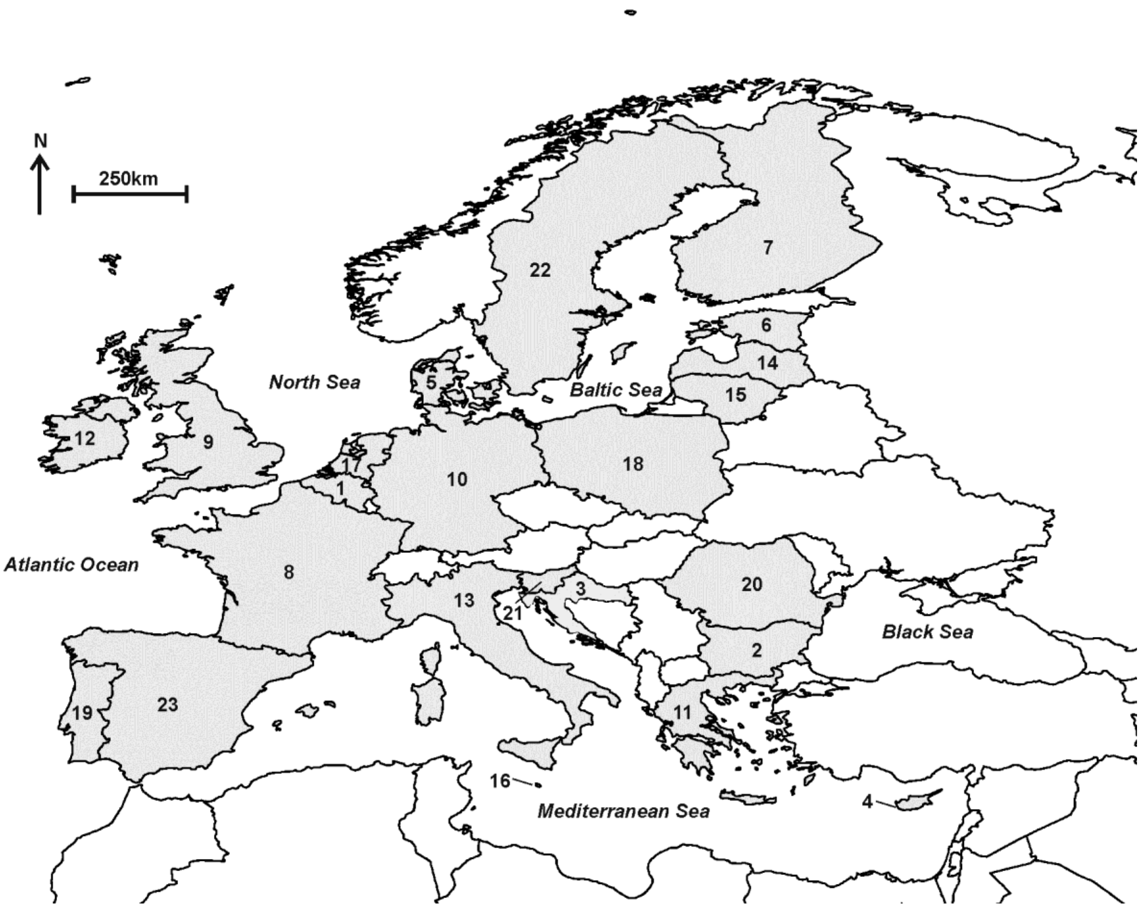

Figure 1. European Union countries with a coastline. For country names, see corresponding numbers in Table 1.

This report is structured as follows: First, the background to sea-level rise will be discussed, following by scenarios of sea-level rise. The methodology to undertake impact assessment is then explained. Results are presented at EU and country level, and then discussed in the broader context of climate mitigation, climate adaptation policies and shoreline management.

2. Background to sea-level rise

IMPACT2C focuses on climate change impacts with a rise of 2.0°C with respect to pre-industrial (1881-1910), with the temperature measurement taken over a thirty-year means for each climate model. For many impact studies, raising the global mean surface temperature by 2°C will produce an impact that may be apparent within hours to a few years. With the impacts of sea-level rise, the situation is not as simple as oceans can take many decades to respond to warming surface temperatures (Church et al. 2013; Schaffer et al. 2012; Wong et al. 2014). Furthermore ice sheets can continue to melt for hundreds of years, even if temperatures stabilise (Church et al. 2013). To understand why this occurs, it is important to understand what components contribute to sea-level rise.

A rise in global mean surface temperature leads to a global increase in mean sea-levels through the contribution and interactions of:

- (i) thermal expansion (the expansion of water volume due to the increase in water temperature);
- (ii) glaciers and ice caps;
- (iii) the large ice sheets; and
- (iv) changes to groundwater, such as through extraction or impoundment.

Thermal expansion contributes the largest component to sea-level rise. Due to their depth, oceans can take many decades to absorb the additional atmospheric warming (Schaffer et al. 2012) down to the bottom layers. This gradual increase in ocean temperatures results in the slow increase in ocean height. Hence there is a time-lag between atmospheric warming and a subsequent increase in the sea-level. Therefore, atmospheric warming from the last century may not appear apparent in the sea-level rise record until this century. This is known as the 'commitment to sea-level rise' (Wigley and Raper, 1993). Thermal expansion is a direct output from a Global Circulation Models, and can be output as a global mean value, or as a range of geographically-specific values which reflect regional variations, such as both halosteric and thermosteric change. These regional variations are known as a pattern. Glaciers and ice caps contain relatively small land-based ice melt contributions compared with the large ice sheets of Greenland and Antarctica. Natural variations in temperature and other geological or geographical processes mean that the magnitude of ice melt varies year-on-year, but this pattern is expected to change. Understanding how ice melts and the rate of melting is challenging due to the remoteness and limited historic surveying of land-based ice, so there is much uncertainty in the projections. Changes to groundwater volumes only contribute a small magnitude of sea-level rise, and as the science is still emerging (c.f. Church et al. 2013), this component is not yet considered in the most up-to-date scenarios used in IMPACT2C.

The delayed response of sea-level rise to an increase in global temperature is shown in Figure 2 (extracted from Hinkel et al. 2014). The figure illustrates outputs from four climate models, with a number of Representative Concentration Pathway (RCP) scenarios, ranging from a scenario of climate mitigation (RCP2.6) to one with a high rate of global emissions

(RCP8.5). The shaded areas represent uncertainty in ice melt. Where climate mitigation occurs and temperatures stabilise (around 1°C to 2°C), sea-levels keep on rising, whereas for the higher emissions scenarios both temperature and sea-levels continue to rise.

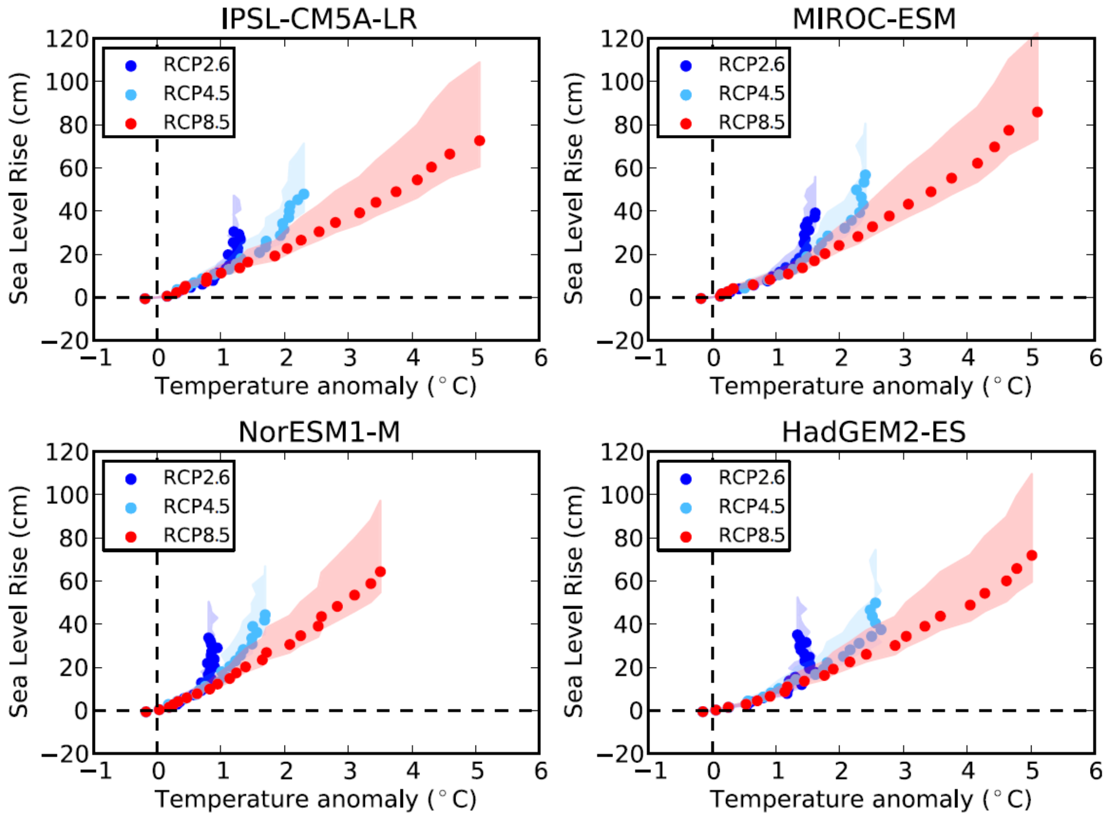

Figure 2. The commitment to sea-level rise: Sea-level rise against temperature anomaly (both with respect to 1985-2005) (extracted from Hinkel et al. 2014).

Therefore, determining impacts for a 2°C rise in temperature offers little meaning unless the atmosphere is subject to the long-term stabilisation of greenhouse gases, as sea-levels will keep on rising, potentially increasing impacts. Thus in this report, impacts will be analysed at a range of temperature projections, focusing on the benefits of climate mitigation. Further information about scenarios is presented in Section 4.

3. Methodology

3.1 Coastal impacts model: DIVA

The Dynamic Interactive Vulnerability Assessment (DIVA) modelling framework is an integrated model of coastal systems that assesses biophysical and socio-economic impacts of sea-level rise and socio-economic development (Hinkel 2005; Vafeidis et al., 2008; Hinkel and Klein 2009; Hinkel et al. 2013, 2014)[4]. DIVA is driven by climatic and socio-economic scenarios. The climatic scenarios consist of the variables temperature change and sea-level rise. The socio-economic scenarios consist of the variables land-use class, coastal population growth and gross domestic product (GDP) growth. The impact assessment comprises a number of modules representing physical processes and economic costings, as well as taking into account adaptation (Figure 3).

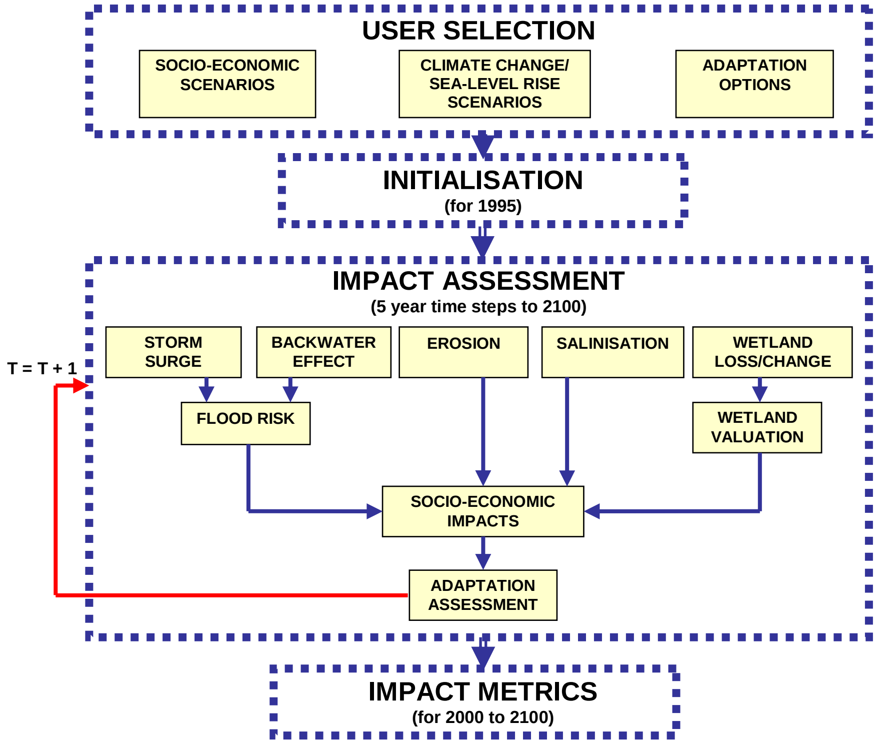

Figure 3. The Dynamic Interactive Vulnerability Assessment modules and model linkages.

DIVA calculates impact metrics by disaggregating the world's coastline (excluding Antarctica) into 12,148 coastal segments. In the European Union, there 1,619 segments, with a mean length of 47km and a median length of 14km. The shortest segment is in Belgium, whilst the longest is located in rural north-west Scotland. The area at risk from flooding for each segment was based on Shuttle Radar Topography Mission (SRTM) dataset which has a resolution of 90m (Rabus et al., 2003). For each segment, DIVA first downscales to relative sea-level rise (RSLR) by combining the sea-level rise scenarios due to global warming with the vertical land movement. The latter is a combination of glacial-isostatic adjustment according to the geophysical model of Peltier (2000a; 2000b). For major European deltas,

[4] For IMPACT2C, DIVA model 5.1.1 was used.

actual subsidence rates (based on past records) were used, extracted from Ericson et al. (2006).

To access damage and costs associated with flooding, land elevation was analysed with respect relative sea-level rise and the frequency of extreme events. Extreme sea-level events produced by a combination of storm surges and astronomical tides will be raised by mean sea level: the return period of extreme sea levels is reduced by higher mean sea levels (e.g., Haigh et al., 2010). The magnitude of this effect depends on the slope of the exceedance curve. Sea-level rise also raises water levels in the coastal parts of rivers (via the backwater effect), increasing the probability of extreme water levels. DIVA considers both these flooding mechanisms. Due to the difficulties of predicting changes in storm surge characteristics (e.g., von Storch and Woth, 2008), the present storm surge characteristics are simply displaced upwards with the rising sea level following 20th century observations (e.g., Zhang et al., 2000; Woodworth and Blackman, 2004; Haigh et al., 2010). Surges represent return periods of the 1-in-1 to the 1-in-1000 year floods. An example of this is shown in Figure 4. Land area and people and assets below this water level were analysed.

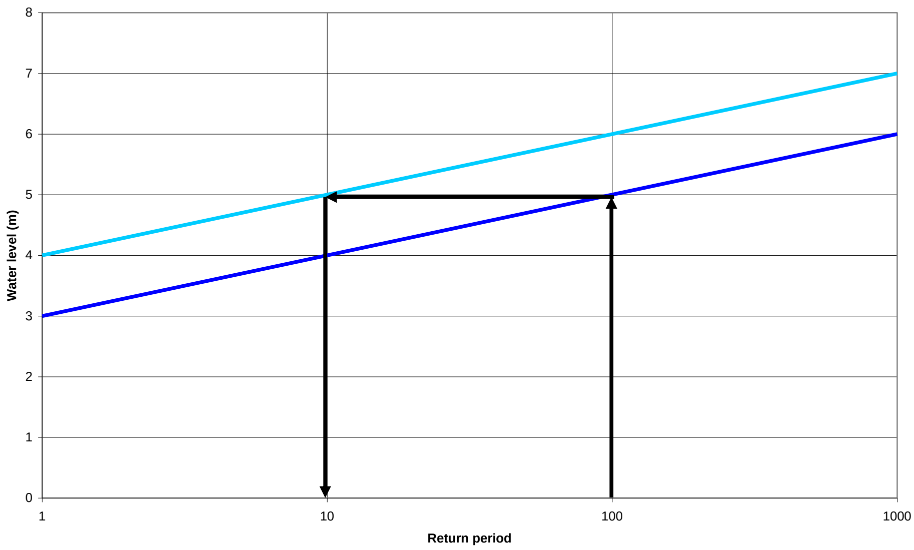

Figure 4. Example of a return period curve indicating where a rise in sea-level creates a higher water level, reducing the return period of an extreme event.

For long-term coastal erosion due to sea-level rise, both the impacts of direct and indirect effects are assessed (Hinkel et al. 2013; 2014). The direct effect of sea-level rise on coastal erosion is estimated using the Bruun Rule (e.g., Zhang et al., 2004; Nicholls, 2010). Sea-level rise also affects coastal erosion indirectly as tidal basins become sediment sinks under rising sea level, trapping sediments from the nearby open coast into tidal basins. This indirect erosion is calculated using a simplified version of the ASMITA (Aggregated Scale Morphological Interaction between a Tidal basin and the Adjacent coast) model (Stive et al., 1998; Van Goor et al., 2003). Globally, around 200 tidal basins around the world are considered in DIVA, of which 40 are in the EU.

Impacts also depend on the level of adaptation. Many European countries are aware of the impacts of coastal climate change (e.g. Tol et al. 2008; Eurobarometer 2009), so engineer and adapt their shorelines. Due to data resolution and computation power, it is not possible to model all types of coastal adaptation. DIVA evaluates the building of sea and river dikes to reduce the risk of flooding (following Hoozemans et al. 1993) and beach/shore nourishment to reduce erosion (Hinkel et al. 2013). For the former, as there is no empirical data on actual dike heights available at a global level, a demand for safety is computed and assumed to be provided by dikes (Tol, 2006; Tol and Yohe, 2007), which changes as sea-levels rise. As a full cost-benefit is computationally too expensive, a demand for safety function was developed, where, as population density increases there is a greater level or protection. There are no dikes where there is very low population density (< 1 person/km^2). Half of the demand for safety is applied at a population density of 20 persons/km^2, and 90% at a population density of 200 persons/km^2. This is akin to providing isolated dikes around individual settlements at lower population densities, to more continuous dikes at higher population densities. Maintenance costs of sea dikes are projected at 1% of their capital costs (Nicholls et al. 2010). In beach nourishment, the sand is placed directly on the intertidal beach, while in shore nourishment the sand is placed below low tide where the sand will progressively feed onshore due to wave action, following current Dutch practice (van Koningsveld et al., 2008). Shore nourishment is substantially cheaper than beach nourishment, but the benefits are not felt immediately.

3.2 Parameters to report

DIVA translates these physical changes into social and economic consequences. The following parameters were analysed:

a) **Expected number of people flooded annually (thousands/yr):** The expected number of people subject to annual flooding due to submergence.

In DIVA the number of people exposed is superimposed on the digital elevation model and interpolated between set elevations. A hazard function relates each extreme sea level with a probability of a flood staying below a certain level, which again is related to the number of people exposed. The expected number of people flooded annually integrates those exposed from flooding for different flood heights and weighted by the probability. Land elevation below 1m is not considered, as these represent uninhabited wetlands.

b) Annual sea flood costs (million Euros / year)

Annual sea flood costs are represented by superimposing assets (obtained through a statistically derived asset to GDP ratio based on Hallegatte et al. (2013)) with the digital elevation data, depth-damage curve from Hinkel et al. (2014) and the probability of occurrence.

c) Annual sea dikes costs (million Euros / year)

Costs of building new and raising modelled (i.e. from 1995) sea dikes are computed through a demand for safety function based on income levels, sea-level rise, population density and the height of the 100 year surge event.

d) Annual dike maintenance costs (million Euros / year): This is the annual cost of maintaining sea dikes based on 1% of capital costs per annum.

e) Annual nourishment costs (million Euros / year). This is the annual costs of beach and shore nourishment in order to maintain sandy beaches

4. Scenarios

To investigate how climate change could affect coastal areas, scenarios of climatic and socio-economic change will be used within the DIVA model.

4.1 Climate change

As described in Section 2, determining the impacts of sea-level rise due to a specific rise in temperature offers little value to end-users due to the range of rates of sea-level rise and dependency on the path of future rise. Engineers who plan to remediate the effects of sea-level rise, need to understand projections above a 2°C boundary so they can consider long-term coastal change with respect to infrastructure lifetime. Therefore, sea-level rise will be considered throughout the 21st century, extending beyond 2°C.

Two GCMs were considered in this analysis, HadGEM2-ES and IPSL-CM5A-LR. Temperature rise with respect to pre-industrial is shown in Figure 5 and Table 2. Both models illustrate that for RCP2.6, temperature with respect to pre-industrial stabilises mid-century, reaching approximately 2°C by the 2080s. For RCP4.5, the 2°C boundary is reached between the 2050s and 2060s. The rate of temperature rise then slows reaching approximately 3°C by the 2080s. For RCP8.5, a 2°C rise in global mean temperatures is reached around the 2040s, reaching 3°C by the 2050s, and 5°C by the 2080s. Unlike RCP2.6 and RCP4.5, temperatures continue to rise and do not stabilise into the 22nd century.

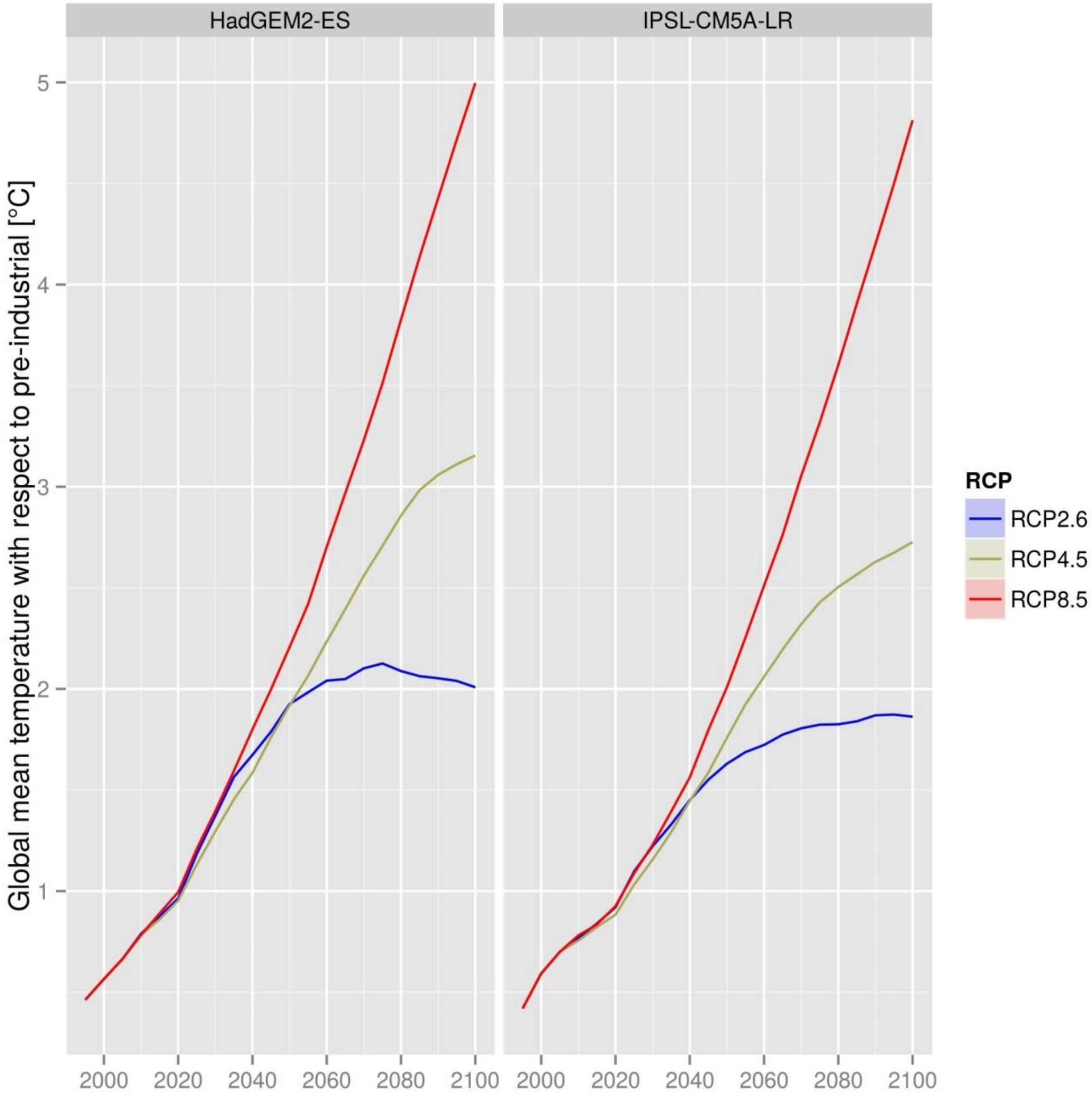

Figure 5. Global mean temperature rise with respect to pre-industrial for HadGEM2-ES and IPSL-CM5A-LR.

Table 2 Projected temperature rise with respect to pre-industrial, given as a thirty year means (to 1dp).

Time period	HadGEM2-ES				IPSL-CM5A-LR			
	No change (°C)	RCP2.6 (°C)	RCP4.5 (°C)	RCP8.5 (°C)	No change (°C)	RCP2.6 (°C)	RCP4.5 (°C)	RCP8.5 (°C)
2010s	0.6	1.0	1.0	1.0	0.6	1.0	0.9	0.9
2030s	0.6	1.8	1.7	1.9	0.6	1.5	1.5	1.7
2050s	0.6	2.1	2.6	3.2	0.6	1.8	2.3	3.1
2080s	0.6	2.0	3.2	5.0	0.6	1.9	2.7	4.8

These temperature changes can be translated to global mean sea-level rise (Hinkel et al. 2014), as listed in Table 3 (HadGEM2-ES) and Table 4 (IPSL-CM5A-LR), and Figure 6. To create scenarios of sea-level rise, the thermal expansion (steric) component was directly output from the GCM. A pattern of sea-level rise was produced, indicating areas of the world with higher than and less than the global mean. This is observed due to the mixing of water masses and changes in salinity, sub-surface densities and ocean dynamics (Pardaens et al. 2011).

To calculate the magnitude of sea-level rise from land-based ice melt, the contribution of the world's glaciers and ice caps (excluding those in Antarctica and Greenland) was taken from glaciers in the Randolph Glacier Inventory (Arendt et al. 2012). Past global surface mass balance was modeled by Marzeion et al. (2012), and then validated and forced with monthly precipitation and temperature data from New et al. (2012). Future changes were projected by comparing historic measurements in precipitation and temperature data against future projections based on 15 GCMS from CMIP5.

For ice melt from Greenland, surface mass balance was taken from Fettweis et al. (2012), and the model forced from output from three GCMs from CMIP5. Ice melt from Antarctica was more challenging to project, so global mean temperatures from 19 GCMs from CMIP5 were scaled to oceanic surface temperature outside of the ice-shelf cavities. This temperature was translated into basal ice-shelf melting, which then forced five different continental ice sheet models, each reflecting different ice-melt processes (further described in Levermann et al. 2012). This did not take account of changes in basal lubrication or surface mass balance, but these factors are thought to be small in comparison. The estimates from Greenland and Antarctica were then regionalised by undertaking gravitational-rotation fingerprinting derived from a model by Bamber and Riva (2011). It was assumed that there was a uniform mass loss over the ice sheets, and also any ice melt resulted in an instantaneous fingerprint due to local uplift due to gravitational changes (this is a different response of glacial isostatic adjustment which can take centuries to respond and contributes to relative sea-level change). Again, this pattern indicated parts of the world with more or less rise than the global mean. These components were summed together to create three scenarios representing uncertainties of high, medium and low ice melt.

The HadGEM2-ES model shows slightly higher sea-level rise scenarios than IPSL-CM5A-LR as the model also corresponds to a marginally higher global mean temperature rise. Across all scenarios, sea-levels remain similar in the 2030s, between 0.09m and 0.16m of rise from all RCP scenarios. After this period, under a world of climate mitigation the rate of rise under an RCP2.6 scenario decreases. In the 2050s, sea-level is projected to be between 0.17m and 0.41m of rise, with a marked difference between the mitigation and high-end scenario. In the 2080s, the rate of rise for RCP2.6 shows a marked decrease, RCP4.5 continues to rise, and RCP8.5 continues to accelerate. Thus, in the 2080s in both models, sea-levels vary between 0.23m and 0.86m, representing a range of warming from 1.9°C to 5.0°C.

Table 3. Global mean sea-level rise for HadGEM2-ES with respect to 1985-2005 (to 1 dp. Data extracted from Hinkel et al. 2014)

Time period	HadGEM2-ES									
	No change	**RCP2.6 (low)**	**RCP2.6 (med)**	**RCP2.6 (high)**	**RCP4.5 (low)**	**RCP4.5 (med)**	**RCP4.5 (high)**	**RCP8.5 (low)**	**RCP8.5 (med)**	**RCP8.5 (high)**
2010s	0	0.02	0.02	0.03	0.02	0.02	0.03	0.02	0.02	0.03
2030s	0	0.09	0.10	0.14	0.09	0.10	0.14	0.10	0.11	0.16
2050s	0	0.18	0.20	0.29	0.21	0.24	0.34	0.25	0.29	0.41
2080s	0	0.26	0.31	0.46	0.35	0.42	0.63	0.48	0.57	0.86

Table 4. Global mean sea-level rise for IPSL-CM5A-LR with respect to 1985-2005 (to 1 dp. Data extracted from Hinkel et al. 2014)

Time period	IPSL-CM5A-LR									
	No change	**RCP2.6 (low)**	**RCP2.6 (med)**	**RCP2.6 (high)**	**RCP4.5 (low)**	**RCP4.5 (med)**	**RCP4.5 (high)**	**RCP8.5 (low)**	**RCP8.5 (med)**	**RCP8.5 (high)**
2010s	0	0.02	0.03	0.03	0.03	0.03	0.04	0.03	0.03	0.04
2030s	0	0.09	0.10	0.13	0.10	0.11	0.15	0.10	0.12	0.15
2050s	0	0.17	0.19	0.27	0.22	0.25	0.35	0.25	0.29	0.40
2080s	0	0.23	0.27	0.42	0.35	0.41	0.60	0.49	0.58	0.85

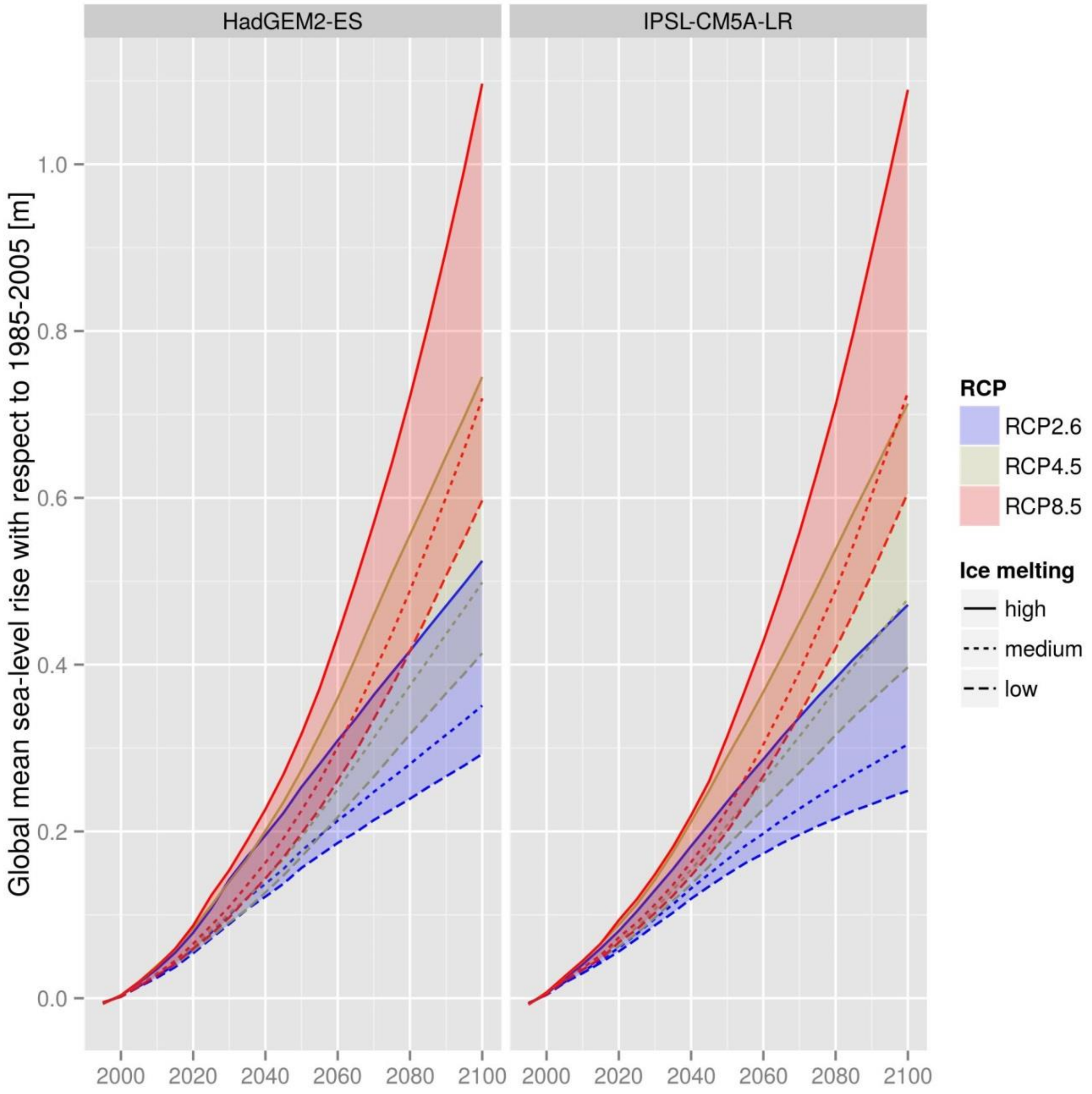

Figure 6. Global mean sea-level rise with respect to 1985-2005 for HadGEM2-ES and IPSL-CM5A-LR.

The relationship between global mean temperature and sea-level rise is shown in Figure 7 for the two models, three families of scenarios and three levels of ice melt uncertainty. For scenarios where climate mitigation occurs, sea-levels continue to rise even when temperatures stabilise. It is important to note that sea-levels will continue to rise beyond 2100, even with climate mitigation, so sea-levels corresponding to a 4°C rise in temperature could be greater than what is presented here. For a 2°C rise in HadGEM2-ES, sea-level varies between 0.11m and 0.21m when 2°C is first reached in the 2030s, but has the potential to extend up to 0.52m by 2100 (still in a 2°C world). For a 3°C, sea-level varies between 0.22m and 0.48m, occurring in the 2050s and 2080s (for RCP8.5 and RCP4.5 respectively). In a 4°C world, which is only reached in RCP8.5, sea-level rise reaches approximately 0.60m. IPSL-CM5A-LR indicates a 2°C rise in temperatures could result in a sea-level between 0.15m and 0.19m (RCP4.5 and RCP8.5), a 3°C world up to 0.40m (RCP8.5), and a 4°C up to 0.62cm (RCP 8.5).

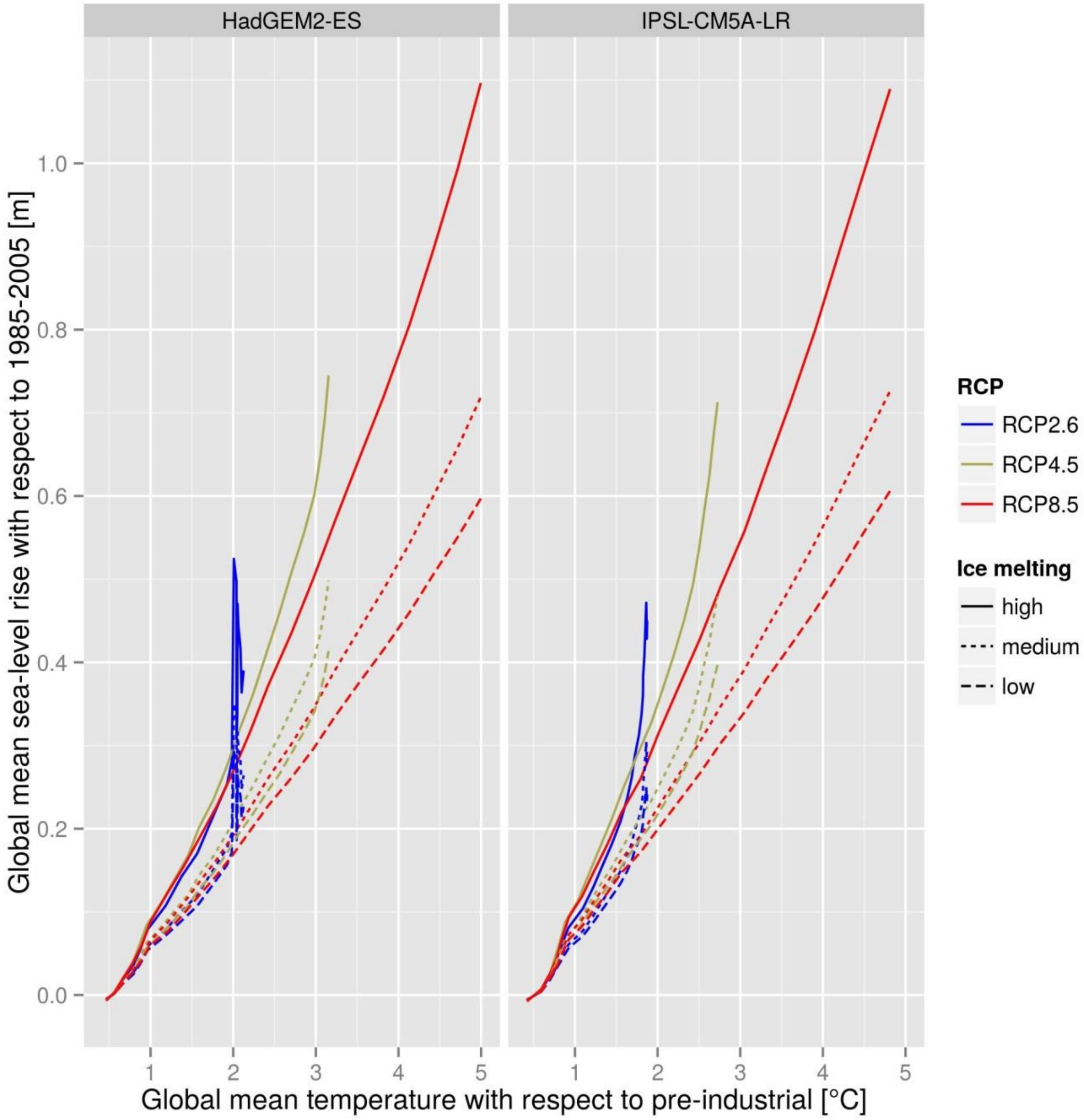

Figure 7. Global mean sea-level rise (with respect to 1985-2005) plotted against global mean temperature rise (with respect to pre-industrial) for HadCM2-ES and IPSL-CM5A-LR.

Spatial changes to sea-level rise are shown for HadGEM2-ES and IPSL-CM5A-LR in Figure 8.

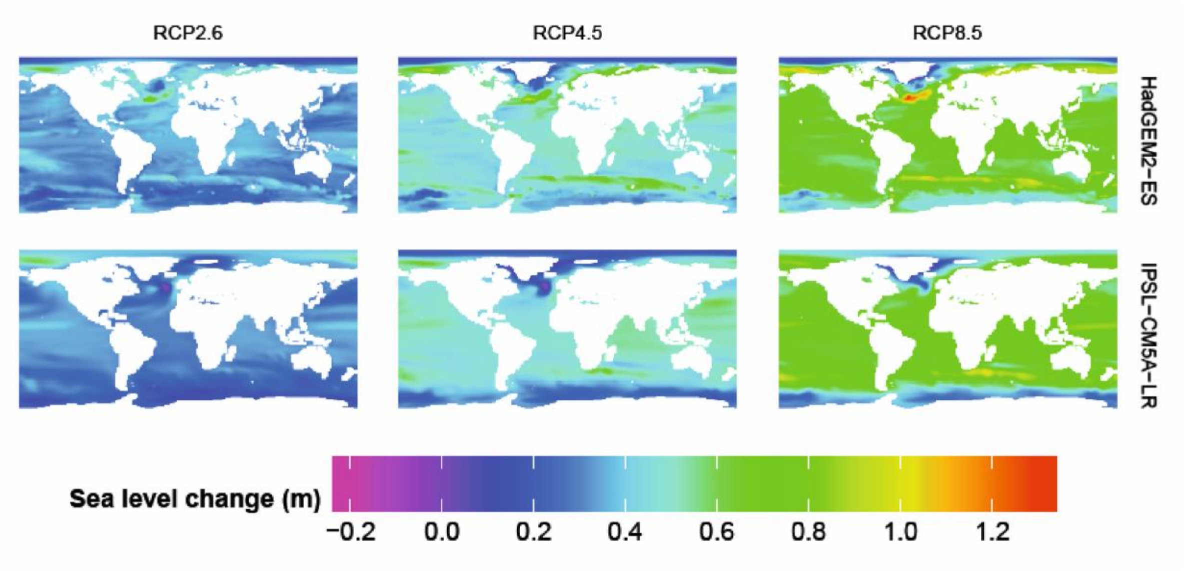

Figure 8. Spatial variations in climate change projections in 2100 with respect to 1985-2005 for HadGEM2-ES and IPSL-CM5A-LR using medium ice melt contributions (data extracted from Hinkel et al. 2014).

4.2 Socio-economic change

Socio-economic change is represented though change in the population and gross domestic product (GDP) through the Shared Socioeconomic Pathways (Moss et al. 2010; O'Neill et al. 2014). These are known as SSP1-5. Their characteristics, for EU coastal countries, are illustrated in Figure 9 and listed in Table 5.

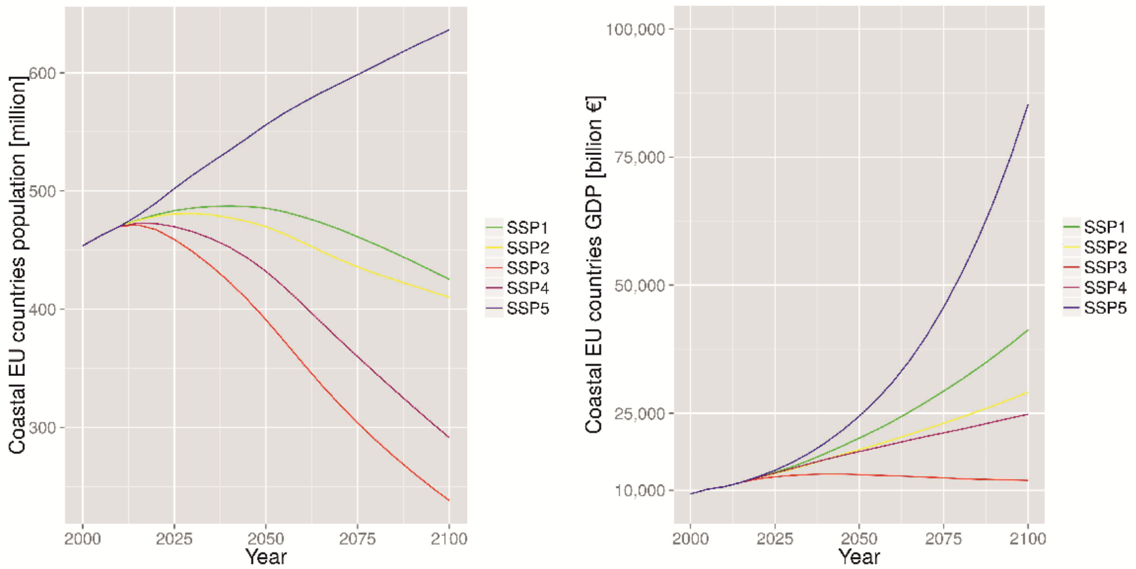

Figure 9. Changes in population and gross domestic product in the EU coastal countries for SSP1-5.

Table 5 Description of shared socioeconomic pathways (SSP).

	Description	EU population and GDP	Selected country details
SSP1	Focus on sustainability, achieving development goals, reducing resource intensity and reliance on fossils fuels.	Overall population growth reaches a maximum of 490 million in the 2050s, and declines to 425 million by 2100. GDP increases to €36,000 billion in 2100.	Population increases in France, GB&NI, Ireland, Denmark and Finland, but declines or stabilises elsewhere. GDP increases exponentially for most countries.
SSP2	Middle of the Road, continuing current trends. Some progress towards development goals, but still dependent on fossil fuels. Uneven development in low-income countries.	EU population peaks in the 2030s, then declines to 410 million people in 2100. GDP increases to €26,700 billion in 2100.	Population declines or stabilises, excluding France, GB&NI and Ireland. GDP continues to increase.
SSP3	Fragmentation. Characterised by extreme poverty, and moderate wealth. Living standard not increased with development. Failure to obtain development goals, with little progress in reducing reliance on fossil fuels.	EU population declines to 238 million in 2100. GDP growth slows after 2030, peaking at €13,200 before declining to €12,100 in 2100.	Most countries have a rapidly declining population, with Cyprus and Lithuania remaining stable or experiencing a slight gain. GDP rises before stabilising mid century. Selective eastern European nations continue to rise.
SSP4	Inequity within and across countries. The rich are largely responsible for emissions, whilst the poor are vulnerable to climate change.	EU population declines to 290 million in 2100. GDP continues to grow to €24,500 billion in 2100.	Population declines but GDP increases at a steady rate for all countries.
SSP5	Convention development, stressing economic growth, and energy system dominated by fossil fuels.	Population steady increases to 640 million by 2100 in the EU. GDP increases exponentially €85,700 billion in 2100.	For most countries population grows or stabilises. GDP grows exponentially (excluding selective eastern European nations as population declines).

4.3 Runs undertaken

As the magnitudes of sea-level rise and temperature from HadGEM2-ES and IPSL-CM5A-LR are very similar, following previous studies (e.g. Hinkel et al. 2014), impacts and costs are also similar. Comparison between the two data sets indicates that whilst global mean sea-level rise varies by an average of 10%, the mean difference in impacts and costs is up to 4%. The largest differences occur under the climate mitigation scenarios (particular for sea dike costs) as the rate of sea-level rise declines at a different point in time. Therefore only the results from the HadGEM2-ES model will be described in the report, with results from IPSL-CM5A-LR listed in Appendix 1. HadGEM2-ES was selected to report over IPSL-CM5A-LR as global mean temperatures and sea-level rise are slightly higher, and therefore, in terms of impacts, would represent the worst of the two cases.

HadGEM2-ES will be run with low, median and high levels of ice melt uncertainty, for RCP2.6, 4.5 and 8.5. A hypothetical scenario of no sea-level rise will also be analysed as a baseline to determine the residual component of climate change. These will be combined with SSP1-6. The results will assume that adaptation evolves as sea-levels rise. This makes a total of 50 model runs.

Due to the commitment to sea-level rise, reporting a set temperature or sea-level rise offers little meaning (see Section 2). Impacts and costs will therefore be reported four timesteps. This is also beneficial as socio-economic scenarios remain constant, and therefore within one timeframe, different magnitudes of sea-level rise may be directly compared.

a) the baseline timeframe (also known as the 2000s): the mean of 1996-2015;

b) the short term (also known as the 2020s): the mean of 2016-2040;

c) the medium term (also known as the 2050s): the mean of 2040-2070;

d) the long term (also known as the 2080s): the mean of 2071-2100.

5. Results: European level

The impacts and costs of sea-level rise are presented first for HadGEM2-ES. Each scenario, including a range of uncertainty with respect to ice melt has been analysed for each SSP, and plotted against time period, temperature and sea-level rise.

5.1 Expected number of people flooded annually

The expected number of people flooded annually is shown in Figure 10. Due to adaptation (and an increase in GDP/capita) the number flooded is expected to fall with time as Europe is projected to have improved defences and becomes a more risk adverse society. During this period, the level of coastal protection increases. Thus a policy agenda to protect has a greater influence on the number of people flooded than the magnitude of sea-level rise, and to a lesser extent socio-economic change.

The maximum number of people flooded annually is 7,000 people / yr (2030s, SSP5), 6,800 people / yr (2060s, SSP2) and 6,600 people / yr (2080s, SSP2). The lowest number in the same time periods are 5,300 people / yr (2030s, SSP3 and SSP4), 3,800 people / yr (2050s, SSP4) and 1,700 people / yr (2080s, SSP5). When considering the magnitude of impacts in a 2°C world, in the 2030s, all scenarios have a relatively small range of the expected number of people flooded, from 5,300 people to 7,000 people per year. Due to the combination of a greater range of sea-level rise and socio-economic change, the range of magnitude of impacts in the 2080s would be greater than the 2030s.

In the short-term, the majority of those at risk from flooding would be a result land subsidence rather than sea-level rise. However, by 2080s sea-level rise becomes increasingly important, and under a SSP2 scenario 75% of those flooded are projected to be due to eustatic sea-level rise, rather than land level change. Even if sea-levels did not rise, people would be still be projected to be flooded due to subsidence, and in areas where defence levels are not sufficient to protect against the most extreme events.

In the 2080s, given a range of uncertainty (i.e. 2.0°C may not be hit precisely in the time frame, but is within a few points of a degree), a RCP2.6 represents a 2°C world with climate mitigation, RCP4.5 a 3°C world, and RCP8.5 a 5°C world with continued temperature and sea-level rise. The benefits of climate mitigation may be calculated, as shown in Figure 11 for each SSP. This indicates the percentage decrease in people flooded due to an emissions reduction: the higher the percentage, the greater the benefit of mitigation. The benefits of mitigation are similar across all socio-economic scenarios – more important is the magnitude of temperature and sea-level rise. The benefits of mitigation are also more significant with the higher scenario of ice melt. When a 2°C world is contrasted with a 3°C world (i.e. to see the benefits of mitigation), 17% fewer people would be expected to be flooded (based on the median scenario). This decreases to 15% if a low ice melt scenario is considered, but increases to 24% is a high ice melt scenario is used. The benefits of comparing a 3°C world with a 5°C world range from a 22% to 35%. When comparing a 2°C world with a 5°C, the

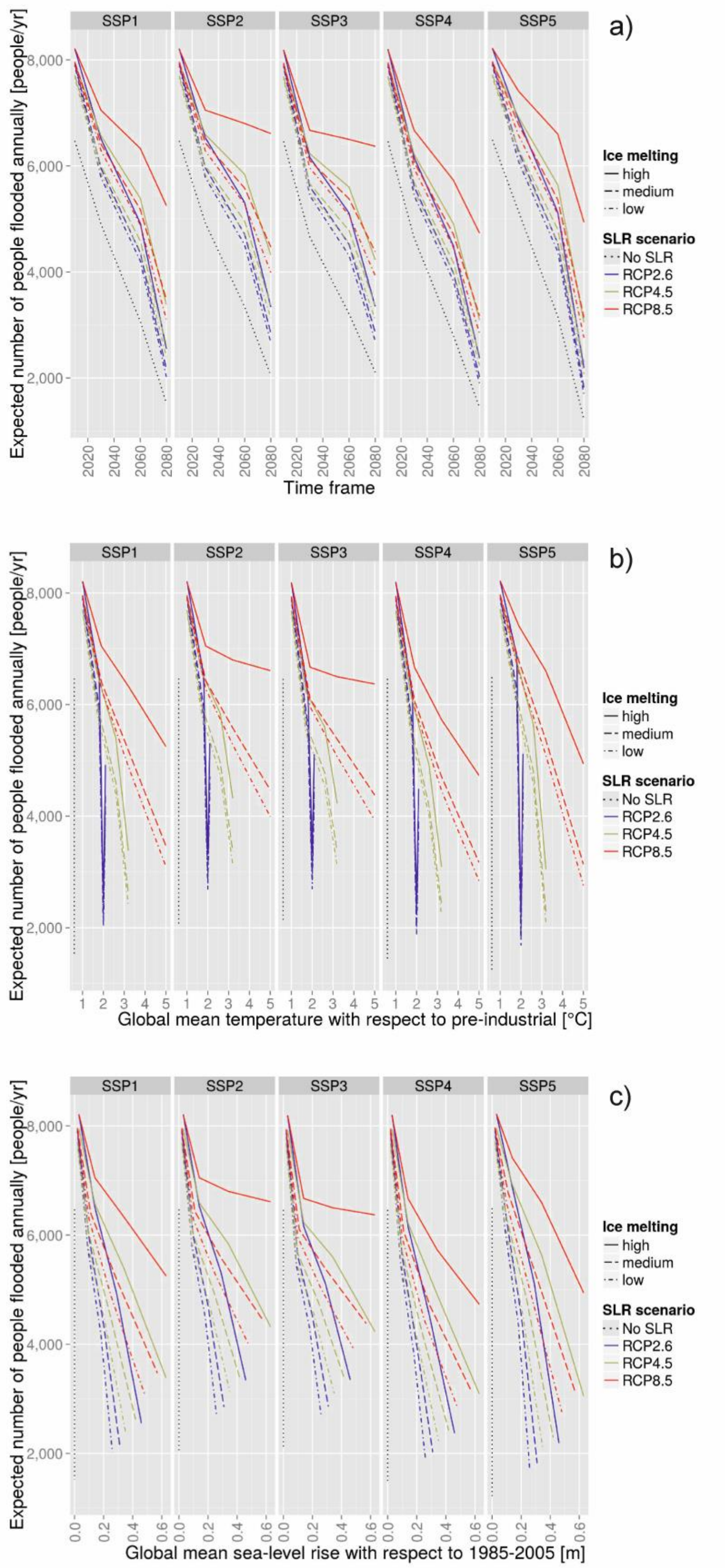

Figure 10. Expected number of people flooded annually in the EU countries due to sea-level rise and socio-economic change for HadGEM2-ES, plotted against a) Timeframe, b) Temperature, c) Sea-level rise.

median scenario is projected to be a 37% increase in people flooded compared with the unmitigated scenario, with a range of 34% to 51%. Thus, the greatest benefits of mitigation will be felt for the highest rises in temperature, and therefore sea-level rise.

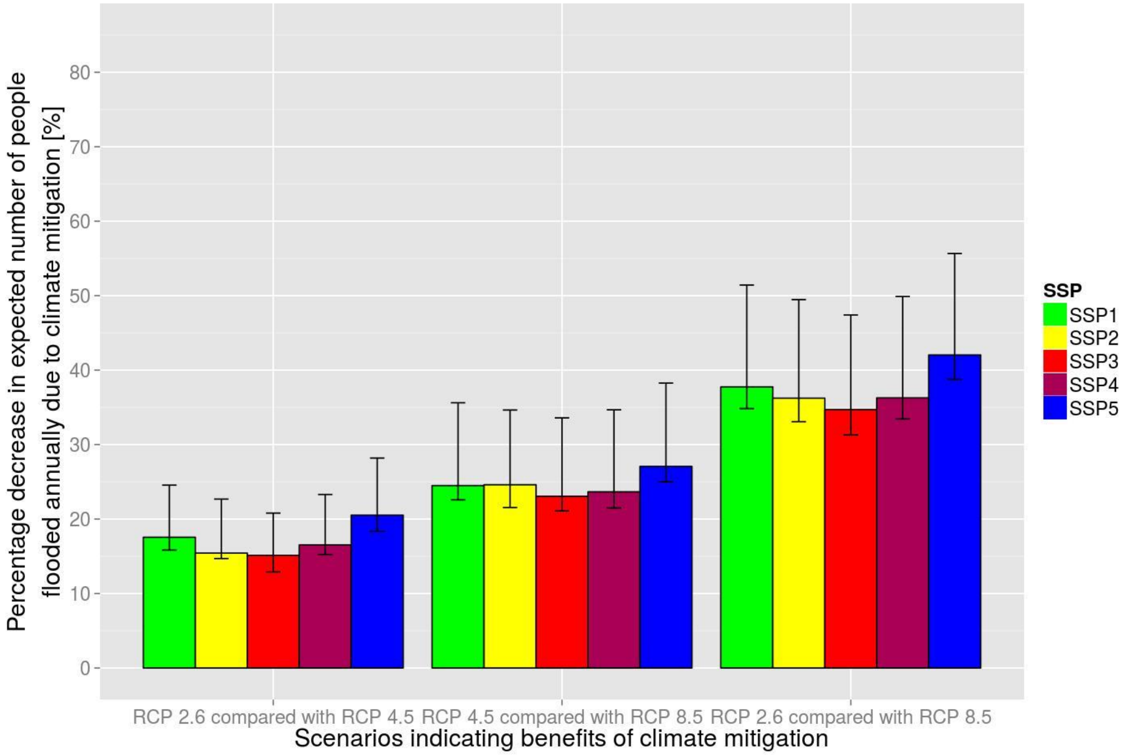

Figure 11. Percentage increase in expected number of people flooded annually in EU countries due to warming temperatures for HadGEM2-ES in the 2080s for the five SSPs. The columns indicate the median scenario, whilst the uncertainty bars indicate the high and low equivalent ice melt scenario.

5.2 Annual sea flood costs

Even with adaptation, some flooding is inevitable as defences will not protect against the most extreme events, particularly in less populated areas. The annual cost of sea floods are shown in Figure 12.

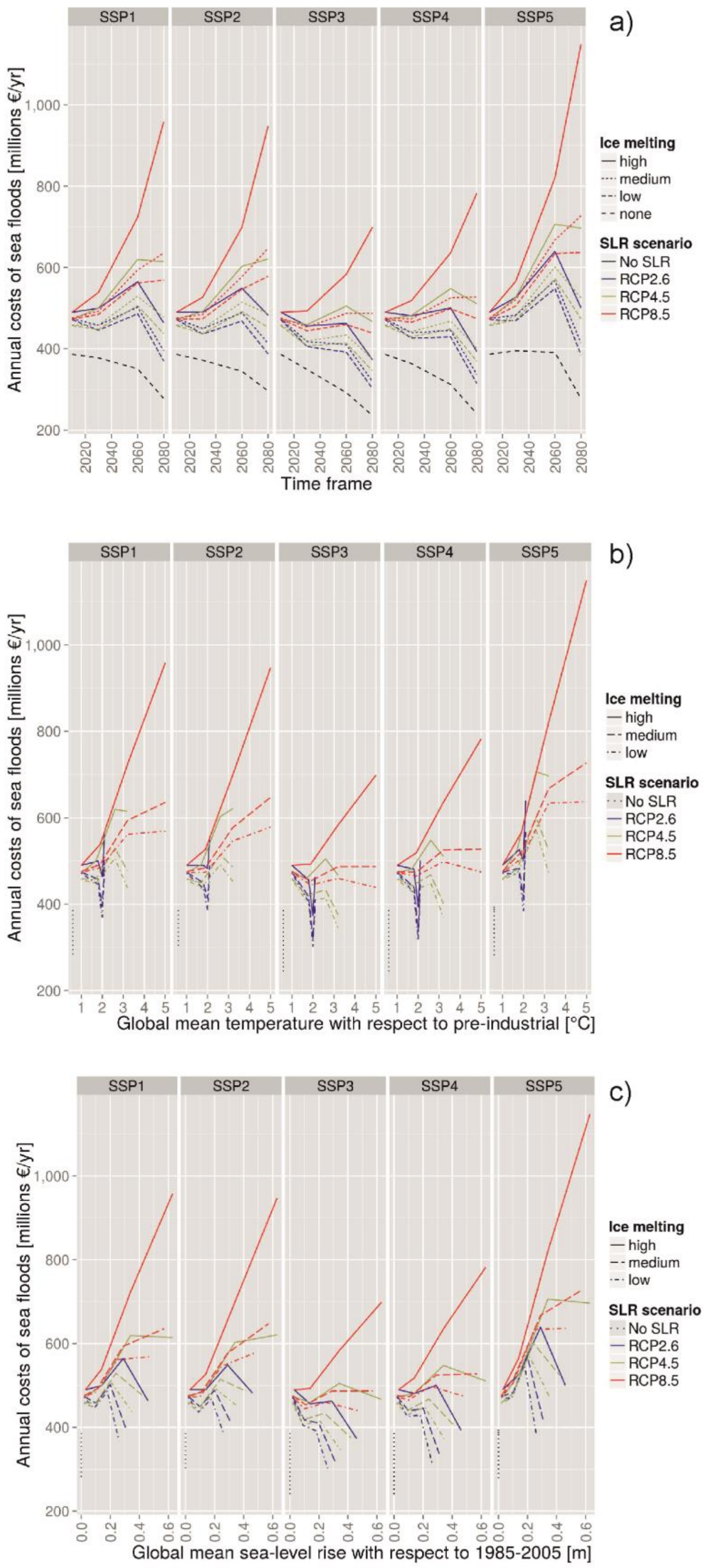

Figure 12. Annual costs of sea floods in EU countries due to sea-level rise and socio-economic change for HadGEM2-ES, plotted against a) Timeframe, b) Temperature, c) Sea-level rise.

Sea flood costs increase throughout time for all socio-economic scenarios, but not all climate scenarios. Costs only increase where there is an acceleration in sea-level rise between each time step. This is best shown through the climate mitigation scenario, where, as the rate of rise slows, sea flood costs decrease. Figure 12 also shows a marked difference between sea flood costs for the RCP8.5 (low and med) scenarios compared with the RCP8.5 (high) scenario (at 0.86m in the 2080s). This suggests that for larger magnitudes of sea-level rise, flood costs will continue to increase. Thus the incentive to mitigate and reduce economic costs and other damages is even greater.

The maximum costs of annual sea floods are € 0.57 billion / yr (2030s, SSP5), € 0.82 billion / yr (2060s, SSP5) and € 1.15 billion / yr (2080s, SSP5). The lowest number in the same time periods are € 0.41 billion / yr (2030s, SSP3), € 0.39 billion / yr (2050s, SSP3) and € 0.30 billion / yr (2080s, SSP3). Similarly to the number of people flooded, the greatest similarity of costs occurs in the short term, and over the longer term projected costs diverge.

Under a scenario of no sea-level rise, floods would still occur, but the costs would be reduced, particularly over the long-term and for the highest rises in sea-level. Under the scenario with the lowest projected flood costs (SSP3) in the 2080s, relative land level change would account for 78% of flood costs, whilst for the highest flood costs (SSP5), relative land level change in the 2080s is attributable of 25% of the costs. Hence, even with protection, floods will always have a residual cost.

As with the expected number of people flooded, the benefits mitigation may be projected. In the 2080s, given a range of uncertainty (i.e. 2.0°C may not be hit precisely in the time frame, but is within a few tenths of a degree), a RCP2.6 represents a 2°C world with climate mitigation, RCP4.5 a 3°C world, and RCP8.5 a 5°C world with continued temperature and sea-level rise. Climate mitigation also becomes more beneficial over time. Figure 13 illustrates the percentage decrease in costs due an emissions reduction in the 2080s. The higher the percentage, the greater than benefit. The greatest variation in the benefits of mitigation is due to the difference in temperature change (and therefore sea-level rise) rather than socio-economic change, with the exception of SSP5 due to a faster growing population and GDP compared with the other socio-economic scenarios (see Figure 9). The greatest differences are seen when comparing the most extreme climate scenarios (RCP2.6 against RCP8.5), where sea flood costs may decrease by 56% if mitigation occurs.

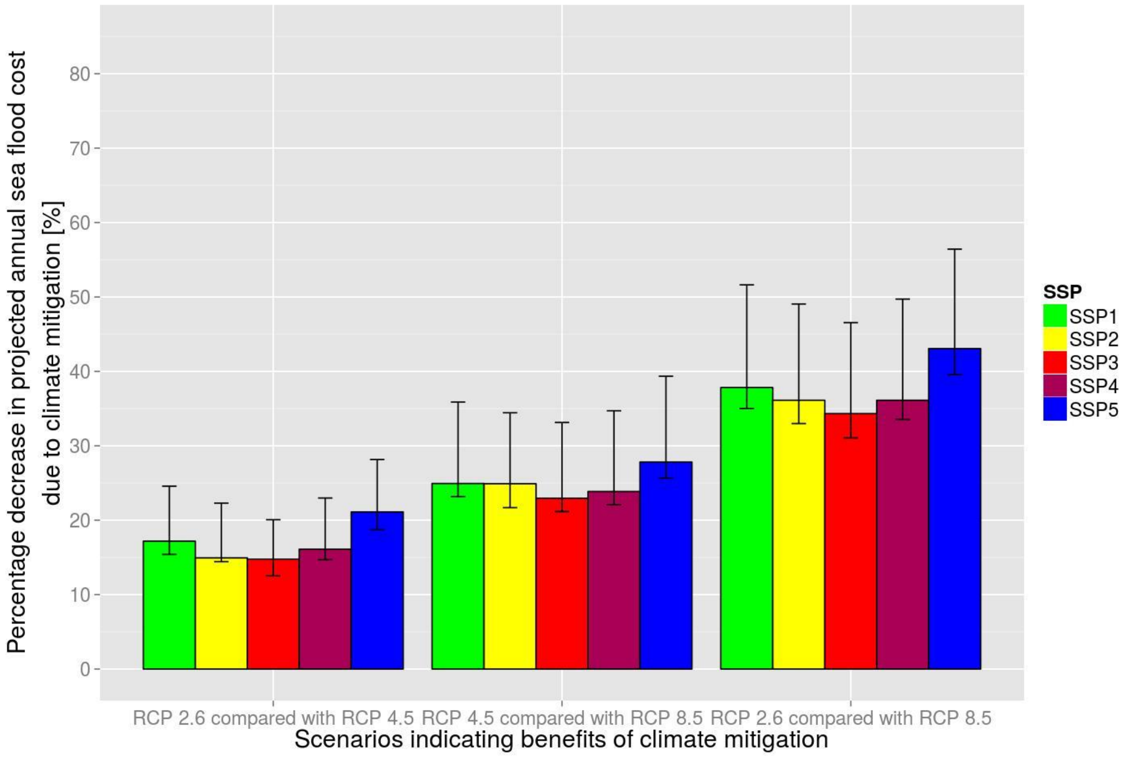

Figure 13. Percentage increase in annual sea flood costs annually in EU countries due to warming temperatures for HadGEM2-ES in the 2080s for the five SSPs. The columns indicate the median scenario, whilst the uncertainty bars indicate the high and low equivalent ice melt scenarios.

5.3 Annual sea dike costs

DIVA calculates the annual costs of building sea dikes to reduce flood risk. This is shown in Figure 14 for HadGEM2-ES.

All scenarios initially experience an increase in sea dike costs as the rate of sea-level rise continues to accelerate. By the 2050s, the annual costs of constructing sea dikes decreases for RCP2.6 as climate mitigation reduces the rate of rise, and thus the annual additional cost. A similar, but smaller decrease is seen in the 2080s for the RCP4.5 scenario. Costs continue to accelerate for RCP8.5. For all scenarios the level of protection offered by dikes increases, even if temperatures stabilise as GDP/capita continues to grow.

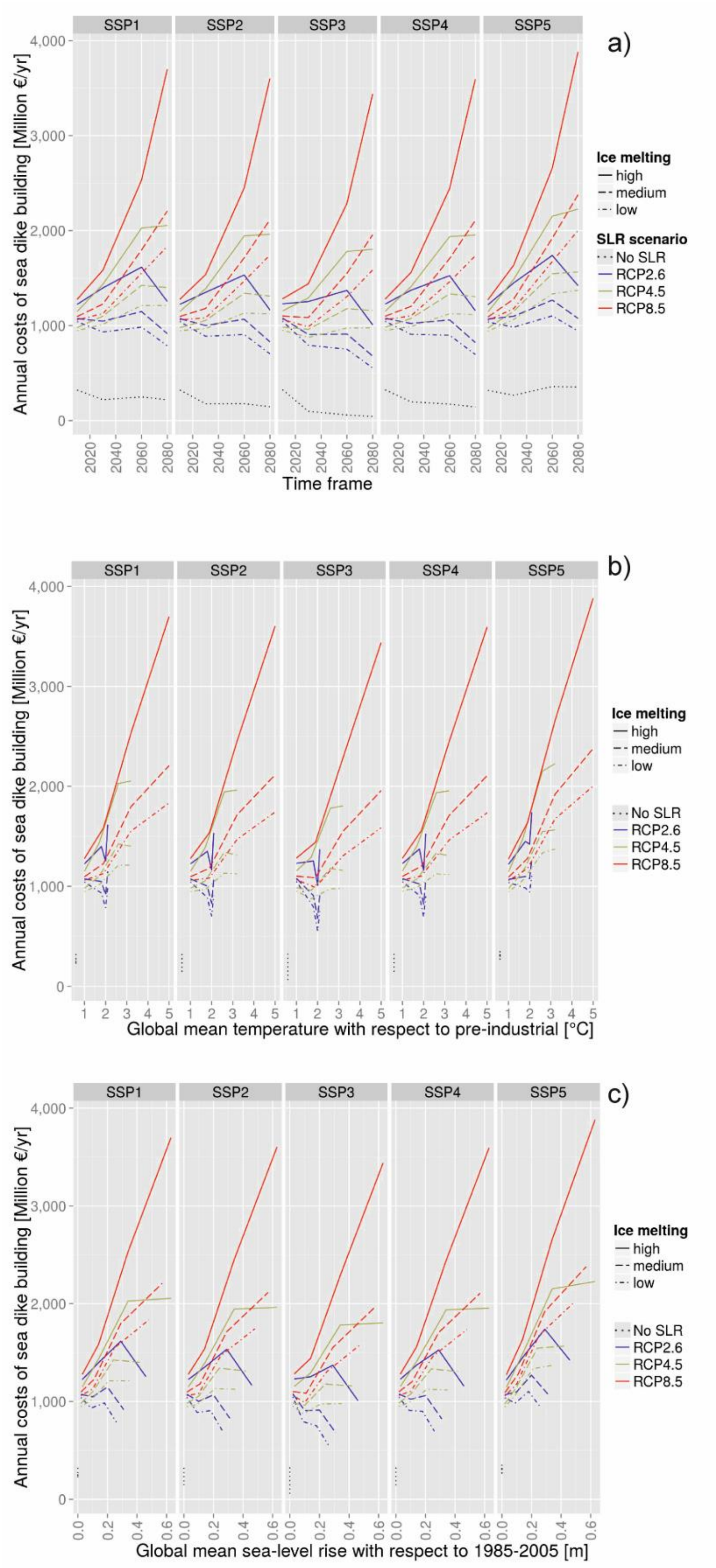

Figure 14. Annual costs of building sea dikes in EU countries due to sea-level rise and socio-economic change for HadGEM2-ES, plotted against a) Timeframe, b) Temperature, c) Sea-level rise.

The maximum costs of annual sea dike building are € 1.6 billion / yr (2030s, SSP5), € 2.6 billion / yr (2060s, SSP5) and € 3.9 billion / yr (2080s, SSP5). The lowest number in the same time periods are € 0.79 billion / yr (2030s, SSP3), € 0.75 billion / yr (2050s, SSP3) and € 0.55 billion / yr (2080s, SSP3). Thus the lowest potential adaptation costs under climate mitigation remain similar throughout the time, whilst the maximum costs have a greater potential to increase. As sea-level rise is not projected to stablise or reduce immediately beyond 2100, the costs of building new dikes or increasing dike height on existing stock will continue.

Some of these costs would be expected regardless of climate change, due to relative land level change alone. Taking a SSP3 scenario as this reports the lowest annual sea dikes costs, relative land level changes account for up to 8% of costs in the 2030, 8% in the 2050s and 12% in 2080s. However, in absolute terms the costs due to land level change alone decrease over the same time period.

The benefits of mitigation are shown in Figure 15. In the 2080s, given a range of uncertainty (i.e. 2.0°C may not be hit precisely in the time frame, but is within a few tenths of a degree), a RCP2.6 represents a 2°C world with climate mitigation, RCP4.5 a 3°C world, and RCP8.5 a 5°C world with continued temperature and sea-level rise. A higher percentage means a higher proportion of costs are saved due to climate mitigation. The benefits of mitigation are similar when 2°C and 3°C world are compared with each other (RCP2.6 and RCP4.5), and when a 3°C and 5°C world are compared with one another (RCP4.5 and RCP8.5). This is in part due to a reduction in the costs of building sea dikes as the rate of sea-level rise decreases in the RCP2.6 and RCP4.5 scenarios. The greatest benefits are seen when comparing the 2°C world with a 5°C world. There is also a lower sensitivity between uncertainty associated with the ice melt.

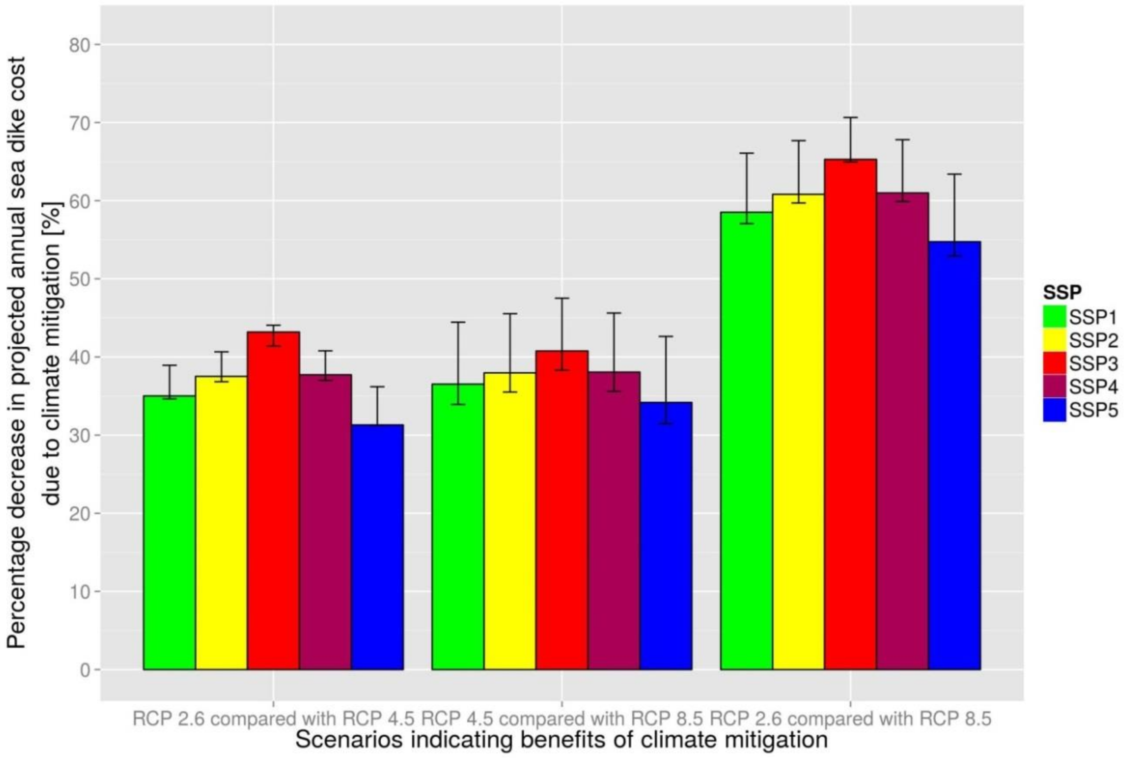

Figure 15. Percentage increase in annual sea dike costs annually in EU countries due to warming temperatures for HadGEM2-ES in the 2080s for the five SSPs. The columns indicate the median scenario, whilst the uncertainty bars indicate the high and low equivalent ice melt scenarios.

6. Results: Country level

Country level results are discussed for the three impact and cost metrics.

6.1 Expected number of people flooded annually

The number of people expected to be flooded annually at EU country level is shown in Figure 16. It illustrates the potential impact in the 2080s, with a RCP4.5 (med) value, and then the upper (RCP8.5 high) and lower levels (RCP2.6 low) of projected impacts, indicated by the uncertainty bars. A scenario of no sea-level rise is shown by a light blue bar, indicating socio-economic and land level change only.

The figure illustrates that under all scenarios the top five countries affected (in terms on absolute numbers) are Belgium, France, Germany, Netherlands, and Great Britain and Northern Ireland. In practice, the Netherlands are very risk adverse, and have protection to higher defence levels than the ones in modelled in DIVA (as DIVA is a global model, it assumes a set of 'rules' for protection, but does not take account those countries which are particularly risk adverse).

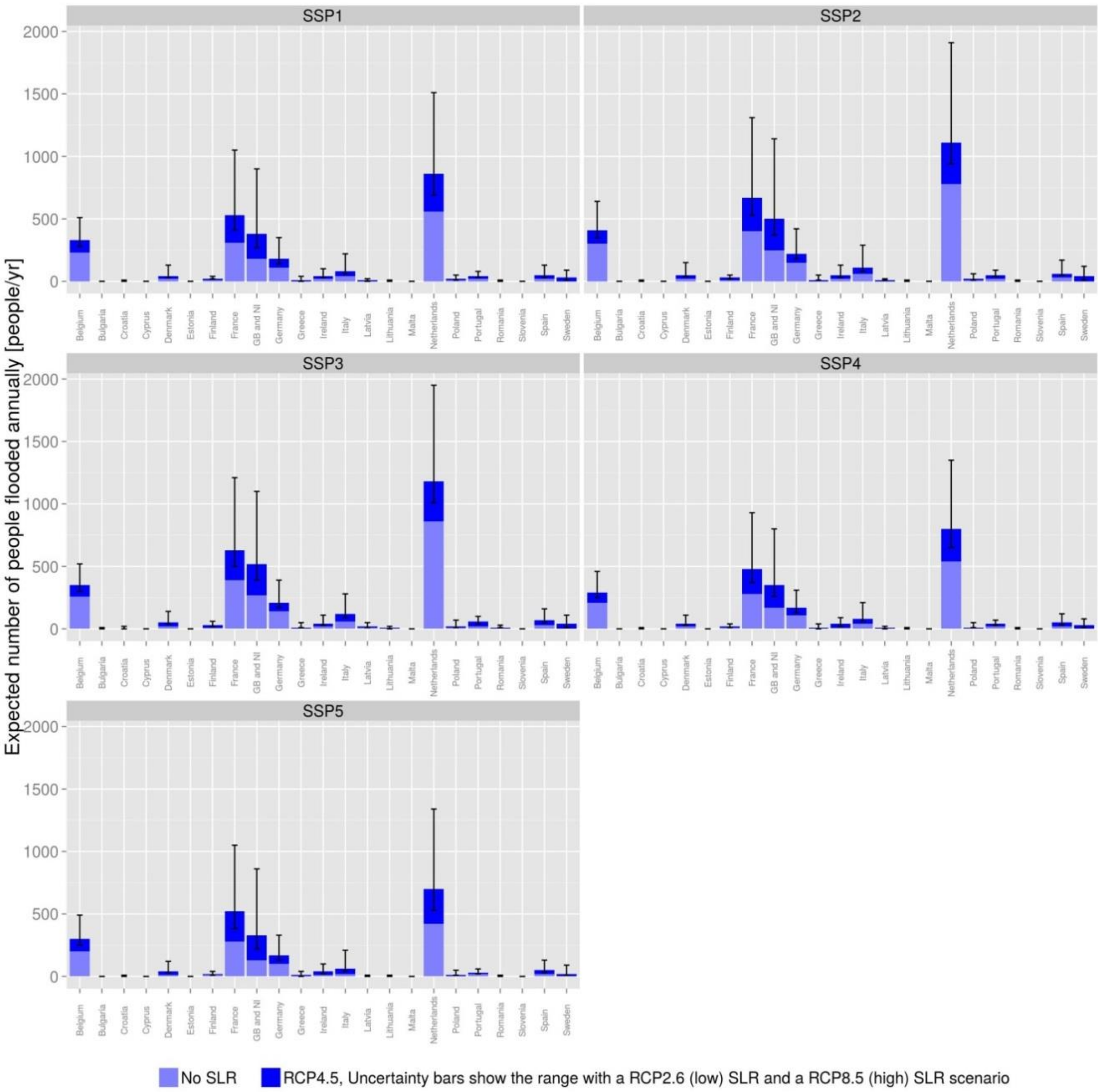

Figure 16. Expected number of people flooded annually per EU country for each SSP scenario in the 2080s. The dark blue bar indicates a RCP4.5 mid scenario, with uncertainty bars showing the range of impacts with low (RCP2.6 low) and high (RCP8.5) scenario. A scenario of no sea-level rise is indicated for each country by the lighter blue bar.

The countries which benefit most from climate mitigation (in relative terms) are listed in Table 6. Where several countries are listed in joint position, they share the same mitigation benefit. In the case of the top position, all these countries reduce the number of people flooded to zero. Croatia, Latvia, Lithuania, Sweden, Greece, Poland and Denmark are in the top five across all socio-economic scenarios, so would best benefit from climate mitigation. Interestingly, small islands and nations do not feature highly in relative terms, as they have sufficient protection standards. However, they are likely to be affected indirectly, or as people would be situated in the hazard zone, having a potential to affect tourism in the coastal zone.

Table 6. EU countries that will benefit most in relative terms from climate mitigation, for the expected number of people flooded annually. Where several countries are listed, they share the same mitigation benefit.

	SSP1	SSP2	SSP3	SSP4	SSP5
1	Romania, Latvia, Lithuania, Greece, Croatia	Croatia, Lithuania, Romania	Bulgaria, Croatia, Lithuania	Croatia, Greece, Latvia, Lithuania, Romania	Croatia, Greece, Latvia, Lithuania, Romania
2	Sweden	Sweden	Sweden	Sweden	Sweden
3	Poland	Poland	Poland	Poland	Italy
4	Greece	Ireland	Ireland	Ireland	Ireland, Portugal
5	Denmark, Spain	Denmark	Denmark	Denmark	Denmark, Finland

6.1 Annual sea flood costs

Figure 17 illustrates the annual sea flood costs for EU countries. It illustrates the potential impact in the 2080s, with a RCP4.5 (med) value, and then the upper (RCP8.5 high) and lower levels (RCP2.6 low) of projected impacts, indicated by the uncertainty bars. A scenario of no sea-level rise is shown by a light blue bar, indicating socio-economic and land level change only. The Netherlands, France, Great Britain and Northern Ireland, and Belgium have in absolute terms the greatest annual sea flood costs, probably as parts of their country are low-lying, or that they have a long coastline. In the Netherlands, such high flood costs are unlikely as they protect to much higher defence standards than the ones modelled in DIVA. There is the greatest uncertainty in costs for the higher end of the scenarios, illustrated by the upper limit of the uncertainty bar. Floods would still occur even if sea-levels did not rise, this represents the majority of the flood cost. Continued flooding should therefore be anticipated even without climate change. The greatest sea flood costs per kilometer of defences are projected to occur in Belgium.

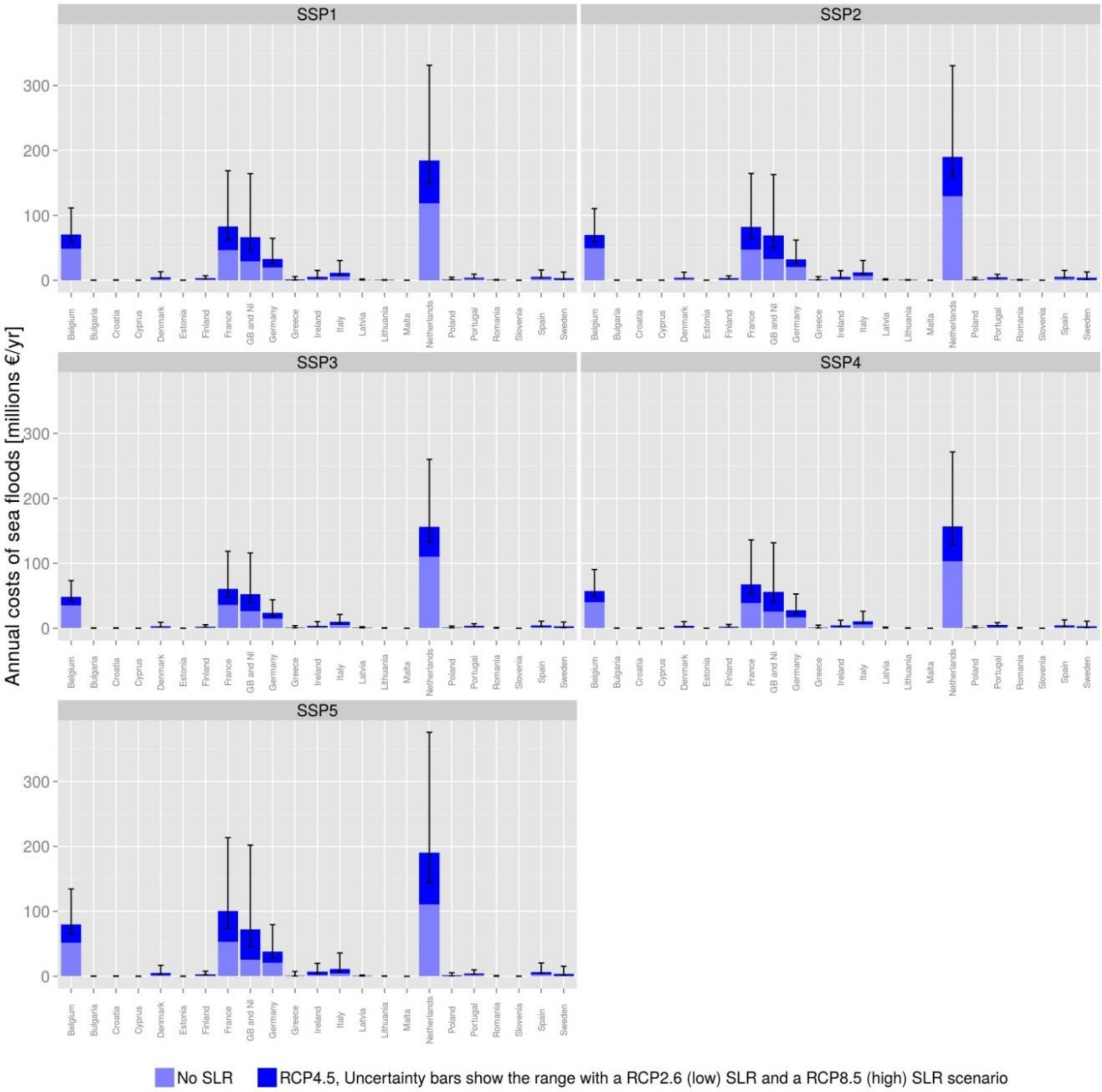

Figure 17. Annual costs of sea floods per EU country for each SSP scenario in the 2080s. The dark blue bar indicates a RCP4.5 mid scenario, with uncertainty bars showing the range of impacts with low (RCP2.6 low) and high (RCP8.5) scenario. A scenario of no sea-level rise is indicated for each country by the lighter blue bar.

Table 7 lists those countries that would most benefit from climate mitigation. With a few exceptions, it is generally the small economies, some of whom are very dependent on their coastal zones to generate incomes that would most benefit. Those that would least benefit from climate mitigation are in western Europe (France, Belgium, Germany, Netherlands, Portugal). These countries typically experience the greatest sea flood costs as they have long and/or low-lying coasts. Consequently planning for climate change, come what may, is extremely important for these countries.

Table 7. EU countries that will benefit most in relative terms from climate mitigation, for annual sea flood costs. Where several countries are listed, they share the same mitigation benefit.

	SSP1	SSP2	SSP3	SSP4	SSP5
1	Slovenia	Malta	Malta	Malta	Malta
2	Malta	Cyprus	Cyprus	Slovenia	Cyprus
3	Cyprus	Slovenia	Sweden	Sweden	Slovenia
4	Greece	Sweden	Slovenia	Greece	Greece
5	Bulgaria	Greece, Croatia	Greece	Croatia	Bulgaria

6.2 Annual sea dike costs

Figure 18 illustrates the annual dike costs for EU countries. It illustrates the potential impact in the 2080s, with a RCP4.5 (med) value, and then the upper (RCP8.5 high) and lower levels (RCP2.6 low) of projected impacts, indicated by the uncertainty bars. A scenario of no sea-level rise is shown by a light blue bar, indicating socio-economic and land level change only. Across all scenarios, the greatest costs (in terms of absolute numbers) occur in Denmark, France, Germany, Great Britain and Northern Ireland and Ireland. Many of these countries have coastline surrounding the North Sea. These coasts tend to be low-lying or comprised of erodible sediment, and hence would result in high costs of protection (McFadden et al. 2006). Across all socio-economic scenarios for RCP 4.5 (med), the highest costs per km of protection are found in Belgium and Germany, and the lowest costs in Sweden and Slovenia. The median cost across all scenarios in the 2080s for the RCP 4.5 (median) scenario is €15,300 per annum. Additionally, the costs of maintaining dikes need to be considered, which for some countries could be at least twice as much as capital costs per year (see Section 7.2.2.1).

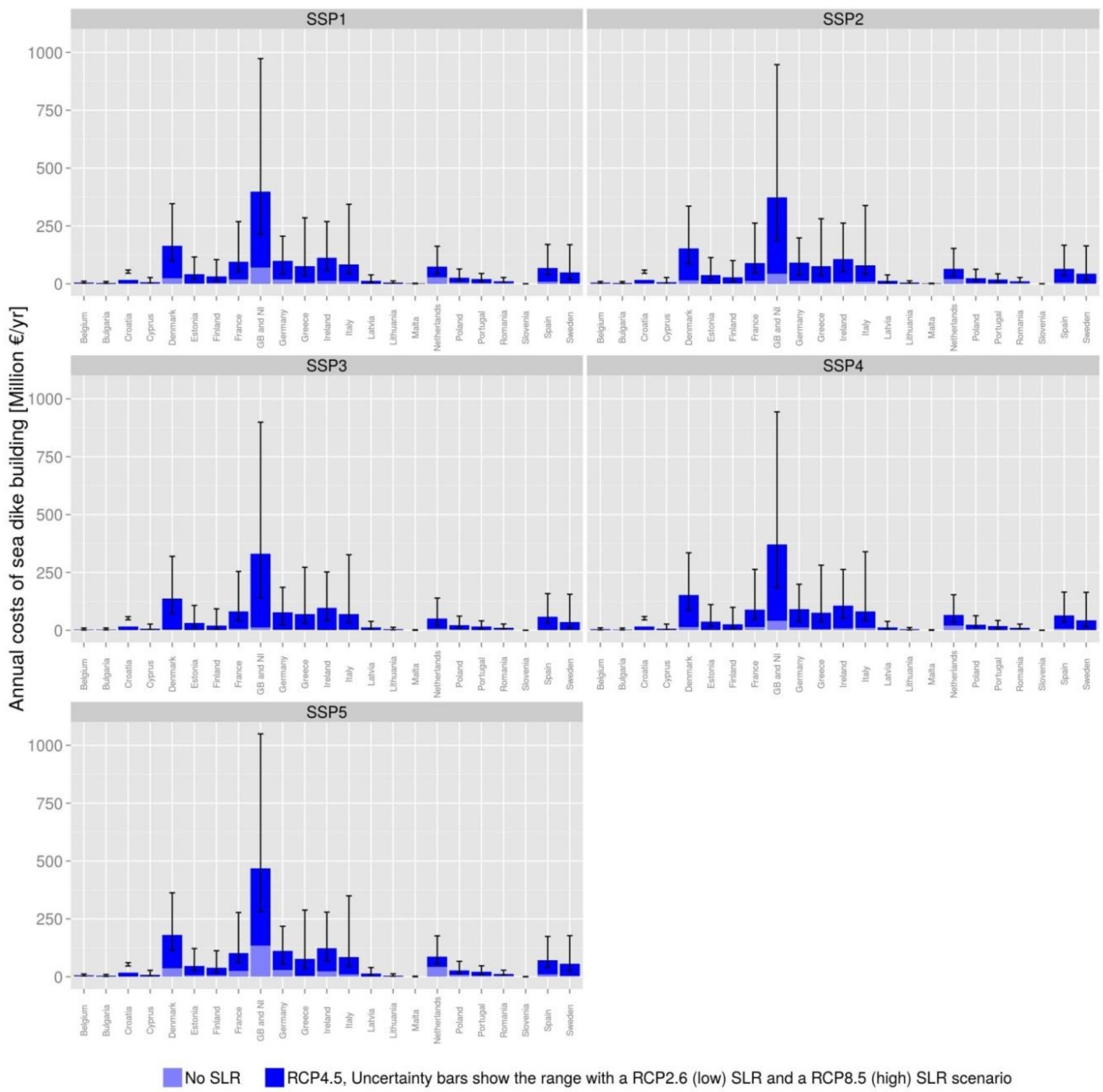

Figure 18. Annual costs of building sea dikes per EU country for each SSP scenario in the 2080s. The dark blue bar indicates a RCP4.5 mid scenario, with uncertainty bars showing the range of impacts with low (RCP2.6 low) and high (RCP8.5) scenario. A scenario of no sea-level rise is indicated for each country by the lighter blue bar.

The countries that will benefit most from climate mitigation, in terms of relative change are listed in Table 8. Sweden (up to 93%) and Greece (up to 89%) again have some of the greatest benefits of mitigation for reducing the costs of dike building to protect against relative sea-level rise. Reducing the costs of dike building is also important for the EU's island nations of Cyprus and Malta. Those countries which benefit least from climate mitigation in monetary terms tend to benefit more from a reduction in the expected number of people flooded annually, such as Lithuania, Croatia and Poland.

Table 8. EU countries that will benefit most in relative terms from climate mitigation, for the annual costs of building sea dikes.

	SSP1	SSP2	SSP3	SSP4	SSP5
1	Sweden	Sweden	Sweden	Sweden	Greece
2	Greece	Finland	Finland	Finland	Italy
3	Italy	Italy	Italy	Greece	Sweden
4	Finland	Greece	Greece	Italy	Cyprus
5	Cyprus	Cyprus	Estonia	Cyprus	Malta

7. Discussion

7.1 Climate change mitigation: What does living in a 2°C world mean?

These results show that after adaptation policies, the magnitude of sea-level rise is the next greater factor affecting the magnitude of impacts, followed by socio-economic change. Due to the commitment to sea-level rise, a 2°C world can mean many things. Firstly, it may mean a world where 2°C is reached by the 2030s and where temperatures continue to rise, resulting in rapidly growing costs in order to maintain or increase protection levels. Secondly, it could represent a world where costs due to building dikes and residual flood events rise more slowly. Thirdly, a 2°C world could represent a world where temperatures are stablised, and although sea-levels are still increasing, it is at a much slower rate, leading to a reduction in the additional costs of dike building or increasing the heights of existing dikes. In all of these worlds, due to the investment in defences and raising standards of protection, the expected number of people flooded decreases to lower levels than seen today. This is particularly acute under the climate mitigation scenario as sea-levels rise at a lower rate, yet wealth is maintained or increases. Thus investment in coastal adaptation (in the cases modelled here, hard protection) is key to maintaining flood risk and therefore a confident, strong coastal economy.

As with many impact studies, much focus and uncertainty is given to the climate change scenarios and specific emissions pathways. Additional attention needs to be brought for the magnitude of ice melt, which for the RCP8.5 (and similarly for high scenarios not presented here) could represent a step-change in the costs of dike building and flooding, rather than maintaining or decreasing costs as seen in other scenarios. Since there is already much investment in coastal zones, the magnitude of sea-level rise can become very important, more so than socio-economic change. Socio-economical change becomes more important for sea flood costs as the population declines, and whilst GDP is maintained or has low growth. The continued growth in GDP/capita is also important for projections of the expected number of people flooded, as without an increase in capita wealth, relative defence standards decline (as there is less money to invest) leading to a greater number of people at risk.

One factor not considered in this report is the cost of climate mitigation itself. Developed countries, including those in Europe have an important role to play in climate mitigation since they have the financial ability to change their emissions, such as through greater efficiency in fuel use, or a change to renewable energy resources. However investing in new and emerging technologies shift finances away from other sectors, particularly in the short term where set up costs may be high. This could lead to overall reduction in a nation's GDP (Tavoni and Tol 2010). For instance, with an associated reduction in GDP for achieving a CO_2 stabilisation scenario (concentration of 550ppm by 2100), Tol (2007) found that economic growth was reduced. Less money may be spent on adaptation, leading to a reduction in avoided impacts: A maximum of 25% for dryland loss and 20% for wetlands. Thus there remains a careful balance between mitigation and adaptation.

As the results demonstrate, the benefits of mitigation with respect to SLR will not be felt substantially until the latter part of the century. By this time, many adverse impacts, including those generated due to other climatic changes (e.g. temperature), may have already started to occur. Whilst adaptation can protect people where it is possible and affordable to do so, the natural environment is highly threatened as it may not be able to respond at a fast enough pace to cope with rising sea-levels, so mitigation then becomes extremely important. This includes low-lying wetlands, which could be subject to permanent inundation. Maintaining wetlands is particularly important as they provide dual benefits for adaptation (as they attenuate wave energy, thus protecting coastline and help retain sediment, and are cheaper and more cost-effective as a means of defence compared with hard adaptation) and mitigation (as they absorb and store carbon). Climate change mitigation also has important implications for other sectors, including river basins, forestry, agriculture and the built environment.

7.2 Climate change adaptation: Managing a rise in global mean temperature and sea-levels.

7.2.1 Shoreline management

Section 6 indicated that policies of coastal zone adaptation to climatic change have a greater effect on the costs and impacts of sea-level rise than the magnitude of sea-level rise itself. These results indicate that as sea-levels rise, society is becoming more risk adverse as protection standards are raised as population and wealth also increases. In the modelling used, it is assumed that this happens instantaneously, but in reality defence stocks are upgraded periodically, planning many years (often decades) into the future. Consequently costs may rise faster than projected here. It is therefore essential from a European perspective that Integrated Coastal Zone Management is maintained, taking into account multiple drivers or change, and set in broad and flexible policy framework.

Even with climate change adaptation and upgrades to protection, some residual damages would be expected as protection may not have been built to anticipate the most extreme events, such as seen in Cyclone Xynthia, France (2010) or the UK coastal storms (2013-14). In the latter example, repeated storm events washed away beach material, exposing coastal protection structures leaving them vulnerable to damage or collapse (BBC, 2014; Wadey et al. 2015). Events such as these may catch scientists, engineers and planners by surprise; the type or sequence of event may not have been anticipated or planned for, coastal protection structures did not work as expected, or more predictably, protection standards may be lower than required, such as in rural areas, through limited funding, or local choice. Given that extreme events do result in unexpected damage, equally as important to defending the coast are the contingency plans to cope with floods when they occur. For example, in response to the extreme weather conditions in 2013-14, the UK had frequent emergency planning meetings, and where damage did occur, engineering response was rapid: At Dawlish sea wall, south-west England where train track was lost, recovery started within 4 hours despite continued storm conditions (Total Rail Solutions 2015). Over the following year, a further €11.2 million (£8m) has been spent on increasing the sea wall's resilience by raising and strengthening the wall. The longer term implications of having major transport routes located adjacent to sea walls also requires debate as to whether continuing strengthening and increasing the height of sea wall is viable, or to manage realign sites rerouting the train track inland.

7.2.2 Coastal adaptation

The impact and cost projections assume that adaptation to sea-level rise will occur. Adaptation is defined as the planned or unplanned, reactive or anticipatory, successful or unsuccessful response of a system to a change in its environment (Klein et al., 2001; Linham and Nicholls, 2010; Tol et al., 2008). Without adaptation, flood costs and the expected number of people flooded significantly increase (Hinkel et al. 2014) and these costs are greater than the costs of inaction. This is supported by previous studies (e.g. Wong et al., 2014; Nicholls, 2011), that state whilst mitigation can help reduce to rate of sea-level rise, adaptation can reduce local impacts.

The results generated in this report focus on building sea dikes as a means of protection. Other forms of protection exist, including soft defences. Additionally, two other methods of adaptation could reduce the risk of sea-level rise: Accommodation and retreat (Figure 19). Retreat involves the deliberate inaction or realignment of the coast to make space for water. Accommodation includes methods that mean population remains in vulnerable areas, but undertake local adjustments to reduce flood risk, such as raising buildings, insurance or flood proof buildings. These have not been modelled due to lack of available data, but are likely to become more prominent in the future. Each of these three methods will be discussed in turn.

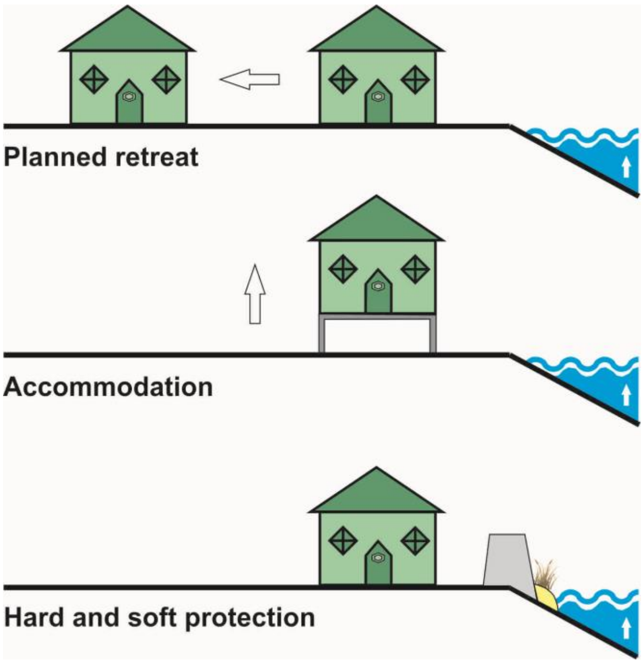

Figure 19. Retreat, accommodation and protection as forms of adaptation (adapted from Brown et al. 2013).

7.2.2.1 Protection

Protection is divided into hard and soft retreat. Hard defence includes traditional coastal engineering structures that have greater permanency than hard structures, such as dikes, groynes, seawalls, dikes and breakwaters. Soft defence are more movable, often having a shorter duration, and complement the landscape, by working with nature. It includes beach nourishment, dune building and wetland recreation.

Approximately 7.5% of the EU coast is defended (in 2001 (excludes Croatia) extracted from Eurosion (2004)). Dikes and other hard structures were traditionally more favourable as defence, and also provided the public with confidence against erosion and flooding as they could see a solid barrier between land and sea. However, whilst effective, they can induce other, sometimes unforeseen problems. For example, the coastline of Norfolk, UK comprises of a large groyne field wooden revetments constructed parallel in from of the cliff during the 1950s and 1960s, with seawalls protecting low-lying areas. The cliffs previously eroding at approximately 0.5m/yr, supplying the beach with sediment. Over many decades beach levels started to lower due to a sediment deficit. Subsequently the flood-prone low-lying down-drift coast became more susceptible to flooding. Hence building hard defences can reduce erosion risk, but can result in an increased flood risk elsewhere (Dawson et al. 2009). Other studies also describe the effects of groynes and sea walls on the coastal landscape. At Ofir-Apúlia, north-west Portugal, Granja and Carvalho (1991, 1995) describe how after the construction of groynes and revetments to protect against coastline retreat, severe erosion increased on the down-drift coast threatening infrastructure, including tourist properties. Subsequently the defence was extended. This again pushed the problems of excess erosion onto the down-drift coast. Sea walls also induce similar issues, known as end effects. This is where sea walls reflect and diffract waves, leading to scour, which can potential undermine the sea wall (Griggs et al., 1990; Tait and Griggs, 1990; Griggs 2005). On the island of Sylt, Germany, end effects have resulted in progressive extensions of the sea wall (Dette and Gärtner, 1987). Sand nourishment has also been a major defence strategy, which is beneficial as it does not produce down-drift erosion effects on Sylt. However, one disadvantage is that the beach requires maintenance and top ups (Jensen and Schwarzer, 2013). Therefore, the building of new hard defences needs to be treated with care as it can induce a legacy of other issues.

Additionally, to maintain efficiency, defences required regular maintenance. For sea dikes, following a review of common practise, this was determined to be 1% of capital costs per annum (Nicholls et al. 2010). Over time, the maintenance of dikes can be more costly that capital costs (Figure 20). The figure illustrates that in the present timeframe, maintenance costs are on average across all scenarios €5.0 million per annum, and have the potential to increase up to €7.1 million per annum by the 2080s. Unlike the capital costs of dike building, maintenance costs continue to increase even under a scenario of climate mitigation. Therefore with hard defences, such as dikes, there is a commitment to maintenance costs over the long-term.

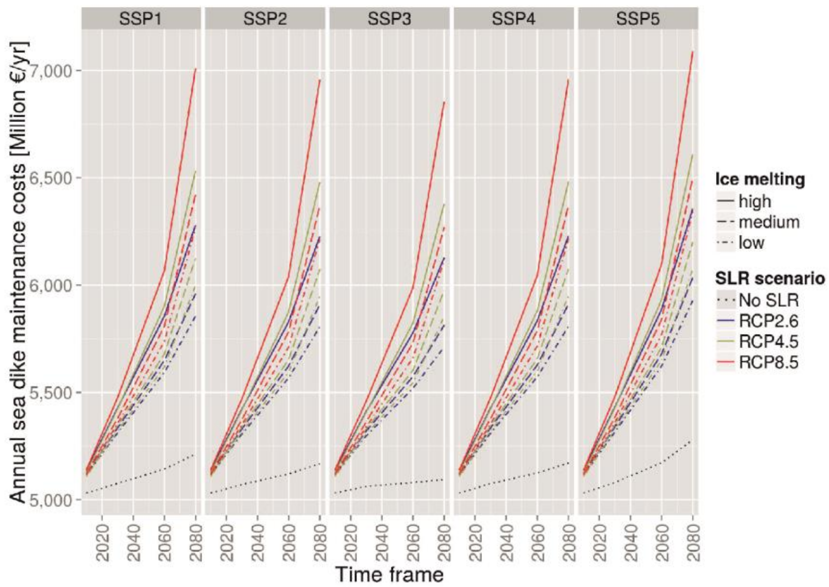

Figure 20. Annual costs of the maintenance of sea dikes in EU countries due to sea-level rise and socio-economic change for HadGEM2-ES, plotted against timeframe.

Another form of protection is beach nourishment. This is considered in the DIVA model to reduce erosion risk. Beach nourishment is commonly undertaken in places were tourism is a major economy, and so it follows too in the DIVA model. Annual costs of beach nourishment are shown in Figure 21. In the 2010s, model projections suggest that beach nourishment costs between 6% and 7% of capital dike costs, but by the 2080s could increase to between 8% and 31% of capital dike costs. This sharp increase of costs is due to the increased unit cost of sediment, which is linked to a nation's GDP. Hence beach nourishment is more sensitive to economic conditions than dike building. Countries which are projected to have high nourishment costs per km include Germany and Portugal, whilst those with the lowest unit costs include Lithuania and Spain. As a proportion of sea dike costs in the 2080s, Germany, Netherlands, Belgium and France are projected to spend the greatest amount out of EU countries on beach nourishment. This is probably because these coasts are low lying and prone to erosion. Beach nourishment is projected to have a much lower proportion of costs in countries dominated in cliffed and hard-rock environment, including Greece and Ireland.

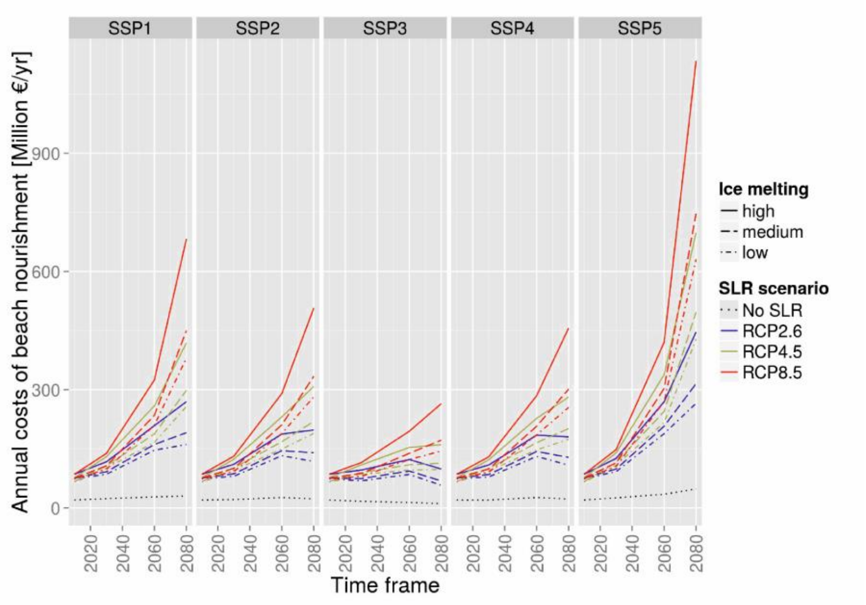

Figure 21. Annual costs of beach nourishment in EU countries due to sea-level rise and socio-economic change for HadGEM2-ES, plotted against timeframe.

Best scientific and engineering practices relating to beach nourishment are still developing, for instance, where the optimum location is for placing dredged material and also the volume of sediment. Nourishment requires periodic upgrade to maintain beach levels as sand is subject to cross-shore and longshore drift. For example, in Poole Bay, UK the beach has been nourished in 1974/75, 1988/89 and 2005/06/07 (May, 1990; SCOPAC, 2005; Borough of Poole, 2008). As the understanding of local coastal processes improve, the scheme is becoming more effective as dredged material is locally sourced and dredged volumes have increased. The Dutch are moving on from this practice of period nourishment, instead focusing on a very large single nourishment known as a sand engine. This fundamental change to managing the Dutch coast involves a 21.5Mm^3 nourishment scheme that over many decades they anticipate will be more economical and environmentally friendly. The sand engine aims to protect a 10km to 20km stretch of coast over the next two decades by increasing the beach area by 200 hectares (Stive et al. 2013). If successful and appropriate on other coasts, other countries may follow suit. Given the increase emphasis and shift to soft engineering schemes, global sand availability is likely to become more competitive.

7.2.2.2 Accommodation

Policies of accommodation involve remaining in vulnerable coastal areas, but increasing the ability to cope with an extreme event (de Graaf et al., 2007; Linham and Nicholls, 2010). Land use management options could include flood proofing (e.g. elevated buildings, sealing walls with waterproof coatings), additional insurance, monitoring stations, or planning of emergency evacuation routes (Linham and Nicholls, 2010). An example of accommodation is in Germany, where Hamburg's 157 hectare HafenCity district, situated on the Elbe has been created since 2000 by rising all new buildings by 8m-9m, and roads and bridges by at least 7.5m above mean sea-levels (HafenCity Hamburg GmbH, 2013). As a multi-purpose residential, work, tourism and shopping area, there is green space and walkways with direct access, water is integrated into the city functioning, boosting the economy, ecology and the environment. Even though it is not protected by dikes, in an extreme event combined with rising sea-levels, the district will continue to function.

Accommodation of sea-level rise and associated storm surges has also been considered in the Danish Metro system (Climate-ADAPT, 2015). Critical elements of the infrastructure, such as stairs, ventilation tunnels or maintenance areas on newly constructed metro lines have been raised 0.25m above the existing level on older lines. Accommodation also includes raised doorsteps to essential areas, waterproofing walls and protecting stations from back flow of sewage in times of flood. Key to the success of implementing improvements have been the involvement of stakeholders and the early integration of accommodation strategies in the construction of the metro line.

In these case studies, the vision is to invest now in successful, long term land use adaptation policies, so to prevent excess expenses in the long term. While rising sea-levels are not the sole reason for adaptation, it can be the catalyst for the adoption of multi-purpose planning, integrating multiple needs with a long-term economic, ecological and sustainable vision. Regeneration of land-use can therefore bring new opportunities to the cityscape.

7.2.2.3 Retreat

More common in rural environments, planned retreat includes managed realignment (also known as de-embankment) and regulated tidal exchange. Managed realignment involves the deliberate breaching or removal of existing defences allowing the land behind to be inundated and revert to natural inter-tidal conditions. Regulated tidal exchange using controls such as sluice gates, spillways, culverts or pipes to control water levels (ABPmer, 2015a,b) and encourages intertidal habitat creation. ABPmer (2015c) records around 100 managed realignment schemes in Europe, with approximately half in the UK and one quarter in Germany. Retreat has occurred when other defences become engineering more challenging (on site or elsewhere) or costly to implement, or to improve biodiversity. At times controversial, realigning defences means sacrificing smaller, less built up areas, for the larger benefits of society as flood risk is reduced over a wider zone.

For some nations, retreat is part of a larger scheme of protection. For example, in the Netherlands, €2.3 billion 'Room for the River' programme aims, between 2006 and 2015, to give space for the Rhine river (whose high discharges are anticipated to increase in frequency) to improve flood safely whilst increasing all-round environmental quality (boosting economic, ecological and scenic values). Setting back the dikes landward, reinstating the natural floodplain, long-term depolderising, storage and flood by-passing have or are planned to be increased (Dutch Government, 2006). Continued monitoring and maintenance of structures is required to ensure protection levels are maintained as climatic conditions (not just sea-level rise) and other environmental factors change.

7.3 Planning for sea-level rise in a 2°C, 3°C and 5°C world

The results from IMPACT2C indicate that the benefits of mitigation become increasingly important throughout the 21st century as the magnitude of sea-level rise diverges under different emissions scenarios. However, in the intermediate term, adaptation can reduce potential damages (Wong et al. 2014; Nicholls 2011). Planning for climate change, sea-level rise and subsequent adaptation is increasingly important as nations strive to reduce costs and damages for extreme weather events today. Awareness in the causes of climate change and sea-level rise, plus ways to mitigate has increased in recent years. European nations have improved policy in place to reduce greenhouse gas emissions and some undertake Climate Change Risk Assessments (e.g. HM Government, 2012). However, there are still many uncertainties with regard to mitigation, and improved policies encouraging mitigation are required at international, national and local levels.

Climate mitigation remains an important process to reduce sea-level rise in the long-term as defences, in their present form, cannot be relied upon into the 22nd century and beyond. Mitigation is particularly important to reduce the likelihood of very high rises in sea-level, such as those associated with in an increase in ice sheet dynamics (Wong et al. 2014).

Maintaining and upgrading adaptation remains a key part of the coastal planners' toolkit to reduce the impacts and costs of sea-level rise. By planning ahead, costs can be reduced and impacts avoided (e.g. Nicholls et al. 2010). As our knowledge of the natural environment and it social-physical interlinkages increases, long-term shoreline management planning and climate change adaptation will evolve to take in the numerous processes and policies affecting the coastal zone. Additionally, recent research into the dual benefits of adaptation and mitigation (e.g Berry et al. 2015), help highlights where potential gains may be made that best benefit the wider environment.

This research asserts that both short and long-term adaptation policies augmented with integrated shoreline management planning will be beneficial, even under a scenario of climate mitigation. Planning and adaptation is a matter of choice. At present, many European countries do not have an overall shoreline management plan (e.g. the Republic of Ireland has no overall coastal management policy, but government departments are responsible for managing the coast either side of mean high water (O'Connor et al. 2009)), but coastal climate change adaptation planning is started to emerge (such as demonstrated in the EU THESEUS project e.g. Hissel et al. 2015; Trifonova et al. 2015). Planning and adaptation policies may be implemented at local (e.g. town), regional (e.g. sediment cell / regional government), national and international levels. Past changes in shoreline management have often been instigated by extreme events causing much damage and/or loss of life, thus opening a period of opportunity (policy window) to analyses causes, impacts and to instigate change (Hall et al. 2012). The challenge for Europe is to make coastal communities catalysts of change in climate change adaptation and shoreline management planning, including a wide range of adaptation, before an extreme event occurs, whilst maintaining environmental quality and social needs.

8. Conclusions

This research set out to answer the question 'What will the impacts and costs of sea-level rise around Europe in a 2°C world?'. Answering this has been challenging due to multiple uncertainties and complexities.

Firstly, despite climate mitigation promising to reduce global mean temperatures, this does not translate into an immediate decrease in global mean sea-levels, as due to the commitment to sea-level rise, a reduction in the rate of sea-level rise could take many decades. Using one climate model (HadGEM2-ES) as an example, sea-level rise in a 2°C world could range from 0.11m (in the 2030s under a high emissions RCP8.5 scenario) to 0.46m (in the 2080s under a climate mitigation scenario, RCP2.6), and could raise further into the 22nd century.

Secondly, this creates uncertainties in adaptation modelling. Results indicate, assuming that present day adaptive measures such as dikes are raised with sea-level rise, the expected number of people at risk from flooding annually in the EU could between 5,300 and 7,000 people per year, largely in the low-lying countries surrounding the North Sea. A climate mitigation (2°C) scenario compared with a high emissions (5°C) scenario could reduce the effective number of people flooded annually by 50%. Annual sea flood costs are expected to increase with sea-level rise, with a step change in costings with flooding associated with a high-end scenarios. Increasingly, sea-level rise would be responsible for these costs, rather than land subsidence. Climate mitigation is projected to reduce sea flood costs by greater than 50%. The benefits of climate mitigation are mostly likely to be felt by the EU's smaller economies and small island nations, such as Cyprus and Malta.

Thirdly, there is uncertainty in how we adapt to sea-level rise. The methodology used assumes that following present day practices, hard adaptation measures such as sea dikes will continue an important method to reduce impacts. The cost of hard protection (projected to be €3.9 billion / year for a high emissions scenario, reducing more than six fold under a 2°C climate mitigation scenario) could continue to increase throughout time due to maintenance costs. However, costs of climate change adaptation could also reduce if alternative approaches of sand nourishment, accommodation of key infrastructure to sea-level rise or selective managed realignment were considered.

This study concludes that the quantification of impacts, costs and adaptation remain highly uncertain. Apart from depending of known science and plausible future of greenhouse gas emissions, it also largely depends on decision making and the potential and willingness for nations to adapt. Adaptation is a key measure to ensure a safe coast in the future, as the benefits of climate mitigation may be many decades away, and cannot be relied upon to reduce risk. The challenge now is determining how best to respond to ensure a safe, sustainable less risky coast in the future, taking a full range of potential future sea-level rise. Having a tool kit of options to account for all uncertainties and multiple drivers of change is advantageous. This includes a range of engineering measures, but also being aware of risk levels and social acceptability.

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10. Appendix 1: Tables of results.

10.1 HadGEM2-ES

Expected number of people flooded annually

Table A1.1 Expected number of people flooded annually in the EU, for HadGEM2-ES and SSP1 (thousands / yr, 2dp).

HadGEM2-ES	2010s	2030s	2060s	2080s
RCP8.5 (high)	8.21	7.05	6.33	5.25
RCP8.5 (med)	7.96	6.41	5.18	3.47
RCP8.5 (low)	7.91	6.29	4.89	3.10
RCP4.5 (high)	7.95	6.57	5.39	3.38
RCP4.5 (med)	7.71	6.00	4.59	2.62
RCP4.5 (low)	7.66	5.85	4.39	2.40
RCP2.6 (high)	8.21	6.51	4.92	2.55
RCP2.6 (med)	7.93	5.95	4.36	2.16
RCP2.6 (low)	7.89	5.78	4.21	2.02
No SLR	6.47	4.90	3.07	1.52

Table A1.2 Expected number of people flooded annually in the EU, for HadGEM2-ES and SSP2 (thousands / yr, 2dp).

HadGEM2-ES	2010s	2030s	2060s	2080s
RCP8.5 (high)	8.20	7.05	6.80	6.61
RCP8.5 (med)	7.96	6.43	5.58	4.47
RCP8.5 (low)	7.91	6.28	5.28	3.99
RCP4.5 (high)	7.95	6.59	5.84	4.32
RCP4.5 (med)	7.70	6.00	4.96	3.37
RCP4.5 (low)	7.66	5.83	4.73	3.13
RCP2.6 (high)	8.21	6.53	5.31	3.34
RCP2.6 (med)	7.93	5.96	4.71	2.85
RCP2.6 (low)	8.21	6.53	5.31	3.34
No SLR	6.47	4.92	3.34	2.05

Table A1.3 Expected number of people flooded annually in the EU, for HadGEM2-ES and SSP3 (thousands / yr, 2dp).

HadGEM2-ES	2010s	2030s	2060s	2080s
RCP8.5 (high)	8.19	6.67	6.50	6.37
RCP8.5 (med)	7.94	6.10	5.38	4.38
RCP8.5 (low)	7.89	5.96	5.07	3.93
RCP4.5 (high)	7.93	6.23	5.60	4.23
RCP4.5 (med)	7.69	5.66	4.78	3.37
RCP4.5 (low)	7.64	5.49	4.55	3.10
RCP2.6 (high)	8.19	6.16	5.11	3.35
RCP2.6 (med)	7.92	5.61	4.52	2.86
RCP2.6 (low)	7.87	5.44	4.31	2.70
No SLR	6.46	4.66	3.21	2.11

Table A1.4 Expected number of people flooded annually in the EU, for HadGEM2-ES and SSP4 (thousands / yr, 2dp).

HadGEM2-ES	2010s	2030s	2060s	2080s
RCP8.5 (high)	85.41	129.50	284.80	456.41
RCP8.5 (med)	76.00	98.79	207.21	301.43
RCP8.5 (low)	73.83	90.52	185.35	255.01
RCP4.5 (high)	76.57	122.13	227.25	281.38
RCP4.5 (med)	67.25	100.25	165.46	201.30
RCP4.5 (low)	65.12	94.35	147.20	173.77
RCP2.6 (high)	85.38	108.91	184.72	180.18
RCP2.6 (med)	75.79	84.62	143.20	128.17
RCP2.6 (low)	73.75	78.53	130.72	108.46
No SLR	19.91	19.78	26.52	22.49

Table A1.5 Expected number of people flooded annually in the EU, for HadGEM2-ES and SSP5 (thousands / yr, 2dp).

HadGEM2-ES	2010s	2030s	2060s	2080s
RCP8.5 (high)	85.41	148.03	420.05	1134.28
RCP8.5 (med)	76.00	114.39	303.35	746.62
RCP8.5 (low)	73.83	105.32	270.26	630.54
RCP4.5 (high)	76.57	139.80	337.86	698.38
RCP4.5 (med)	67.25	115.28	244.49	496.90
RCP4.5 (low)	65.12	108.66	216.47	428.13
RCP2.6 (high)	85.38	125.71	269.19	446.33
RCP2.6 (med)	75.79	98.80	207.26	315.26
RCP2.6 (low)	73.75	92.03	188.49	265.42
No SLR	19.91	25.57	34.58	48.12

Annual sea flood costs

Table A1.6 Annual costs of sea floods in the EU, for HadGEM2-ES and SSP1 (millions € / yr, 2dp).

HadGEM2-ES	2010s	2030s	2060s	2080s
RCP8.5 (high)	489.67	538.20	723.12	958.29
RCP8.5 (med)	475.43	492.01	593.80	635.36
RCP8.5 (low)	472.95	484.29	561.60	568.79
RCP4.5 (high)	472.33	499.77	619.31	614.47
RCP4.5 (med)	458.99	458.22	529.06	476.93
RCP4.5 (low)	456.83	447.57	505.97	436.95
RCP2.6 (high)	489.77	499.54	564.55	463.48
RCP2.6 (med)	474.04	457.85	502.07	394.99
RCP2.6 (low)	471.57	445.53	485.97	369.64
No SLR	386.28	377.58	350.72	277.67

Table A1.7 Annual costs of sea floods in the EU, for HadGEM2-ES and SSP2 (millions € / yr, 2dp).

HadGEM2-ES	2010s	2030s	2060s	2080s
RCP8.5 (high)	489.67	526.77	698.83	946.82
RCP8.5 (med)	475.43	483.93	577.12	647.04
RCP8.5 (low)	472.95	473.45	546.30	578.11
RCP4.5 (high)	472.33	491.37	602.67	620.77
RCP4.5 (med)	458.99	449.19	514.41	485.89
RCP4.5 (low)	456.83	436.99	491.13	452.72
RCP2.6 (high)	489.77	489.91	548.89	482.39
RCP2.6 (med)	474.04	449.27	488.73	413.28
RCP2.6 (low)	471.57	436.23	468.23	387.39
No SLR	386.28	371.67	344.65	296.13

Table A1.8 Annual costs of sea floods in the EU, for HadGEM2-ES and SSP3 (millions € / yr, 2dp).

HadGEM2-ES	2010s	2030s	2060s	2080s
RCP8.5 (high)	489.67	492.86	583.01	698.25
RCP8.5 (med)	475.43	453.67	486.64	486.82
RCP8.5 (low)	472.95	444.20	459.52	438.67
RCP4.5 (high)	472.33	459.29	504.85	466.86
RCP4.5 (med)	458.99	419.22	433.51	375.07
RCP4.5 (low)	456.83	406.69	413.99	345.82
RCP2.6 (high)	489.77	456.07	462.52	373.17
RCP2.6 (med)	474.04	417.62	410.00	319.71
RCP2.6 (low)	471.57	405.27	391.75	302.46
No SLR	386.28	349.04	292.03	236.33

Table A1.9 Annual costs of sea floods in the EU, for HadGEM2-ES and SSP4 (millions € / yr, 2dp).

HadGEM2-ES	2010s	2030s	2060s	2080s
RCP8.5 (high)	489.67	518.13	635.48	782.27
RCP8.5 (med)	475.43	473.60	525.12	527.46
RCP8.5 (low)	472.95	465.22	498.30	474.21
RCP4.5 (high)	472.33	481.60	547.77	510.73
RCP4.5 (med)	458.99	441.97	467.72	401.58
RCP4.5 (low)	456.83	429.33	448.41	369.47
RCP2.6 (high)	489.77	480.90	500.32	393.34
RCP2.6 (med)	474.04	439.19	445.39	336.93
RCP2.6 (low)	471.57	425.77	429.11	315.12
No SLR	386.28	363.59	312.33	240.15

Table A1.10 Annual costs of sea floods in the EU, for HadGEM2-ES and SSP5 (millions € / yr, 2dp).

HadGEM2-ES	2010s	2030s	2060s	2080s
RCP8.5 (high)	489.67	565.54	820.09	1148.58
RCP8.5 (med)	475.43	520.41	667.47	727.05
RCP8.5 (low)	472.95	505.17	633.85	636.80
RCP4.5 (high)	472.33	525.89	706.00	696.62
RCP4.5 (med)	458.99	480.59	601.16	524.80
RCP4.5 (low)	456.83	470.94	572.02	473.55
RCP2.6 (high)	489.77	526.21	639.27	500.48
RCP2.6 (med)	474.04	482.73	567.39	413.99
RCP2.6 (low)	471.57	468.62	547.95	384.75
No SLR	386.28	395.18	390.92	276.97

Annual sea dike costs

Table A1.11 Annual costs of sea dikes in the EU, for HadGEM2-ES and SSP1 (millions € / yr, 2dp).

HadGEM2-ES	2010s	2030s	2060s	2080s
RCP8.5 (high)	1276.72	1584.25	2532.47	3698.43
RCP8.5 (med)	1095.67	1227.35	1796.61	2207.13
RCP8.5 (low)	1059.65	1127.78	1551.44	1834.15
RCP4.5 (high)	1148.84	1435.05	2027.12	2054.55
RCP4.5 (med)	979.61	1100.18	1423.23	1401.03
RCP4.5 (low)	946.85	1014.60	1212.08	1212.02
RCP2.6 (high)	1224.14	1397.27	1615.67	1254.55
RCP2.6 (med)	1073.31	1047.26	1147.89	915.70
RCP2.6 (low)	1042.02	932.72	984.75	787.61
No SLR	322.10	219.72	249.95	219.06

Table A1.12 Annual costs of sea dikes in the EU, for HadGEM2-ES and SSP2 (millions € / yr, 2dp).

HadGEM2-ES	2010s	2030s	2060s	2080s
RCP8.5 (high)	1277.19	1537.51	2450.04	3602.36
RCP8.5 (med)	1096.12	1180.88	1714.20	2115.13
RCP8.5 (low)	1060.10	1082.04	1468.88	1743.29
RCP4.5 (high)	1149.31	1388.41	1944.93	1962.03
RCP4.5 (med)	980.06	1054.66	1340.95	1312.07
RCP4.5 (low)	947.30	969.34	1132.44	1124.23
RCP2.6 (high)	1224.61	1350.57	1533.62	1164.30
RCP2.6 (med)	1073.76	1001.11	1067.95	828.79
RCP2.6 (low)	1042.47	887.39	906.54	702.51
No SLR	322.40	177.28	178.56	145.47

Table A1.13 Annual costs of sea dikes in the EU, for HadGEM2-ES and SSP3 (millions € / yr, 2dp).

HadGEM2-ES	2010s	2030s	2060s	2080s
RCP8.5 (high)	1282.45	1440.37	2285.92	3437.44
RCP8.5 (med)	1101.24	1084.79	1550.38	1956.97
RCP8.5 (low)	1065.22	987.82	1305.53	1585.54
RCP4.5 (high)	1154.55	1291.52	1781.01	1803.95
RCP4.5 (med)	985.14	960.95	1178.86	1159.11
RCP4.5 (low)	952.38	876.08	975.40	977.88
RCP2.6 (high)	1229.84	1253.57	1370.89	1009.10
RCP2.6 (med)	1078.87	906.67	911.54	679.41
RCP2.6 (low)	1047.56	793.86	751.49	555.53
No SLR	325.81	98.76	59.48	44.40

Table A1.14 Annual costs of sea dikes in the EU, for HadGEM2-ES and SSP4 (millions € / yr, 2dp).

HadGEM2-ES	2010s	2030s	2060s	2080s
RCP8.5 (high)	1280.19	1559.31	2442.48	3593.48
RCP8.5 (med)	1099.05	1202.64	1706.80	2107.07
RCP8.5 (low)	1063.02	1103.35	1461.82	1735.40
RCP4.5 (high)	1152.30	1410.18	1937.15	1954.21
RCP4.5 (med)	982.97	1075.90	1333.76	1305.00
RCP4.5 (low)	950.20	990.49	1125.07	1117.65
RCP2.6 (high)	1227.59	1372.37	1526.10	1157.08
RCP2.6 (med)	1076.68	1022.84	1060.66	821.98
RCP2.6 (low)	1045.38	908.59	899.36	696.01
No SLR	324.46	198.06	173.28	143.47

Table A1.15 Annual costs of sea dikes in the EU, for HadGEM2-ES and SSP5 (millions € / yr, 2dp).

HadGEM2-ES	2010s	2030s	2060s	2080s
RCP8.5 (high)	1272.05	1636.39	2657.67	3881.23
RCP8.5 (med)	1091.11	1279.03	1920.76	2378.30
RCP8.5 (low)	1055.10	1179.14	1674.80	2002.16
RCP4.5 (high)	1144.18	1487.09	2151.56	2226.79
RCP4.5 (med)	975.07	1151.38	1546.29	1565.29
RCP4.5 (low)	942.33	1065.03	1333.87	1372.16
RCP2.6 (high)	1219.48	1449.35	1739.49	1420.89
RCP2.6 (med)	1068.77	1098.87	1268.99	1076.21
RCP2.6 (low)	1037.48	983.38	1103.15	942.63
No SLR	319.17	266.33	359.25	353.94

Annual sea dike maintenance costs

Table A1.16 Annual costs of maintaining sea dikes in the EU, for HadGEM2-ES and SSP1 (millions € / yr, 2dp).

HadGEM2-ES	2010s	2030s	2060s	2080s
RCP8.5 (high)	5139.12	5475.07	6066.04	7009.11
RCP8.5 (med)	5120.77	5378.67	5808.20	6421.98
RCP8.5 (low)	5117.26	5354.78	5737.02	6265.43
RCP4.5 (high)	5128.09	5423.55	5901.02	6531.81
RCP4.5 (med)	5111.54	5343.16	5678.33	6124.84
RCP4.5 (low)	5108.26	5320.51	5619.07	5999.03
RCP2.6 (high)	5137.54	5427.13	5855.13	6278.82
RCP2.6 (med)	5120.34	5334.78	5648.18	5959.57
RCP2.6 (low)	5117.10	5310.85	5592.67	5855.35
No SLR	5031.09	5075.76	5142.94	5212.78

Table A1.17 Annual costs of maintaining sea dikes in the EU, for HadGEM2-ES and SSP2 (millions € / yr, 2dp).

HadGEM2-ES	2010s	2030s	2060s	2080s
RCP8.5 (high)	5139.15	5469.67	6040.36	6956.03
RCP8.5 (med)	5120.80	5373.33	5782.69	6369.59
RCP8.5 (low)	5117.28	5349.55	5711.65	6213.26
RCP4.5 (high)	5128.11	5418.46	5875.44	6479.47
RCP4.5 (med)	5111.56	5338.29	5653.10	6073.17
RCP4.5 (low)	5108.29	5315.69	5594.37	5948.44
RCP2.6 (high)	5137.57	5421.80	5829.58	6226.65
RCP2.6 (med)	5120.36	5329.85	5623.28	5908.96
RCP2.6 (low)	5117.13	5306.09	5568.38	5805.92
No SLR	5031.10	5070.87	5120.10	5167.65

Table A1.18 Annual costs of maintaining sea dikes in the EU, for HadGEM2-ES and SSP3 (millions € / yr, 2dp).

HadGEM2-ES	2010s	2030s	2060s	2080s
RCP8.5 (high)	5139.41	5459.08	5988.29	6854.20
RCP8.5 (med)	5121.05	5362.99	5731.03	6269.24
RCP8.5 (low)	5117.54	5339.45	5660.74	6113.32
RCP4.5 (high)	5128.37	5408.65	5823.45	6379.18
RCP4.5 (med)	5111.82	5329.03	5602.52	5974.72
RCP4.5 (low)	5108.54	5306.55	5544.70	5852.83
RCP2.6 (high)	5137.83	5411.51	5777.79	6126.87
RCP2.6 (med)	5120.61	5320.52	5573.80	5813.23
RCP2.6 (low)	5117.38	5297.00	5519.76	5711.43
No SLR	5031.27	5062.11	5080.08	5094.65

Table A1.19 Annual costs of maintaining sea dikes in the EU, for HadGEM2-ES and SSP4 (millions € / yr, 2dp).

HadGEM2-ES	2010s	2030s	2060s	2080s
RCP8.5 (high)	5139.30	5474.58	6045.01	6958.11
RCP8.5 (med)	5120.94	5378.17	5787.32	6371.77
RCP8.5 (low)	5117.43	5354.28	5716.26	6215.49
RCP4.5 (high)	5128.26	5423.15	5880.00	6481.58
RCP4.5 (med)	5111.71	5342.82	5657.64	6075.42
RCP4.5 (low)	5108.43	5320.19	5598.83	5950.70
RCP2.6 (high)	5137.72	5426.66	5834.20	6228.98
RCP2.6 (med)	5120.50	5334.44	5627.91	5911.43
RCP2.6 (low)	5117.27	5310.55	5572.93	5808.35
No SLR	5031.20	5075.35	5124.69	5171.07

Table A1.20 Annual costs of maintaining sea dikes in the EU, for HadGEM2-ES and SSP5 (millions € / yr, 2dp).

HadGEM2-ES	2010s	2030s	2060s	2080s
RCP8.5 (high)	5138.89	5480.32	6098.45	7089.31
RCP8.5 (med)	5120.54	5383.85	5840.35	6500.13
RCP8.5 (low)	5117.03	5359.86	5769.01	6342.98
RCP4.5 (high)	5127.85	5428.44	5933.32	6610.15
RCP4.5 (med)	5111.31	5347.81	5710.24	6201.58
RCP4.5 (low)	5108.04	5325.07	5650.54	6074.62
RCP2.6 (high)	5137.31	5432.28	5887.37	6356.41
RCP2.6 (med)	5120.11	5339.55	5679.82	6035.34
RCP2.6 (low)	5116.88	5315.43	5623.53	5929.03
No SLR	5030.94	5080.55	5171.98	5279.91

Annual beach nourishment costs

Table A1.21 Annual costs of beach nourishment in the EU, for HadGEM2-ES and SSP1 (millions € / yr, 2dp).

HadGEM2-ES	2010s	2030s	2060s	2080s
RCP8.5 (high)	85.41	138.38	324.47	682.14
RCP8.5 (med)	76.00	106.56	235.05	449.93
RCP8.5 (low)	73.83	98.00	209.77	380.22
RCP4.5 (high)	76.57	130.02	258.90	418.65
RCP4.5 (med)	67.25	107.15	187.55	298.40
RCP4.5 (low)	65.12	100.98	166.31	257.30
RCP2.6 (high)	85.38	117.10	208.70	269.47
RCP2.6 (med)	75.79	91.78	160.90	191.02
RCP2.6 (low)	73.75	85.41	146.40	160.96
No SLR	19.91	23.46	28.01	30.08

Table A1.22 Annual costs of beach nourishment in the EU, for HadGEM2-ES and SSP2 (millions € / yr, 2dp).

HadGEM2-ES	2010s	2030s	2060s	2080s
RCP8.5 (high)	85.41	131.27	290.14	507.29
RCP8.5 (med)	76.00	100.53	211.00	333.95
RCP8.5 (low)	73.83	92.25	188.68	281.98
RCP4.5 (high)	76.57	123.59	230.97	308.46
RCP4.5 (med)	67.25	101.58	167.97	219.53
RCP4.5 (low)	65.12	95.65	149.33	189.10
RCP2.6 (high)	85.38	110.71	187.51	197.71
RCP2.6 (med)	75.79	86.36	145.21	140.04
RCP2.6 (low)	73.75	80.24	132.50	118.01
No SLR	19.91	20.95	26.53	22.86

Table A1.23 Annual costs of beach nourishment in the EU, for HadGEM2-ES and SSP3 (millions € / yr, 2dp).

HadGEM2-ES	2010s	2030s	2060s	2080s
RCP8.5 (high)	85.41	114.95	194.41	264.40
RCP8.5 (med)	76.00	87.21	138.50	171.80
RCP8.5 (low)	73.83	79.74	122.76	144.28
RCP4.5 (high)	76.57	109.10	153.47	160.52
RCP4.5 (med)	67.25	89.65	109.28	113.51
RCP4.5 (low)	65.12	84.41	96.31	97.60
RCP2.6 (high)	85.38	96.04	122.80	98.64
RCP2.6 (med)	75.79	74.31	93.40	68.52
RCP2.6 (low)	73.75	68.89	84.72	57.53
No SLR	19.91	16.82	13.73	11.04

Table A1.24 Annual costs of beach nourishment in the EU, for HadGEM2-ES and SSP4 (millions € / yr, 2dp).

HadGEM2-ES	2010s	2030s	2060s	2080s
RCP8.5 (high)	85.41	129.50	284.80	456.41
RCP8.5 (med)	76.00	98.79	207.21	301.43
RCP8.5 (low)	73.83	90.52	185.35	255.01
RCP4.5 (high)	76.57	122.13	227.25	281.38
RCP4.5 (med)	67.25	100.25	165.46	201.30
RCP4.5 (low)	65.12	94.35	147.20	173.77
RCP2.6 (high)	85.38	108.91	184.72	180.18
RCP2.6 (med)	75.79	84.62	143.20	128.17
RCP2.6 (low)	73.75	78.53	130.72	108.46
No SLR	19.91	19.78	26.52	22.49

Table A1.25 Annual costs of beach nourishment in the EU, for HadGEM2-ES and SSP5 (millions € / yr, 2dp).

HadGEM2-ES	2010s	2030s	2060s	2080s
RCP8.5 (high)	85.41	148.03	420.05	1134.28
RCP8.5 (med)	76.00	114.39	303.35	746.62
RCP8.5 (low)	73.83	105.32	270.26	630.54
RCP4.5 (high)	76.57	139.80	337.86	698.38
RCP4.5 (med)	67.25	115.28	244.49	496.90
RCP4.5 (low)	65.12	108.66	216.47	428.13
RCP2.6 (high)	85.38	125.71	269.19	446.33
RCP2.6 (med)	75.79	98.80	207.26	315.26
RCP2.6 (low)	73.75	92.03	188.49	265.42
No SLR	19.91	25.57	34.58	48.12

10.2 IPSL-CM5A-LR

Table A1.26 Expected number of people flooded annually in the EU, for IPSL-CM5A-LR and SSP1 (thousands / yr, 2dp).

IPSL-CM5A-LR	2010s	2030s	2060s	2080s
RCP8.5 (high)	7.49	7.22	6.36	5.08
RCP8.5 (med)	7.27	6.66	5.24	3.33
RCP8.5 (low)	7.24	6.55	4.98	2.96
RCP4.5 (high)	7.55	7.15	5.34	3.02
RCP4.5 (med)	7.33	6.56	4.61	2.38
RCP4.5 (low)	7.29	6.44	4.44	2.20
RCP2.6 (high)	7.52	7.14	4.73	2.60
RCP2.6 (med)	7.29	6.67	4.15	2.15
RCP2.6 (low)	7.24	6.51	3.98	2.00
No SLR	6.47	4.90	3.07	1.52

Table A1.27 Expected number of people flooded annually in the EU, for IPSL-CM5A-LR and SSP2 (thousands / yr, 2dp).

IPSL-CM5A-LR	2010s	2030s	2060s	2080s
RCP8.5 (high)	7.49	7.24	6.86	6.42
RCP8.5 (med)	7.27	6.70	5.65	4.31
RCP8.5 (low)	7.24	6.57	5.35	3.85
RCP4.5 (high)	7.55	7.15	5.78	3.89
RCP4.5 (med)	7.33	6.58	4.98	3.09
RCP4.5 (low)	7.29	6.45	4.81	2.86
RCP2.6 (high)	7.52	7.17	5.09	3.43
RCP2.6 (med)	7.29	6.67	4.48	2.84
RCP2.6 (low)	7.24	6.56	4.28	2.64
No SLR	6.47	4.92	3.34	2.05

Table A1.28 Expected number of people flooded annually in the EU, for IPSL-CM5A-LR and SSP3 (thousands / yr, 2dp).

IPSL-CM5A-LR	2010s	2030s	2060s	2080s
RCP8.5 (high)	7.48	6.85	6.59	6.24
RCP8.5 (med)	7.26	6.36	5.45	4.24
RCP8.5 (low)	7.23	6.21	5.17	3.82
RCP4.5 (high)	7.53	6.80	5.54	3.88
RCP4.5 (med)	7.31	6.23	4.81	3.13
RCP4.5 (low)	7.27	6.11	4.61	2.89
RCP2.6 (high)	7.50	6.80	4.89	3.38
RCP2.6 (med)	7.28	6.31	4.24	2.82
RCP2.6 (low)	7.22	6.20	4.06	2.62
No SLR	6.46	4.66	3.21	2.11

Table A1.29 Expected number of people flooded annually in the EU, for IPSL-CM5A-LR and SSP4 (thousands / yr, 2dp).

IPSL-CM5A-LR	2010s	2030s	2060s	2080s
RCP8.5 (high)	64.15	147.13	283.91	440.57
RCP8.5 (med)	56.39	120.56	210.57	290.77
RCP8.5 (low)	54.68	113.87	190.55	246.73
RCP4.5 (high)	67.58	139.37	215.46	238.71
RCP4.5 (med)	60.07	112.37	161.07	163.60
RCP4.5 (low)	67.58	139.37	215.46	238.71
RCP2.6 (high)	67.48	137.61	163.43	191.48
RCP2.6 (med)	58.91	113.84	128.01	142.90
RCP2.6 (low)	57.05	108.02	117.59	124.68
No SLR	19.91	19.78	26.52	22.49

Table A1.30 Expected number of people flooded annually in the EU, for IPSL-CM5A-LR and SSP5 (thousands / yr, 2dp).

IPSL-CM5A-LR	2010s	2030s	2060s	2080s
RCP8.5 (high)	64.15	166.32	419.86	1090.86
RCP8.5 (med)	56.39	137.09	310.16	717.30
RCP8.5 (low)	54.68	129.72	280.13	607.73
RCP4.5 (high)	67.58	157.49	316.27	566.73
RCP4.5 (med)	60.07	127.63	235.04	380.92
RCP4.5 (low)	58.43	119.61	211.92	323.88
RCP2.6 (high)	67.48	155.51	235.18	488.19
RCP2.6 (med)	58.91	129.24	180.46	363.02
RCP2.6 (low)	57.05	122.78	164.04	316.28
No SLR	19.91	25.57	34.58	48.12

Annual sea flood costs

Table A1.31 Annual costs of sea floods in the EU, for IPSL-CM5A-LR and SSP1 (millions € / yr, 2dp).

IPSL-CM5A-LR	2010s	2030s	2060s	2080s
RCP8.5 (high)	443.37	548.18	718.29	910.06
RCP8.5 (med)	431.11	507.77	595.13	602.18
RCP8.5 (low)	429.47	499.48	566.56	537.29
RCP4.5 (high)	444.03	541.99	607.25	535.93
RCP4.5 (med)	431.83	499.11	527.06	423.54
RCP4.5 (low)	429.72	490.71	507.48	392.38
RCP2.6 (high)	443.36	542.23	530.68	485.04
RCP2.6 (med)	430.83	508.02	467.78	403.82
RCP2.6 (low)	427.80	496.17	449.63	375.95
No SLR	386.28	377.58	350.72	277.67

Table A1.32 Annual costs of sea floods in the EU, for IPSL-CM5A-LR and SSP2 (millions € / yr, 2dp).

IPSL-CM5A-LR	2010s	2030s	2060s	2080s
RCP8.5 (high)	443.37	537.67	695.25	905.58
RCP8.5 (med)	431.11	499.75	577.31	615.63
RCP8.5 (low)	429.47	490.32	547.89	552.66
RCP4.5 (high)	444.03	531.33	591.99	550.93
RCP4.5 (med)	431.83	490.19	513.28	440.44
RCP4.5 (low)	429.72	481.64	496.16	407.56
RCP2.6 (high)	443.36	533.23	517.13	502.43
RCP2.6 (med)	430.83	498.04	456.50	419.49
RCP2.6 (low)	427.80	490.45	437.44	391.17
No SLR	386.28	371.67	344.65	296.13

Table A1.33 Annual costs of sea floods in the EU, for IPSL-CM5A-LR and SSP3 (millions € / yr, 2dp).

IPSL-CM5A-LR	2010s	2030s	2060s	2080s
RCP8.5 (high)	443.37	502.83	581.31	670.57
RCP8.5 (med)	431.11	469.35	485.84	464.75
RCP8.5 (low)	429.47	457.97	462.44	420.92
RCP4.5 (high)	444.03	499.92	495.13	423.56
RCP4.5 (med)	431.83	458.92	432.83	344.32
RCP4.5 (low)	429.72	450.91	416.40	318.57
RCP2.6 (high)	443.36	500.46	436.94	379.30
RCP2.6 (med)	430.83	465.46	380.22	319.41
RCP2.6 (low)	427.80	458.65	364.31	297.10
No SLR	386.28	349.04	292.03	236.33

Table A1.34 Annual costs of sea floods in the EU, for IPSL-CM5A-LR and SSP4 (millions € / yr, 2dp).

IPSL-CM5A-LR	2010s	2030s	2060s	2080s
RCP8.5 (high)	443.37	527.67	636.81	741.09
RCP8.5 (med)	431.11	487.04	525.13	502.75
RCP8.5 (low)	429.47	479.26	501.76	450.40
RCP4.5 (high)	444.03	520.44	538.63	452.78
RCP4.5 (med)	431.83	482.27	466.04	361.08
RCP4.5 (low)	429.72	473.50	447.36	333.62
RCP2.6 (high)	443.36	522.13	472.41	402.41
RCP2.6 (med)	430.83	485.61	414.21	339.26
RCP2.6 (low)	427.80	479.51	397.14	316.40
No SLR	386.28	363.59	312.33	240.15

Table A1.35 Annual costs of sea floods in the EU, for IPSL-CM5A-LR and SSP5 (millions € / yr, 2dp).

IPSL-CM5A-LR	2010s	2030s	2060s	2080s
RCP8.5 (high)	443.37	578.12	818.78	1087.10
RCP8.5 (med)	431.11	535.58	673.80	688.83
RCP8.5 (low)	429.47	524.31	641.72	605.90
RCP4.5 (high)	444.03	569.39	689.62	588.65
RCP4.5 (med)	431.83	525.17	594.53	451.86
RCP4.5 (low)	429.72	515.40	571.11	411.68
RCP2.6 (high)	443.36	569.98	600.59	537.84
RCP2.6 (med)	430.83	532.25	524.38	444.35
RCP2.6 (low)	427.80	520.02	504.64	406.27
No SLR	386.28	395.18	390.92	276.97

Annual sea dike costs

Table A1.36 Annual costs of sea dikes in the EU, for IPSL-CM5A-LR and SSP1 (millions € / yr, 2dp).

IPSL-CM5A-LR	2010s	2030s	2060s	2080s
RCP8.5 (high)	1017.46	2019.83	2624.68	3579.21
RCP8.5 (med)	861.50	1606.57	2008.12	2122.76
RCP8.5 (low)	831.55	1523.71	1820.34	1725.43
RCP4.5 (high)	1230.93	1813.22	1884.32	1659.33
RCP4.5 (med)	975.71	1496.25	1429.51	1070.70
RCP4.5 (low)	947.19	1412.33	1278.36	905.31
RCP2.6 (high)	1230.10	1745.95	1363.43	1333.12
RCP2.6 (med)	1059.07	1442.76	997.24	922.34
RCP2.6 (low)	1026.42	1356.24	834.57	796.79
No SLR	322.10	219.72	249.95	219.06

Table A1.37 Annual costs of sea dikes in the EU, for IPSL-CM5A-LR and SSP2 (millions € / yr, 2dp).

IPSL-CM5A-LR	2010s	2030s	2060s	2080s
RCP8.5 (high)	1017.92	1972.76	2542.67	3483.05
RCP8.5 (med)	861.96	1559.98	1925.94	2030.67
RCP8.5 (low)	832.01	1477.14	1738.20	1635.07
RCP4.5 (high)	1231.37	1767.44	1801.37	1573.31
RCP4.5 (med)	947.61	1368.48	1194.69	840.95
RCP4.5 (low)	947.61	1368.48	1194.69	840.95
RCP2.6 (high)	1230.57	1699.48	1284.33	1240.07
RCP2.6 (med)	1059.54	1396.60	922.59	832.06
RCP2.6 (low)	1026.89	1310.17	762.08	705.82
No SLR	322.40	177.28	178.56	145.47

Table A1.38 Annual costs of sea dikes in the EU, for IPSL-CM5A-LR and SSP3 (millions € / yr, 2dp).

IPSL-CM5A-LR	2010s	2030s	2060s	2080s
RCP8.5 (high)	1023.16	1875.17	2379.04	3318.09
RCP8.5 (med)	867.19	1463.33	1762.64	1872.75
RCP8.5 (low)	837.24	1380.52	1575.20	1479.90
RCP4.5 (high)	1236.41	1674.65	1634.81	1429.30
RCP4.5 (med)	981.01	1361.37	1179.26	886.81
RCP4.5 (low)	952.38	1277.82	1028.92	732.58
RCP2.6 (high)	1235.83	1603.18	1129.27	1078.01
RCP2.6 (med)	1064.81	1300.84	776.22	672.51
RCP2.6 (low)	1032.15	1214.76	622.57	542.40
No SLR	325.81	98.76	59.48	44.40

Table A1.39 Annual costs of sea dikes in the EU, for IPSL-CM5A-LR and SSP4 (millions € / yr, 2dp).

IPSL-CM5A-LR	2010s	2030s	2060s	2080s
RCP8.5 (high)	1020.92	1994.71	2534.95	3474.23
RCP8.5 (med)	864.94	1581.77	1918.42	2022.67
RCP8.5 (low)	834.99	1498.92	1730.73	1627.43
RCP4.5 (high)	1234.26	1789.77	1793.46	1567.96
RCP4.5 (med)	978.92	1474.59	1337.70	997.10
RCP4.5 (low)	950.33	1390.84	1187.02	837.05
RCP2.6 (high)	1233.58	1721.36	1277.36	1232.43
RCP2.6 (med)	1062.55	1418.47	916.72	824.17
RCP2.6 (low)	1029.90	1332.02	756.76	697.60
No SLR	324.46	198.06	173.28	143.47

Table A1.40 Annual costs of sea dikes in the EU, for IPSL-CM5A-LR and SSP5 (millions € / yr, 2dp).

IPSL-CM5A-LR	2010s	2030s	2060s	2080s
RCP8.5 (high)	1012.79	2072.29	2749.69	3761.69
RCP8.5 (med)	856.84	1658.58	2132.21	2294.20
RCP8.5 (low)	826.89	1575.65	1944.00	1893.29
RCP4.5 (high)	1226.45	1864.54	2009.29	1822.77
RCP4.5 (med)	971.40	1545.34	1554.70	1210.47
RCP4.5 (low)	942.95	1461.17	1402.90	1036.67
RCP2.6 (high)	1225.41	1798.10	1483.36	1502.88
RCP2.6 (med)	1054.39	1494.31	1109.58	1087.43
RCP2.6 (low)	1021.73	1407.71	944.13	959.47
No SLR	319.17	266.33	359.25	353.94

Annual sea dike maintenance costs

Table A1.41 Annual costs of maintaining sea dikes in the EU, for IPSL-CM5A-LR and SSP1 (millions € / yr, 2dp).

IPSL-CM5A-LR	2010s	2030s	2060s	2080s
RCP8.5 (high)	5101.72	5462.39	6125.91	7073.41
RCP8.5 (med)	5086.15	5379.43	5896.49	6512.00
RCP8.5 (low)	5083.20	5359.86	5837.71	6368.66
RCP4.5 (high)	5120.78	5479.12	6001.66	6574.38
RCP4.5 (med)	5095.03	5396.13	5797.15	6206.36
RCP4.5 (low)	5092.16	5378.45	5739.69	6101.78
RCP2.6 (high)	5112.54	5484.03	5938.30	6263.44
RCP2.6 (med)	5095.18	5405.57	5760.67	5971.69
RCP2.6 (low)	5091.86	5386.45	5708.62	5878.38
No SLR	5031.09	5075.76	5142.94	5212.78

Table A1.42 Annual costs of maintaining sea dikes in the EU, for IPSL-CM5A-LR and SSP2 (millions € / yr, 2dp).

IPSL-CM5A-LR	2010s	2030s	2060s	2080s
RCP8.5 (high)	5101.74	5456.98	6100.27	7020.35
RCP8.5 (med)	5086.18	5374.07	5871.01	6459.91
RCP8.5 (low)	5083.22	5354.51	5812.32	6316.91
RCP4.5 (high)	5120.80	5473.77	5976.06	6522.53
RCP4.5 (med)	5095.05	5390.88	5771.78	6156.18
RCP4.5 (low)	5092.18	5373.21	5714.47	6052.15
RCP2.6 (high)	5112.56	5478.65	5913.69	6212.58
RCP2.6 (med)	5095.21	5400.23	5736.86	5922.73
RCP2.6 (low)	5091.89	5381.12	5685.45	5830.46
No SLR	5031.10	5070.87	5120.10	5167.65

Table A1.43 Annual costs of maintaining sea dikes in the EU, for IPSL-CM5A-LR and SSP3 (millions € / yr, 2dp).

IPSL-CM5A-LR	2010s	2030s	2060s	2080s
RCP8.5 (high)	5102.00	5446.38	6048.26	6918.55
RCP8.5 (med)	5086.44	5363.60	5819.40	6360.24
RCP8.5 (low)	5083.48	5344.08	5760.92	6217.86
RCP4.5 (high)	5121.06	5463.39	5924.24	6423.61
RCP4.5 (med)	5095.29	5380.64	5720.58	6060.20
RCP4.5 (low)	5092.42	5363.02	5663.60	5956.88
RCP2.6 (high)	5112.83	5468.10	5863.94	6115.74
RCP2.6 (med)	5095.47	5389.77	5689.58	5830.19
RCP2.6 (low)	5092.15	5370.73	5639.95	5741.53
No SLR	5031.27	5062.11	5080.08	5094.65

Table A1.44 Annual costs of maintaining sea dikes in the EU, for IPSL-CM5A-LR and SSP4 (millions € / yr, 2dp).

IPSL-CM5A-LR	2010s	2030s	2060s	2080s
RCP8.5 (high)	5101.89	5461.88	6104.92	7022.41
RCP8.5 (med)	5086.33	5378.93	5875.67	6462.15
RCP8.5 (low)	5083.37	5359.36	5816.99	6319.28
RCP4.5 (high)	5120.95	5478.68	5980.72	6524.91
RCP4.5 (med)	5095.19	5395.76	5776.46	6158.74
RCP4.5 (low)	5092.32	5378.08	5719.17	6054.76
RCP2.6 (high)	5112.71	5483.54	5918.50	6215.21
RCP2.6 (med)	5095.36	5405.09	5741.76	5925.61
RCP2.6 (low)	5092.04	5385.97	5690.47	5833.80
No SLR	5031.20	5075.35	5124.69	5171.07

Table A1.45 Annual costs of maintaining sea dikes in the EU, for IPSL-CM5A-LR and SSP5 (millions € / yr, 2dp).

IPSL-CM5A-LR	2010s	2030s	2060s	2080s
RCP8.5 (high)	5101.48	5467.64	6158.33	7153.64
RCP8.5 (med)	5085.92	5384.64	5928.64	6589.82
RCP8.5 (low)	5082.96	5365.04	5869.75	6445.76
RCP4.5 (high)	5120.56	5484.34	6033.99	6652.01
RCP4.5 (med)	5094.81	5401.23	5829.14	6281.18
RCP4.5 (low)	5091.95	5383.54	5771.47	6175.61
RCP2.6 (high)	5112.31	5489.28	5969.33	6339.66
RCP2.6 (med)	5094.95	5410.79	5790.77	6044.43
RCP2.6 (low)	5091.63	5391.65	5738.05	5949.79
No SLR	5030.94	5080.55	5171.98	5279.91

Annual beach nourishment costs

Table A1.46 Annual costs of beach nourishment in the EU, for IPSL-CM5A-LR and SSP1 (millions € / yr, 2dp).

IPSL-CM5A-LR	2010s	2030s	2060s	2080s
RCP8.5 (high)	64.15	155.89	323.72	656.46
RCP8.5 (med)	56.39	128.32	239.25	432.22
RCP8.5 (low)	54.68	121.38	216.11	366.18
RCP4.5 (high)	67.58	147.72	244.49	348.39
RCP4.5 (med)	60.07	119.64	181.97	236.37
RCP4.5 (low)	58.43	112.12	164.36	201.29
RCP2.6 (high)	67.48	146.00	184.72	287.34
RCP2.6 (med)	58.91	121.30	143.48	213.17
RCP2.6 (low)	57.05	115.24	131.25	185.35
No SLR	19.91	23.46	28.01	30.08

Table A1.47 Annual costs of beach nourishment in the EU, for IPSL-CM5A-LR and SSP2 (millions € / yr, 2dp).

IPSL-CM5A-LR	2010s	2030s	2060s	2080s
RCP8.5 (high)	64.15	148.83	288.71	487.45
RCP8.5 (med)	56.39	122.24	213.88	320.13
RCP8.5 (low)	54.68	115.54	193.44	270.88
RCP4.5 (high)	67.58	140.86	218.47	259.45
RCP4.5 (med)	60.07	113.81	163.05	176.36
RCP4.5 (low)	58.43	106.56	147.52	150.40
RCP2.6 (high)	67.48	138.99	165.14	211.16
RCP2.6 (med)	58.91	115.20	129.09	157.13
RCP2.6 (low)	57.05	109.38	118.49	136.82
No SLR	19.91	20.95	26.53	22.86

Table A1.48 Annual costs of beach nourishment in the EU, for IPSL-CM5A-LR and SSP3 (millions € / yr, 2dp).

IPSL-CM5A-LR	2010s	2030s	2060s	2080s
RCP8.5 (high)	64.15	130.95	195.69	253.18
RCP8.5 (med)	56.39	107.10	142.71	163.89
RCP8.5 (low)	54.68	101.10	128.28	137.97
RCP4.5 (high)	67.58	123.75	146.07	132.80
RCP4.5 (med)	60.07	99.59	107.08	89.03
RCP4.5 (low)	58.43	93.14	96.25	75.81
RCP2.6 (high)	67.48	122.92	108.51	108.35
RCP2.6 (med)	58.91	101.59	84.03	81.17
RCP2.6 (low)	57.05	96.38	76.94	71.12
No SLR	19.91	16.82	13.73	11.04

Table A1.49 Annual costs of beach nourishment in the EU, for IPSL-CM5A-LR and SSP4 (millions € / yr, 2dp).

IPSL-CM5A-LR	2010s	2030s	2060s	2080s
RCP8.5 (high)	64.15	147.13	283.91	440.57
RCP8.5 (med)	56.39	120.56	210.57	290.77
RCP8.5 (low)	54.68	113.87	190.55	246.73
RCP4.5 (high)	67.58	139.37	215.46	238.71
RCP4.5 (med)	60.07	112.37	161.07	163.60
RCP4.5 (low)	58.43	105.14	145.84	140.08
RCP2.6 (high)	67.48	137.61	163.43	191.48
RCP2.6 (med)	58.91	113.84	128.01	142.90
RCP2.6 (low)	57.05	108.02	117.59	124.68
No SLR	19.91	19.78	26.52	22.49

Table A1.50 Annual costs of beach nourishment in the EU, for IPSL-CM5A-LR and SSP5 (millions € / yr, 2dp).

IPSL-CM5A-LR	2010s	2030s	2060s	2080s
RCP8.5 (high)	64.15	166.32	419.86	1090.86
RCP8.5 (med)	56.39	137.09	310.16	717.30
RCP8.5 (low)	54.68	129.72	280.13	607.73
RCP4.5 (high)	67.58	157.49	316.27	566.73
RCP4.5 (med)	60.07	127.63	235.04	380.92
RCP4.5 (low)	58.43	119.61	211.92	323.88
RCP2.6 (high)	67.48	155.51	235.18	488.19
RCP2.6 (med)	58.91	129.24	180.46	363.02
RCP2.6 (low)	57.05	122.78	164.04	316.28
No SLR	19.91	25.57	34.58	48.12

11. Appendix 2: Maps

The SSP2 'middle of the road' scenario was selected to represent the scenarios for each of the climate scenarios in the 2080s.

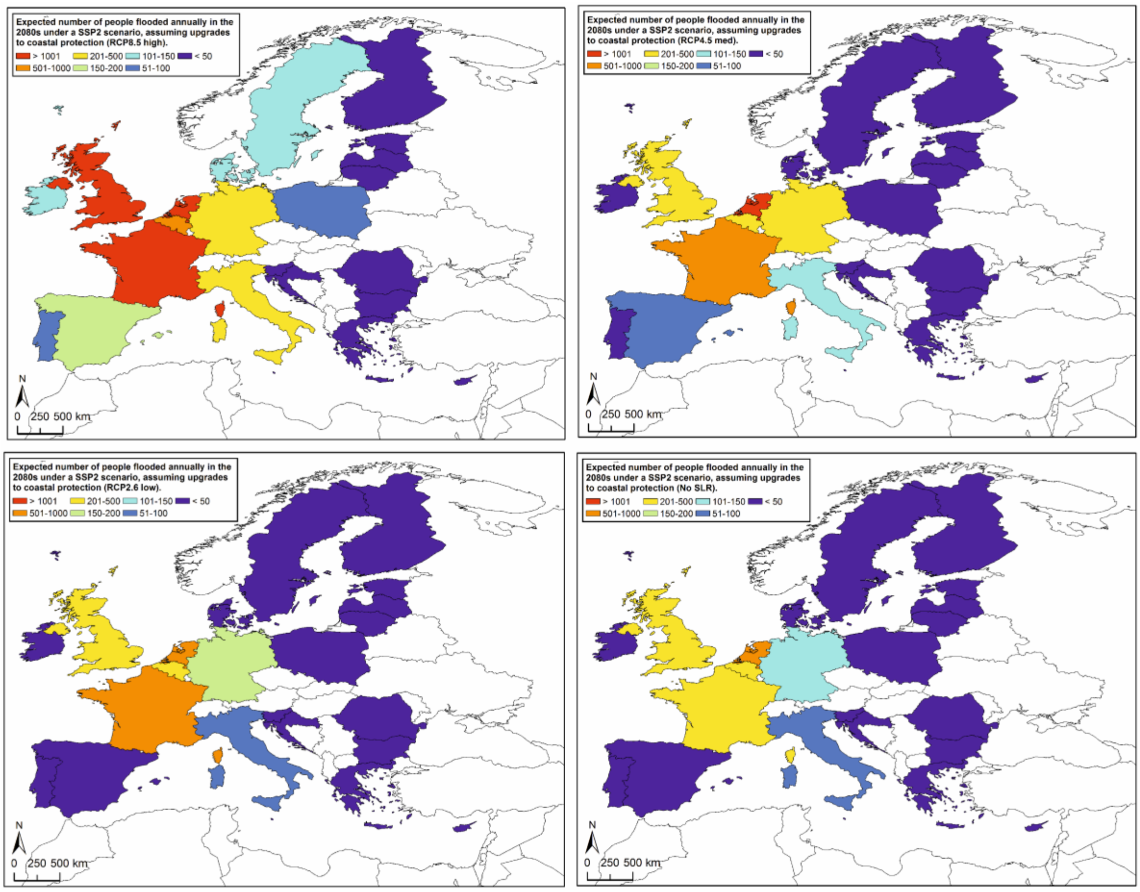

Figure A2.1 Expected number of people at risk annually in the 2080s under a SSP2 scenario for RCP8.5 (high), RCP4.5 (med), RCP2.6 (low) and a no-sea level rise scenario.

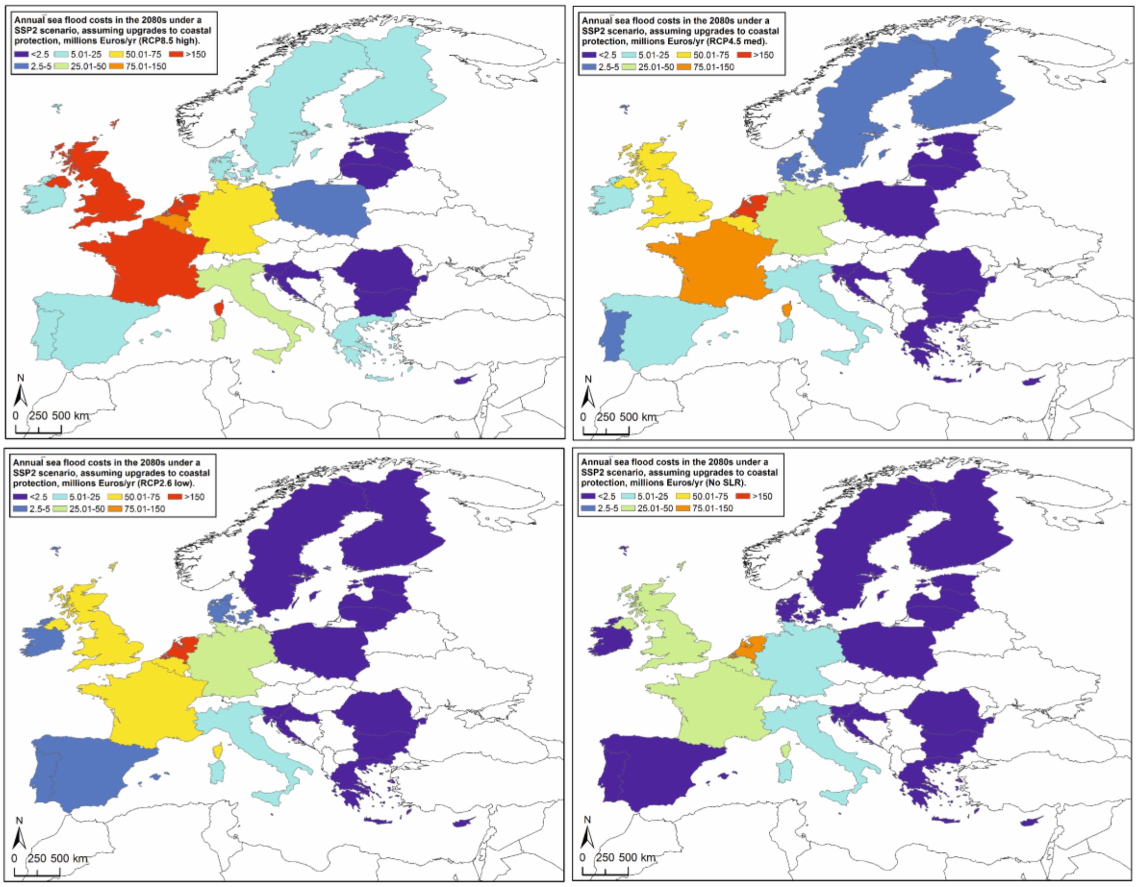

Figure A2.2 Annual sea flood costs in the 2080s under a SSP2 scenario for RCP8.5 (high), RCP4.5 (med), RCP2.6 (low) and a no-sea level rise scenario.

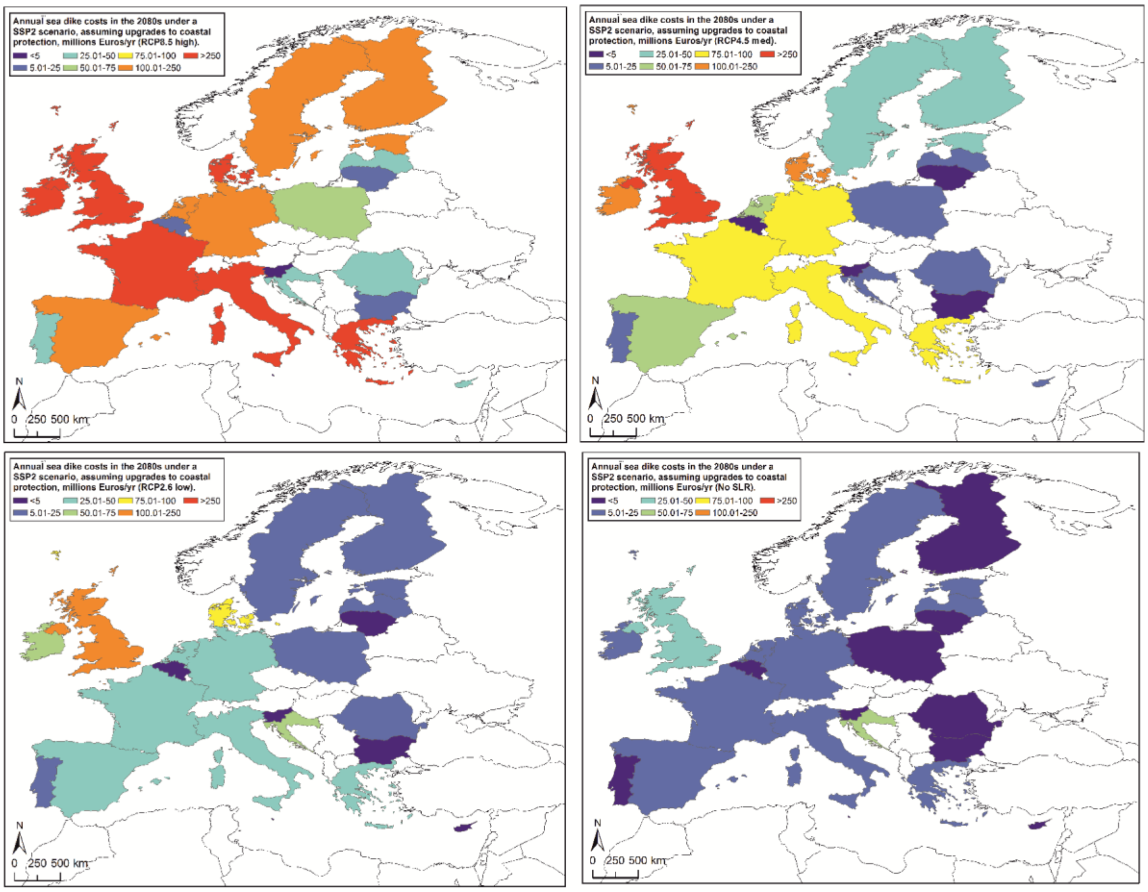

Figure A2.3 Annual sea dike costs in the 2080s under a SSP2 scenario for RCP8.5 (high), RCP4.5 (med), RCP2.6 (low) and a no-sea level rise scenario.