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Executive Summary

Coastal zones contain large human populations and significant socio-economic activities. They also support diverse ecosystems that provide important habitats and sources of food. One third of the EU population lives within 50 km of the coast. Globally about 120 million people are exposed annually to tropical cyclone hazards, which killed more than 300,000 people since 1980. Climate change could have profound impacts on coastal zones due to sea level rise and changes in frequency and/or intensity of storms.

The present document reports the methodology and results of the coastal analysis under PESETA III. We employed the integrated risk assessment tool LISCoAsT (Large scale Integrated Sea-level and Coastal Assessment Tool) for Europe to evaluate coastal flood risk along the European coastline in view of climate change. The overall approach builds on the disaster risk methodology proposed by the IPCC SREX (IPCC, 2012) report, defining risk as the combination of hazard, exposure and vulnerability. We produced projections of Extreme Sea Levels (ESLs) along Europe's coastline using dynamic models forced by CMIP5 climate projections for RCP4.5 and RCP8.5. Extreme sea levels were translated into flood inundation maps using 2-D hydraulic modelling taking into account coastal flood protection. For the flooded areas direct flood damage was calculated by combining flood inundation depth with land use information and regional depth-damage functions for specific land use classes. The number of people affected was estimated by overlaying the flood inundation maps with a high-resolution population density map for Europe. Expected Annual values were used to present the findings, i.e. the expected annual impact obtained after considering all possible flood events.

The study focuses on direct impacts of coastal flooding only and does not address the effects of acidification in coastal areas. Moreover, combined flooding scenarios remain an open research question for the scientific community and are not taken into account (meaning simultaneous fluvial and coastal flooding), but are the topic of ongoing exploratory studies. Processes such as dyke failure and coastal erosion are neglected, as their consideration remains a challenge given the complex processes as well as temporal and spatial scales involved. However, the above processes can drive additional risks therefore it is important to highlight that the present study may underestimate flood impacts.

In a static economic analysis the effects of climate change on present society were assessed. In a dynamic economic analysis we also accounted for socio-economic developments by considering gridded projections of population and GDP defined by Shared Socio-economic Pathways (SSPs) consistent with RCP4.5 (SSP1) and RCP8.5 (SSP3 and SSP5). We show how coastal flood risk may evolve in the case that no further investments are made to reduce flood risks.

Results are summarized in Figure 1 and Table 1. Under present climate conditions, the estimated Expected Annual Damage (EAD) for Europe is 1.25 billion €, while the Expected Annual number of People Affected by coastal flooding (EAPA) equals 102,000 people. Under the static economic analysis, EAD is projected to rise to nearly 4 billion € by 2030 and to more than 6 billion € by mid-century (respectively 6.6 and 8.1 billion € for RCP4.5 and RCP8.5). For this scenario, EAPA will rise to nearly 300,000 people by 2030 and exceed 450,000 people (respectively 467,000 and 558,800 people for RCP4.5 and RCP8.5). In the second halve of the century the figures diverge more strongly between the two RCPs. By 2080, due to the effects of climate change only, EAD (EAPA) could rise to 17 billion € (975,000 people) under RCP4.5 and to 28 billion € (1.35 million people) under RCP8.5. Accelerating Sea Level Rise towards the end of the century results in an exponential increase in coastal flood impacts towards the end of the century, with by the year 2100 EAD (EAPA) amounting to 27 billion € (1.3 million people) and 60 billion € (2.1 million people) under RCP4.5 and RCP8.5, respectively. Impacts at 2˚C warming are similar to those around 2050, but are larger under the RCP4.5 scenario compared to RCP8.5. This is related to inertia effects of global warming on SLR. Because the rate of warming is higher under RCP8.5, with 2˚C warming occurring around 2043, the effect of SLR are less pronounced compared to RCP4.5, for which 2˚C warming is projected around 2057. Nevertheless, at any specific point in time, impacts under RCP8.5 are always larger that under RCP4.5.

The projected impacts are substantially higher when taking into account socio-economic development (see Table 1). EAD for Europe is projected to reach 156, 93 and 961 billion € under RCP4.5-SSP1, RCP8.5-SSP3, and RCP8.5-SSP5, respectively, by the end of the century. For the same year, EAPA will rise to 1.53, 1.52, and 3.65 million people that could be annually flooded due to extreme sea levels. Impacts will put increasing pressure on coastal communities, with the number of people forced to relocate reaching 160, 28,120, and 28,340 under RCP4.5-SSP1, RCP8.5-SSP3, and RCP8.5-SSP5, respectively, towards the end of the century.

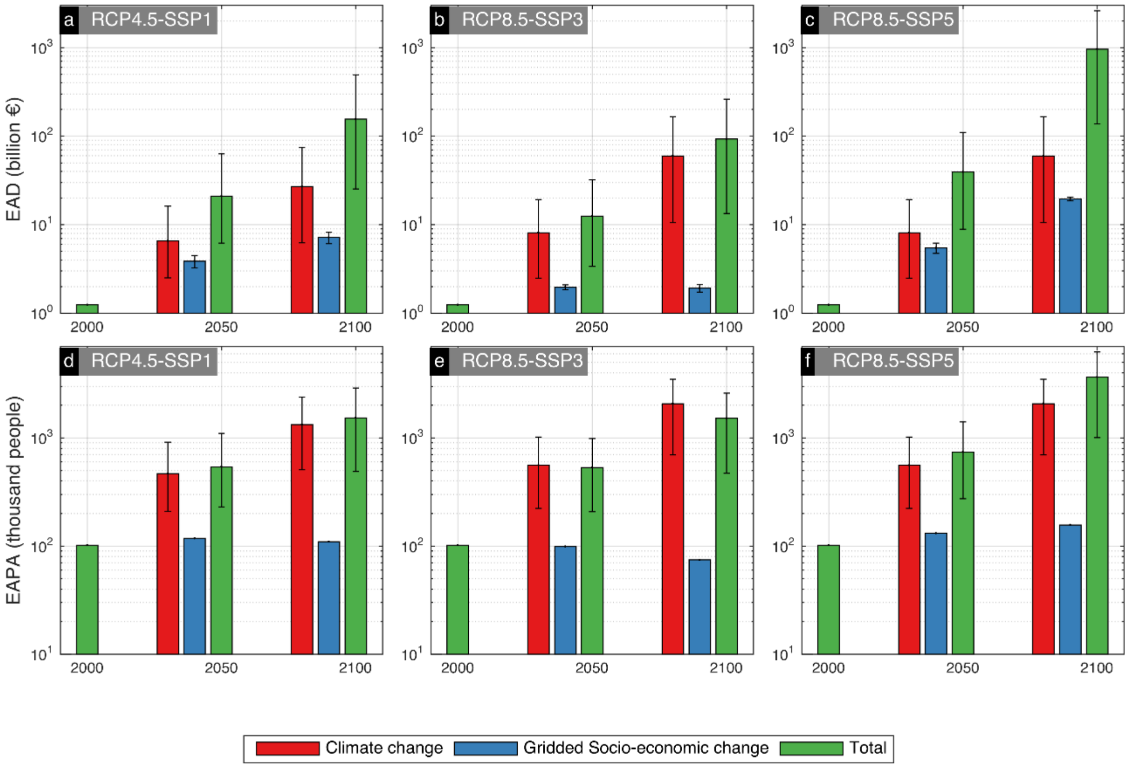
Table 1. Projected evolution in time of coastal flooding impacts aggregated at European level: Expected Annual Damage (EAD; billion €) and Expected Annual number of People Affected (EAPA; thousand people) from coastal flooding under RCP4.5-SSP1, RCP8.5-SSP3, and RCP8.5-SSP5. Values express the ensemble mean projections, for 2030, 2050, 2080, and 2100, as well as under 2°C warming.

	Scenario	Baseline	2030	2050	2080	2100	2°C
EAD	RCP4.5	1.25	3.71	6.56	16.57	26.96	8.9
	RCP8.5	1.25	3.87	8.13	28.44	59.82	6.01
	RCP4.5-SSP1	1.25	7.53	20.96	80.94	155.86	34.96
	RCP8.5-SSP3	1.25	5.3	12.49	45.19	92.72	8.98
	RCP8.5-SSP5	1.25	9.3	39.42	293.76	960.97	22.33
EAPA	RCP4.5	102	273	468	975	1330	586
	RCP8.5	102	291	559	1359	2078	436
	RCP4.5-SSP1	102	299	540	1173	1532	688
	RCP8.5-SSP3	102	294	533	1140	1519	429
	RCP8.5-SSP5	102	336	742	2204	3650	545

We further show that climate change is the main driver of the rise in coastal flood risk, rather than socio-economic changes. Among the physical parameters, warming-induced sea level rise is a more prominent factor than changes in the frequency and intensity of extreme meteorological events. Sea level rise increases the absolute magnitude of ESLs such that they more frequently overtop existing coastal protection or natural barriers. Coastal flood risk is further amplified by economic growth, yet the projected increase in wealth also implies an increase in the capacity to absorb the increase in coastal flood risk.

The increasing burden on European societies calls for adaptation action. Further investments in adaptation measures can be justified as the costs of coastal protection are often lower than the benefits, especially in the long-term with the expected changes in extreme sea levels.

Figure 1. Projected evolution in time of coastal flooding impacts aggregated at European level: only climate change with static exposure (red), static climate combined with gridded socioeconomic change (blue), and climate change combined with gridded socioeconomic change (green). Expected Annual Damage (a, b and c) and Expected Annual number of People Affected (d, e and f) from coastal flooding under RCP4.5-SSP1 (a and d), RCP8.5-SSP3 (b and e), and RCP8.5-SSP5 (c and f). Bars express the ensemble mean projections, black error plots express inter-model variability. Please note that values are in the vertical axis are in logarithmic scale (i.e. 1, 10, 1000).



1 Introduction

The coastal zone is an area of high interest, characterized by high population density, hosting commercial activities and constituting habitats of important socioeconomic value (Costanza, 1999). Nearshore areas also support diverse ecosystems that provide precious habitats and sources of food. One third of the EU population lives within 50 km of the coast. The EU Strategy on Adaptation to Climate Change stresses that coastal zones are particularly vulnerable to the effects of climate change. This is due to the combined effects of sea level rise and potential changes in the frequency and/or intensity of storms. In recent years, substantial research effort has focused on several aspects of coastal hazard and risk in view of climate change (Church and White, 2011; Hinkel et al., 2014; Hogarth, 2014; Hoggart et al., 2014; Jevrejeva et al., 2014; Losada et al., 2013).

Future extreme sea levels (ESLs) and flood risk along European coasts will be strongly impacted by global warming. ESLs originate from the combined effects of mean seal level (MSL), the astronomical tide and episodic water level fluctuations due to waves and storm surges that become important during extreme meteorological events, when intense atmospheric wind and pressure fields transfer significant amounts of energy to the ocean (Losada et al., 2013). Global MSL has increased since the beginning of the 20th century (Hay et al., 2015), with an accelerated rate since the 1990s (Watson et al., 2015), where the rise after 1950 can be explained by global warming (Slangen et al., 2014). Past changes in ESLs are dominated by local MSL dynamics (Menéndez and Woodworth, 2010), depending on variations in and interactions between vertical land movement, the thermal expansion of sea water, ocean circulation and hydrological fluxes between the land and the ocean (Howard et al., 2014). Nevertheless, wave heights along the Atlantic coast of Europe (Young et al., 2011) and storminess in many parts of western, central and northern Europe (Donat et al., 2011) show upward trends in the 20th century, with the 2013-2014 winter being the most energetic on record along most of the Atlantic coast of Europe (Masselink et al., 2016). In addition, there is some evidence of changes in tidal constituents in the 20th century, yet the attribution of reported changes remains unresolved (Woodworth, 2010).

Impacts on coastal societies are largely linked to extreme episodic events (Vigdor, 2008). However, projections of coastal impacts in view of climate change have focused on the effects of sea level rise, neglecting possible changes in the other ESL components. There is limited and often contradicting information about how these factors will evolve in the future. Recently, there has been an increasing number of independent studies discussing projections of storm surges in specific regions (Lowe and Gregory, 2005; Marcos et al., 2011), or the evolution of waves at European (Perez et al., 2015) and global scale (Hemer et al., 2013), but differences in the spatial coverage, scenarios and the methodology make it difficult to draw universal conclusions. The long term dynamics in tidal processes in relation to sea level rise have only been evaluated at regional scale (Arns et al., 2015; Pickering et al., 2012). Despite these important advances, no coherent projections of ESLs exist along the European coastline. The present contribution aims to filling this knowledge gap by combining dynamic simulations of all the major components of ESL considering the latest CMIP5 projections for RCP4.5 and RCP8.5.

The coastal task of PESETAIII provides estimates of coastal impacts in the 21st century by combining (i) projections of all the major components of ESL, estimated from dynamic simulations forced by the latest CMIP5 projections for RCP4.5 and RCP8.5; (ii) flood hazard maps obtained from a hydrological model shown to outperform static inundation approaches (Vousdoukas et al., 2016b); and (iii) projections of population, land use and GDP considering the Shared Socio Economic Pathways (van Vuuren and Carter, 2014). The overall approach builds on the disaster risk methodology proposed by the IPCC SREX (IPCC, 2012) report, defining risk as the combination of hazard, exposure and vulnerability. The study is focussed on coastal flooding only and does not address the effects of acidification in coastal areas. Moreover, combined flooding scenarios are not taken into account (meaning simultaneous fluvial and coastal flooding), as they represent a current knowledge gap and are the topic of current exploratory studies.

2 Data and methods

2.1 Climate scenarios

The present work focuses on a baseline 'historical' period (1980-2010) and climate change scenarios for Representative Concentration Pathways RCP4.5 and RCP8.5 (Meinshausen et al., 2011). RCPs are named after a possible range of radiative forcing values in the year 2100 relative to pre-industrial values (+2.6, +4.5, +6.0, and +8.5 W/m2, respectively). The RCP4.5 and RCP8.5 scenario correspond to a likely global mean temperature increase of 2.0-3.6°C and 3.2-5.4°C in 2081–2100 above the 1850–1900 levels (IPCC, 2013), respectively. RCP4.5 may be viewed as a moderate-emission-mitigation-policy scenario and RCP8.5 as a high-end, business-as-usual scenario.

Due to the specific needs of the coastal analysis, mainly in terms of spatial extent and temporal resolution of the climate data, climate projections from Task 1 could not be used. Instead atmospheric forcing (wind and pressure fields) from six Coupled Model Intercomparison Project Phase 5 (CMIP5) climate models for both RCP trajectories was used (see Section 2.2.4). Climate model uncertainties were reduced to the greatest possible extent by (1) selecting the CMIP5 climate models that according to Perez et al. (2014) are ranked with high skill in reproducing the synoptic climatologies and inter-annual variations across Europe; and (2) using a validated reanalysis, based on detailed atmospheric forcing, to correct for bias in the wave and storm surge projections generated from each GCM (Vousdoukas et al., 2016a).

2.2 Projections of extreme sea levels and inundation

It is important to stress that the modelling approach applied to assess coastal hazard is completely process-based, implying that it is builds on specialized numerical models which respect mass, momentum and energy balance equations. Such an approach implies that the framework is flexible and can be applied to different spatial and temporal scales, and can be constantly improved with anticipated developments in computational power and available datasets.

2.2.1 Extreme sea levels definitions

Extreme sea levels (ESL) are the result of the contributions from the mean sea level (MSL), the tide and the contribution from extreme events:

$$ESL = \eta_{HTWL} + \eta_{w-ss} \qquad 1$$

where $\eta_{w\text{-}ss}$ is extreme event component, and η_{HTWL} the high tide water level, defined as:

$$\eta_{HTWL} = MSL + RSLR + \eta_{tide} \qquad 2$$

where *RSLR* is the Relative Sea Level Rise, and η_{tide} is the tidal elevation.

The extreme event contribution $\eta_{w\text{-}ss}$ results from the combined effect of waves and storm surge, estimated according to the following equation:

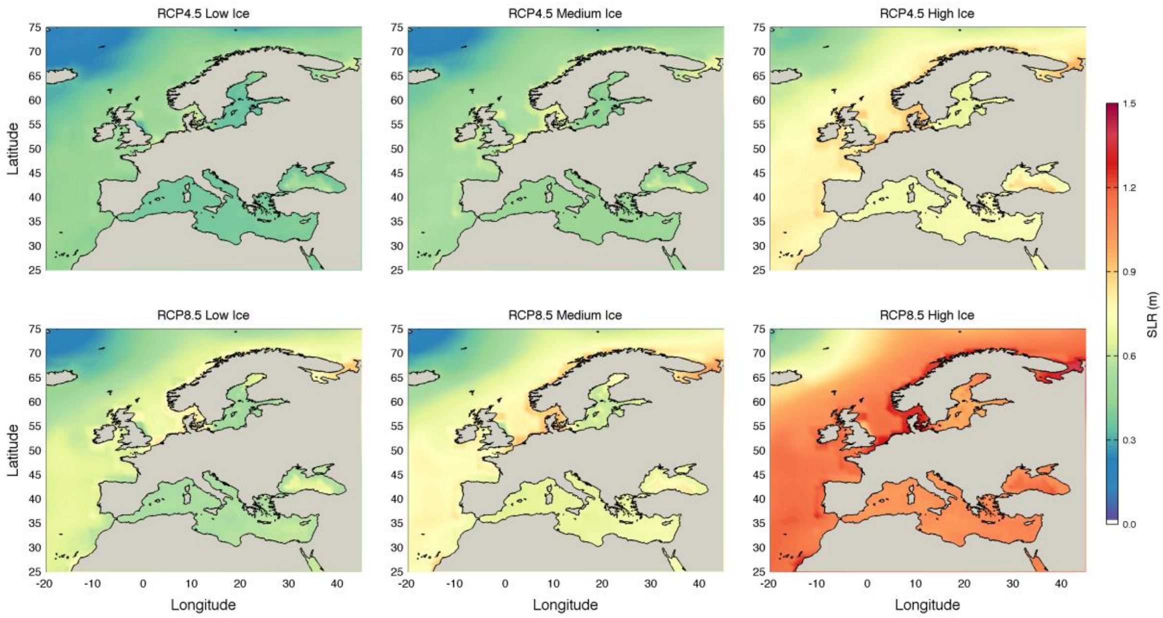
$$\eta_{w-ss} = SSL + 0.2 \cdot H_s \qquad 3$$

where SSL is the storm surge level, H_s is the significant wave height and $0.2H_s$ is considered to be a reliable approximation of the wave setup; i.e. the elevation in mean water level near the coast due to wave shoaling and breaking (US Army Corps of Engineers, 2002). More elaborate ways to estimate wave setup exist, considering apart from the significant wave height also the wave period, length and nearshore slope of the sea bottom. However, information about the nearshore bathymetry and/or the slope is not available at European scale at the resolution required to resolve wave shoaling processes. Therefore, the applied solution was chosen as the most reliable approach.

2.2.2 Relative Sea Level Rise

Projections of Sea Level Rise (SLR) were available from Hinkel et al. (2010), who combined output from a four-member ensemble of CMIP5 models (Taylor et al., 2011) with three land-ice contribution scenarios, based on the published range of contributions from ice sheets and glaciers. Global Relative Sea Level Rise (RSLR) values for different RCPs and time slices were available after combining SLR with land uplift/subsidence projections from Peltier (2004). Given that the SLR dataset is the result of a 4-member climate model ensemble, the best, worst and ensemble mean RSLR cases were estimated for each RCP.

Figure 2. Projected RSLR for the year 2100, under all the combinations of RCP 4.5 and 8.5, as well as low, medium and high ice scenarios. Based on data from Hinkel et al. (2014) and Peltier (2004).



2.2.3 Astronomical tide

Information about the present-state tidal elevation (η_{tide}) along the European coastline was obtained from the TOPEX/POSEIDON Global Inverse Solution (Egbert and Erofeeva, 2002). Given that the study is focusing on extreme events, the maximum tide was considered as representative. In order to assess how changing sea levels would affect tidal elevations, dynamic simulations of tidally forced ocean circulation took place along a global flexible mesh using the DFLOW FM model. The flexible mesh and model setup implemented has been extensively used and validated (Jagers, 2014; Muis et al., 2016). All simulations covered the period from 1990 to 2110 and considered all the possible combinations of the following projected RSLR cases: (1) RSLR under RCP4.5 and RCP8.5 and; (2) best, worst and ensemble mean RSLR case for each RCP.

Time series of tidal elevations η_{tide} were extracted at hourly intervals every 25 km along the European shoreline. The maximum tidal elevation was estimated for every decade and absolute and relative changes ($\Delta\eta_{\text{tide}}$ and $\%\Delta\eta_{\text{tide}}$, respectively) were obtained after comparing the projected values to the ones of the baseline year 1990:

$$\Delta\eta_{tide} = \eta_{tide,\text{RCP}} - \eta_{tide,\text{baseline}} \qquad 4$$

$$\%\Delta\eta_{tide} = \frac{\eta_{tide,\mathrm{RCP}} - \eta_{tide,\mathrm{baseline}}}{\eta_{tide,\mathrm{baseline}}} \times 100 \qquad 5$$

Given that accurate baseline values were available for η_{tide} they were combined with the projected relative changes to obtain the final η_{tide} projections:

$$\eta_{tide,\mathrm{RCP}} = \eta_{tide,\mathrm{TOPEX}} + \frac{\eta_{tide,\mathrm{TOPEX}} \times \%\Delta\eta_{tide}}{100} \qquad 6$$

2.2.4 Wave and storm surge reanalysis and projections

The storm surge level (SSL) contribution to the ESL was estimated by a reanalysis and projections of extreme SSLs along the European coastline, generated by Vousdoukas et al. (2016a). The SSL projections were obtained from dynamic simulations for a 6-member GCM ensemble available from the Coupled Model Intercomparison Project Phase 5 (CMIP5) database (Taylor et al., 2011) for both RCP trajectories: ACCESS1.0, ACCESS1.3 (CSIRO-BOM), CSIRO-Mk3.6.0 (CSIRO-QCCCE Australia), EC-EARTH (EC-EARTH consortium), GFDL-ESM2G, and GFDL-ESM2M (NOAA Geophysical Fluid Dynamics Laboratory, USA). Information about the model setup, calibration and validation, as well as a link to the dataset can be found in Vousdoukas et al. (2016a).

Wind atmospheric forcing from the same GCM ensemble was used to force the third generation spectral wave model Wavewatch III (Tolman, 2002), in order to generate a global wave dataset for the baseline period, as well as the current century under RCP4.5 and RCP8.5. A detailed description of the model setup and the validation can be found in Vousdoukas et al. (2017).

2.3 Non-stationary extreme value statistical analysis

Non-stationary extreme value statistical analysis (EVA) was applied to the extreme event water level time series $\eta_{w\text{-}ss}$ obtained according to equation 3. The time series covered the 130-year period from 1970 to 2100, combining the simulations for the baseline case and the RCP projections. The statistical analysis consisted in (i) transforming a non-stationary time series into a stationary one to which the stationary EVA theory can be applied; and (ii) reverse-transforming the result into a non-stationary extreme value distribution, thus allowing to estimate values for different return periods and times during the analysed period. A detailed description of the methodology and a link to the source code of the non-stationary EVA approach can be found in Mentaschi et al. (2016).

2.4 Coastal inundation modelling

Coastal inundation modelling took place at pan-European scale following the approach described in Vousdoukas et al. (2016b). The simulations were based on the SRTM Digital Elevation Model (DEM) (Reuter et al., 2007), considered at 100 m spatial resolution. The Lisflood-ACC (LFP) (Bates et al., 2010; Neal et al., 2011) was used, a 2D hydraulic model which is part of the Lisflood-FP model (Bates and De Roo, 2000). The combination of the 2 RCPs, 6 time periods (1995, 2020, 2040, 2060, 2080, 2100) and 8 return periods considered (5, 10, 20, 50, 100, 200, 500, 1000), implies that a total of 96 pan-European flood assessments were carried out for the present study.

2.5 Exposure

2.5.1 Static datasets

Exposure represents the capital and human assets exposed to the hazard. These are typically expressed by statistics on population, socio-economic data on sectorial activities and infrastructure, and information about environmental variables. To assess impacts in coastal zones in Europe the following exposure information has been collected:

Current population: a 100 m resolution population grid map for Europe has been derived for the year 2006 based on a refined version of Corine Land Cover 2006 (with a minimum mapping unit of one hectare for artificial surfaces (Batista e Silva et al., 2013), combined with information on the soil sealing degree.

Current land use: A refined version of the Corine Land Cover 2006 map with an improved minimum mapping unit of 1 hectare for all types of artificial surfaces and inland waters has been generated by incorporating land use/cover information present in finer thematic maps available for Europe. These include the CLC change map, Soil Sealing Layer, TeleAtlas® Spatial Database, Urban Atlas, and SRTM Water Bodies Data. Relevant data from these datasets were extracted and prepared to be combined with CLC in a stepwise approach. Each step increased the level of modifications to the original CLC. The spatial resolution of the map is 100 x 100 m (Batista e Silva et al., 2013).

2.5.2 Country level exposure projections

The static exposure layers described in section 2.5.1 were combined with country level economic projections available from two sources. The first set of projections are based on the Shared Socioeconomic Pathways (SSP) (O'Neill et al., 2014; van Vuuren et al., 2014). RCP4.5 is compatible with global sustainable development (SSP1) and RCP8.5 is compatible with socio-economic development driven by mitigation challenges (SSP5) or both mitigation and adaptation challenges (SSP3). Gross domestic product (GDP) and population projections from IIASA for SSP1, SSP3 and SSP5 were acquired in the form of 5-years multipliers that were applied to the baseline exposure layers (i.e. population density and damage functions) to reflect changes in the future population exposed and value of exposed assets. The second set of country projections that were used in this work are the projections based on the 2015 ECFIN Ageing Report produced in Task 2 of PESETA III, which are not directly linked to a specific greenhouse gas emissions pathway. Both sets of country projections are provided in the form of country aggregated information, hence this step assumes that the growth in GDP and population are homogeneously distributed within each country.

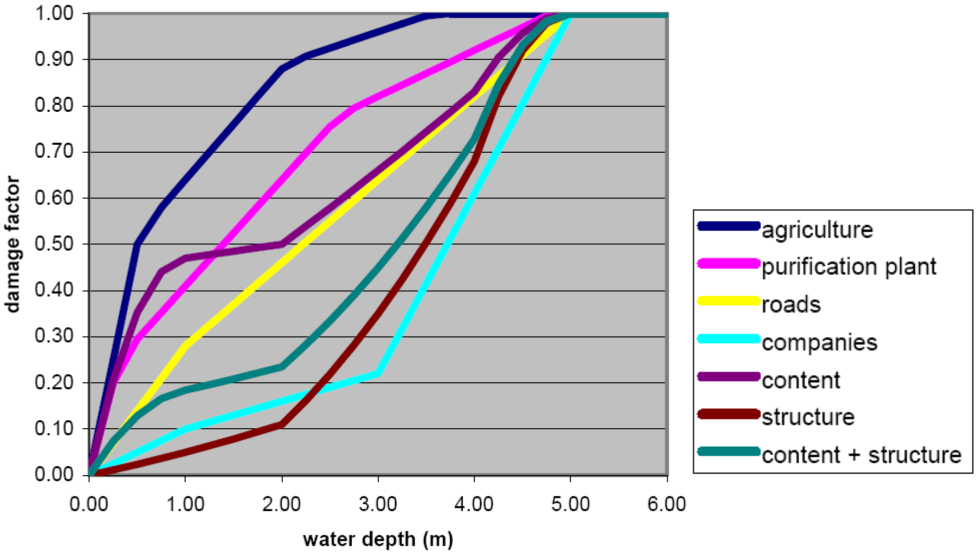
2.5.3 Gridded exposure projections

In order to account for population and economic dynamics within countries an additional assessment of future coastal flooding risk was obtained by considering gridded projections of population density at 1/8° resolution (Jones and O'Neill, 2016) based on SSPs. Spatial changes in GDP for the SSPs considered were derived from the gridded SSP population projections by spatially disaggregating the country-level GDP projections in accordance to the spatial patterns of population change. Given that urban land use classes contribute to >90% of the estimated damages, relative changes in urbanization were similarly derived from the gridded population projections to estimate changes in land use.

2.6 Vulnerability

Vulnerability refers here to the susceptibility of the receptor to be adversely affected by the coastal flood hazard and can be seen as an internal characteristic of the affected element. This includes the capacity to anticipate, cope with, resist, and recover from the adverse effects of the physical event. The vulnerability to coastal flooding of coastal infrastructure, societies and ecosystems is expressed in this work through depth-damage functions (Ciscar et al., 2014; Rojas et al., 2013). JRC has an extensive database of country-specific depth-damage functions (DDFs) that relate water depth with exposed assets and the resulting economic damage. The country based DDFs are piece-wise linear functions from 0 to 6 meter flood depth, defined for each of the 45 land use classes included in the refined CORINE Land Cover (e.g. see; Figure 3). To account for differences in the distribution of wealth within countries, national DDFs were further rescaled to NUTS3 level on the grounds of GDP per capita.

Figure 3. Example depth-damage functions showing relationship between flood water depth and damage factor per land use class (note that damage factors are normalized) and need to be rescaled with maximum damages per land use class prior to their application).



2.7 Data organization

All data related to exposure and vulnerability were organized at the same 100 m resolution grid as the DEM, with the Open Street maps coastline position (www.openstreetmapdata.com) used to define the boundary between land and sea. Following, data were organized in coastal segments, each with a length of 25 km along the shoreline and extending 50 km inland. An example of a division of a piece of coastline in coastal segments in presented in Figure 4 for a stretch of coastline in Southern Portugal.

Figure 4. Example of coastal segments defined in the SW coast of Portugal and Gulf of Cadiz.

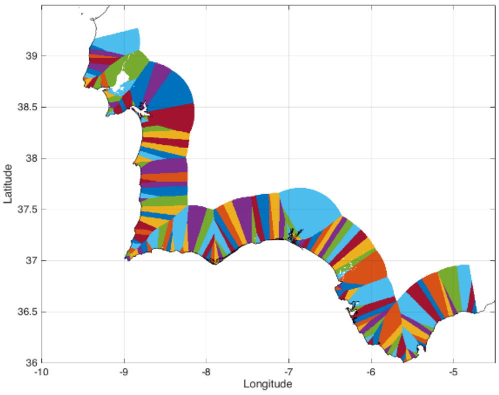
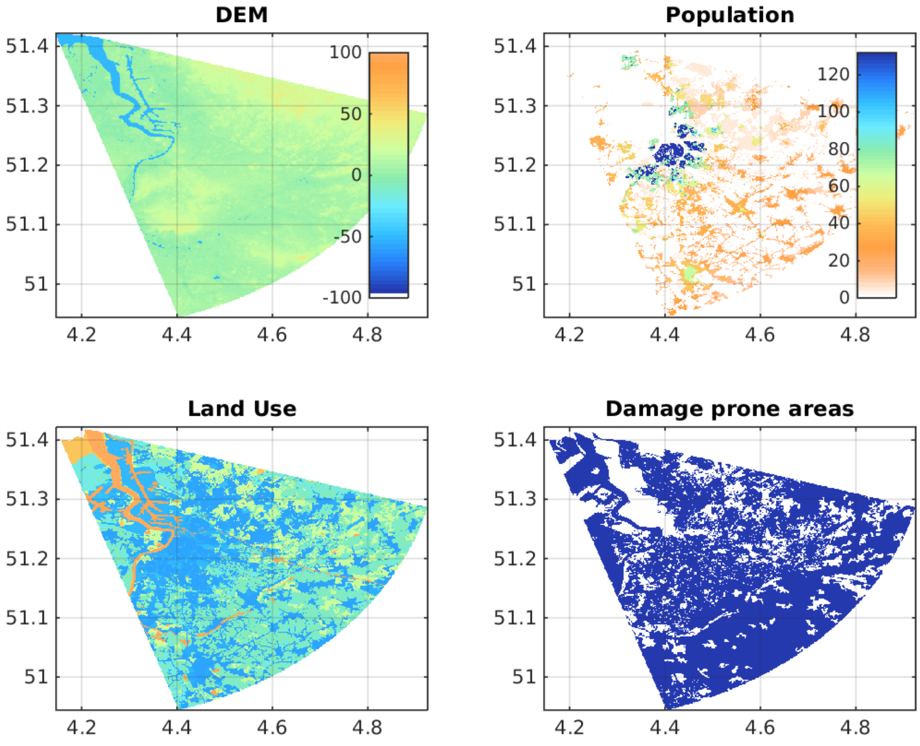


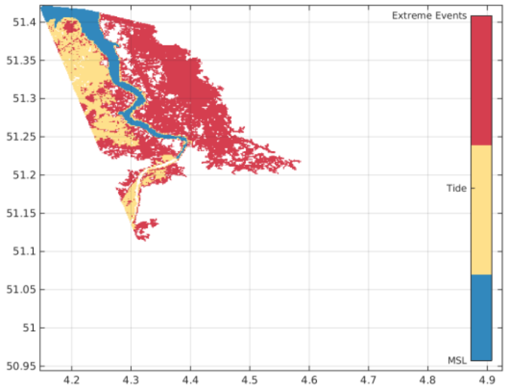
Figure 5. Example of coastal segment data: Digital Elevation Model, Population, Land Use and Damage Prone areas according to the land use and the depth damage functions.



2.8 Impact assessment

Extreme events drive episodic inundation along the coastal zone, while under RSLR conditions the sea can permanently occupy coastal areas. Each of the above inundation cases demand a different impact assessment methodology, and therefore inundation maps were generated for each of the components: i.e. areas flooded only due to the η_{CE} component, or due to the tide, or MSL. RSLR and climate extremes contribute differently to damages, for example areas and assets that lie below MSL (due to future sea level rise) are permanently flooded and can be considered as lost. Therefore, for these areas the direct impacts are estimated after applying the DDFs considering the maximum inundation depth. The same applies to areas that lie inside the intertidal zone (above MSL, but below the maximum tide) and which are inundated on a daily basis. On the other hand, economic losses along areas inundated during extreme events, are estimated considering the inundation depths and the DDFs. The number of people affected by coastal flooding is estimated superimposing the inundation with the exposure maps. As permanently flooded areas are considered the ones inundated by the 1-year ESL, and their population contributes to the number of people expected to be relocated.

Figure 6. Example of the different inundation zones from each TWL component; mean sea level (blue), tide (yellow) and extreme events (red)



All impact components come as a function of time and return period, and Expected Annual Losses are used to summarize the information for a given year. For example the Expected Annual Damage (EAD) is provided from the following equation:

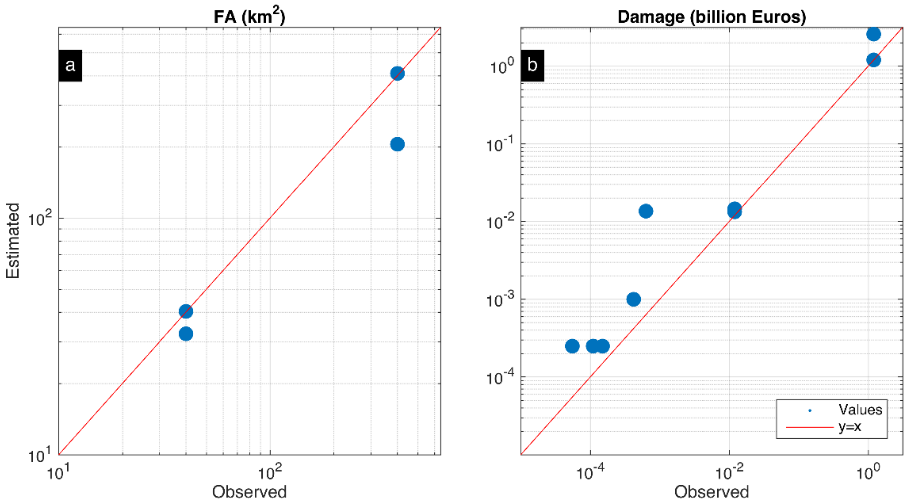
$$EAD = \frac{1}{2}\sum_{i=1}^{n}\left(\frac{1}{T_{r_i}} - \frac{1}{T_{r_{i-1}}}\right)\left(D_i + D_{i+1}\right) \tag*{7}$$

where T_r is the return period and D is the direct impact. Apart from the EAD, the parameters estimated are the Expected Annual Number of People Affected (EAPA), and the Expected Annual Number of People forced to relocate because of SLR (EAFR).

2.9 Validation

Despite recent efforts to create databases of past natural disasters (e.g. http://www.emdat.be/), information on the flood extent and the damage from past coastal flood events is scarce. The Xynthia storm remains one of the few recent events in Europe which has been documented in detail, while additional information for past events was obtained from the European Past Floods Database, available from the European Environmental Agency (http://www.eea.europa.eu/data-and-maps/data/european-past-floods). Inundation maps were obtained from other sources, such as the e-Surge portal (http://www.storm-surge.info/) and from personal communication with national authorities, and were combined with the flood extent and damage data of the EEA database. The resulting database of historical impacts was used to validate the LISCOAST Impact Assessment approach and values were of the same order of magnitude with relative RMSE not exceeding 50%. These results were satisfactory given the different sources of uncertainty both in terms of the methodology and the ground truth dataset.

Figure 7. Validation of the LISCOAST approach in terms of flood extent (FA: a), and damages (b).



Moreover, for several countries there are available baseline inundation maps and losses for different return periods[1,2,3,4], which have been used to calibrate the country level protection standards considered in the analysis and to carry out a country-level validation.

2.10 Studied cases

Given that MSL and $\eta_{extreme}$ are both dynamic parameters, inundation modelling takes place along all the 10328 European coastal segments for the combination of the 2 RCPs, 3 scenarios (ensemble mean, worst- and best-case), 6 time periods (1995, 2020, 2040, 2060, 2080, 2100) and 8 return periods considered (5, 10, 20, 50, 100, 200, 500, 1000). The latter implies a total of 288 pan-European flood assessments, each combined with 3 SSPs to assess three studied scenarios: RCP4.5-SSP1, RCP8.5-SSP3, and RCP8.5-SSP5. The above analysis was applied for different combinations of driving physical processes and socio-economic development:

Physical contributions: in order to understand the contribution of different physical drivers, several set-ups were assessed as summarized below:

	STATIC MSL	DYNAMIC MSL
NO CLIMATE EXTREMES		P1
STATIC CLIMATE EXTREMES WITHOUT WAVES	P2	P3
STATIC CLIMATE EXTREMES WITH WAVES	P4	P5
DYNAMIC CLIMATE EXTREMES WITHOUT WAVES	P6	P7
DYNAMIC CLIMATE EXTREMES WITH WAVES	P8	P9

P9 is considered the most complete assessment covering all ESL components and their dynamics. The importance of the individual physical parameters as drivers of economic losses is expressed by the following ratios:

- P5/P9: percentage of projected impacts explained solely by RSLR
- P6/P9: percentage of projected impacts explained solely by storm surge

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[1] Paprotny, D. and Terefenko, P., 2017. New estimates of potential impacts of sea level rise and coastal floods in Poland. Natural Hazards, 85(2): 1249-1277.

[2] https://www.helpdeskwater.nl/onderwerpen/waterveiligheid/programma'-projecten/veiligheid-nederland/english/flood-risk-the/

[3] http://environment.data.gov.uk/ds/catalogue/#/8c75e700-d465-11e4-8b5b-f0def148f590

[4] https://doi.org/10.9753/icce.v33.posters.23

- (P8-P6)/P9: percentage of projected impacts explained solely by waves
- P8/P9: percentage of projected impacts explained solely by climate extremes (all components)

All the above assessments allow breaking down the contributions from each physical component. For example P1 expresses the impacts driven only from RSLR, and P9-P1 expresses the impacts driven only from climate extremes. Given that waves are usually omitted in such studies, P7-P1 allows to quantify the impacts driven only from dynamic storm surge, and P9-P7 expresses the additional impacts when waves are considered. Climate extremes are considered as static in most similar studies, therefore an additional analysis took place breaking down the contributions from static and dynamic waves/storm surge:

- P3-P1: impacts driven only by static storm surge
- P5-P3: impacts driven only by static waves
- P5-P1: impacts driven only by static climate extremes (all components)
- P9-P5: residual impacts from considering changes in climate extremes (all components)

Climate change *vs* Socio-economic development: P9 is combined with static and dynamic exposure layers, with or without climate change, resulting in the following cases:

	STATIC CLIMATE	DYNAMIC CLIMATE
STATIC EXPOSURE		S1
DYNAMIC COUNTRY-LEVEL EXPOSURE	S2	S3
DYNAMIC GRIDDED EXPOSURE	S4	S5

S5 is considered the most complete assessment covering all physical and socio-economic components, as well as their dynamics. Combinations of the analysed scenarios allow to assess the importance of physical changes *vs* socio-economic development as drivers of economic losses:

- S1/S5: percentage of projected impacts explained by climate change
- S2/S5: percentage of projected impacts explained by country-level changes in exposure
- S4/S5: percentage of projected impacts explained by gridded changes in exposure

Similarly to the assessment of ESL component contributions, it is also possible to break down the contributions from the different components. For example S1 expresses the impacts driven only from climate change, and S5-S1 (S3-S1) expresses the contributions to the total impacts only from gridded (country-level) socio-economic development. S5-S3 allows quantifying the residual change from considering gridded exposure projections.

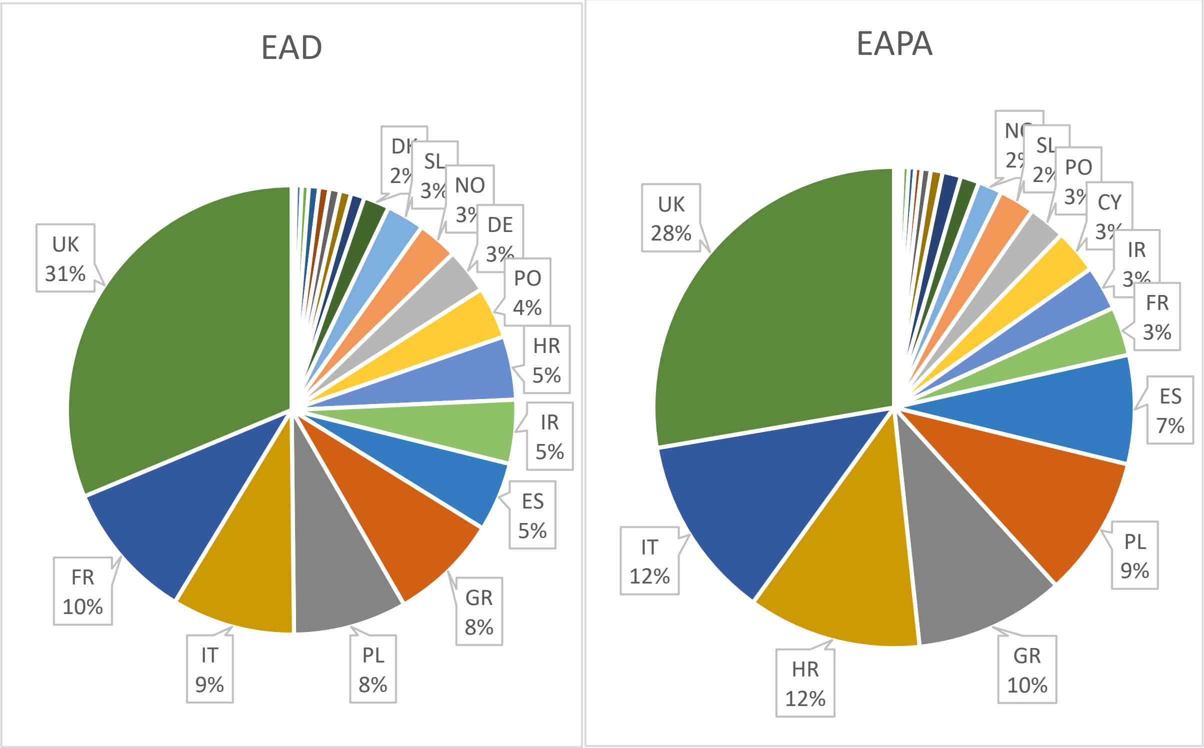
2.11 Post processing

The study focuses on EAD, EAPA and EAFR that are available every 25 km of coastline, but are presented at country level and Europe. Contributions from the different ESL components and the socio-economic development projections are presented at European level, and discussed after averaging all RCP-SSP scenarios studied.

3 Results

The estimated Expected Annual Damage (EAD) value in the baseline for Europe is 1.25 billion €, while the Expected Annual number of People Affected by coastal flooding (EAPA) equals 102,000. The countries contributing more to the European total EAD are the UK, France and Italy (31%, 10% and 9%, respectively). The contributions to the EAPA are dominated by the UK (28%), Italy (12%) and Croatia (12%) (Figure 8).

Figure 8. Contributions of EU countries to the total present day EAD and EAPA from coastal flooding.

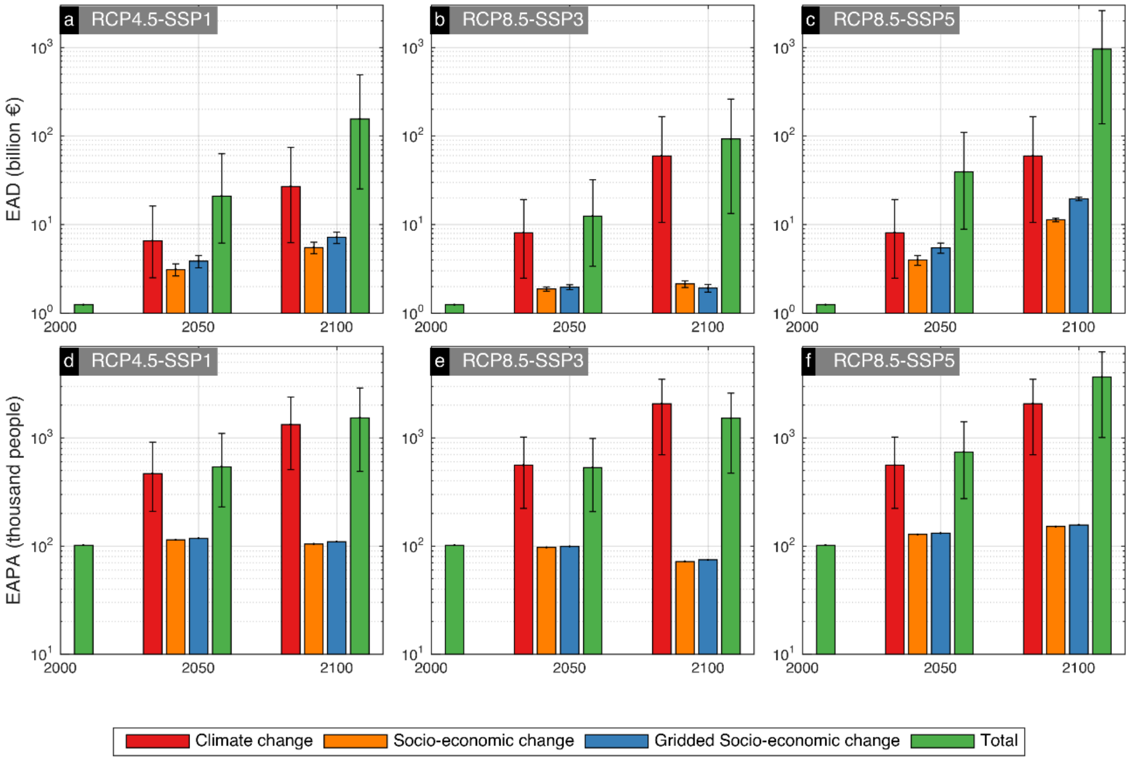


Our estimate for EAPA is considerably higher than the 35,700 reported by Richards and Nicholls (2009) and the ~10,000 and ~15,000 reported by Brown et al (2011) and Hinkel et al. (2010). On the other hand, our estimate EAD is lower than the values reported by previous studies, which usually exceeds 2 billion €. For example, Brown et al. (2011) estimated baseline damages around 2 billion €, while reported values from other studies are even higher, between 3.1 and 4.9 billion € (Ciscar et al., 2014; Hinkel et al., 2010).

Even though the above numbers are of the same order of magnitude, a comparison is challenging, given the substantial differences in the methodology and the datasets used. Among the steps forward taken by the present study is the generation of hazard maps with a hydrological model, in comparison to the static inundation approach that is commonly used. The latter has been shown to overestimate flood extents by more than 30%, and even more than 100% along flat terrains (Vousdoukas et al., 2016b). Moreover, our methodology includes all ESL components and present findings show that considering the wave ESL contribution adds to the estimated impacts by 27%-58% (Figure 10). Among other important differences are the reference year and resolution of the exposure layers, as well as the impact modelling methodology.

Figure 9 shows the evolution of coastal flood risk up to the end of the century for the static and dynamic economic analysis. Under the static economic analysis (with fixed exposure) EAD is projected to exceed 6.5 billion € by mid-century (respectively 6.6 and 8.1 billion € for RCP4.5 and RCP8.5). In the second halve of the century the projections of flood damage diverge more strongly between the two RCPs. By 2100, due to the effects of climate change only, EAD could rise to 27 billion € under RCP4.5 and to 59.8 billion € under RCP8.5, or approximately 20 and 50 times baseline impacts.

Figure 9. Projected evolution in time of coastal flooding impacts aggregated at European level for different economic analyses: only climate change with static exposure (red), static climate combined with country-level socioeconomic change based on SSPs (orange), static climate combined with gridded socioeconomic change (blue), and climate change combined with gridded socioeconomic change (green). Expected Annual Damage (a, b and c) and Expected Annual number of People Affected (d, e and f) from coastal flooding under RCP4.5-SSP1 (a and d), RCP8.5-SSP3 (b and e), and RCP8.5-SSP5 (c and f). Bars express the ensemble mean projections, black error plots express inter-model variability.



When socio-economic development is accounted for in the impact calculations, absolute flood risk shows a more pronounced increase compared to when only climate change (red bars in Figure 9) is accounted for. Flood damages obtained based on the gridded SSPs (blue bars in Figure 9) vs country-based SSPs (orange bars in Figure 9) projections of socio-economic development indicate that the wealth in coastal zones will rise stronger relative to total country increases in wealth. We further note that under a RCP4.5 – ECFIN scenario, flood impacts are approximately 20% lower compared to the RCP4.5 – SSP1 country based projections. This reflects the somewhat slower economic growth projected by the Ageing Report compared to SSP1. For RCP8.5, the results based on the ECFIN projections (with EAD = 238 billion Euro for Europe by 2100) lie in between those for SSP3 (with EAD = 104 billion Euro for Europe by 2100) and SSP5 (with EAD = 555 billion Euro for Europe by 2100).

We further report here impacts for the gridded projections. For Europe the total EAD for the year 2050 is projected to amount to 21, 12.5, and 39 billion € under RCP4.5-SSP1, RCP8.5-SSP3, and RCP8.5-SSP5, respectively (Figure 9). This represents an increase around 9-30 times compared to the baseline. The impacts are projected to accelerate towards the end of the century, reaching 156, 93 and 961 billion € under RCP4.5-SSP1, RCP8.5-SSP3, and RCP8.5-SSP5, respectively (Figure 9), or an increase around 73-770 times compared to the baseline. Under the worst case scenario, damages could exceed 2 trillion €/year. This shows that coastal flood risk is amplified by economic growth. It should be noted, however, that the projected socio-economic conditions imply a wealthier society hence also an increase in the capacity to absorb the increase in coastal flood risk.

The evolution of coastal flood damage at country level is presented in Table 2 for the static economic analysis (so reflecting only the effect of climate change). Country-level projections show that all countries with a coastline follow the continental trend of rising flood damages with time. The UK and France show the highest absolute increase in annual flood damage, which rises towards the end of the century with around 5 and 10 billion € under RCP4.5 and RCP8.5, respectively (Table 2). The absolute increase in annual flood damage is also large in Norway (2.9 and 7.4 billion €, respectively) and Italy (3 and 5.5 billion €, respectively). Albeit that the rise in coastal flood risk is considerable everywhere in Europe, the lowest relative increases in flood damage are projected for Slovenia (+334% by 2100 under RCP8.5), Poland (+692% by 2100 under RCP8.5), Portugal (+824% by 2100 under RCP8.5) and the Baltic States (<1600% by 2100 under RCP8.5). This shows how drastically climate change will affect flood risk along Europe's coasts.

Also reported in Table 2 are EAD values for each country and Europe when global average warming reaches 2˚C under the two RCPs. This shows that impacts at 2˚C warming is larger under the RCP4.5 scenario compared to RCP8.5. This is related to inertia effects of global warming on SLR. Because the rate of warming is higher under RCP8.5, with 2˚C warming occurring around 2043, the effect of SLR are less pronounced compared to RCP4.5, for which 2˚C warming is projected around 2057. Nevertheless, at any specific point in time, impacts under RCP8.5 are always larger that under RCP4.5.

Table 2. Expected Annual Damage (EAD) from coastal flooding per country for the baseline, and for 2050, 2100 and 2˚warming under RCP4.5 and RCP8.5. Damages are expressed in million € (2010 values) and reflect the effects of only climate change (static economic analysis) for a moderate ice-sheet behaviour case.

	BASELINE	**RCP4.5**			**RCP8.5**		
	2000	2050	2100	2˚C	2050	2100	2˚C
BELGIUM	0.01	0.08	0.22	0.09	0.05	0.56	0.04
BULGARIA	0.00	0.01	0.02	0.01	0.01	0.08	0.01
CYPRUS	0.01	0.07	0.23	0.09	0.09	1.00	0.07
GERMANY	0.04	0.26	0.96	0.33	0.29	2.68	0.25
DENMARK	0.02	0.17	1.24	0.27	0.18	3.62	0.13
ESTONIA	0.01	0.02	0.04	0.02	0.02	0.06	0.02
SPAIN	0.06	0.38	1.72	0.55	0.53	3.36	0.40

FINLAND	0.01	0.02	0.04	0.02	0.03	0.30	0.02
FRANCE	0.12	1.05	4.85	1.49	1.37	11.49	0.94
GREECE	0.10	0.74	2.22	0.91	0.86	4.40	0.69
CROATIA	0.06	0.21	0.81	0.28	0.27	1.51	0.20
IRELAND	0.06	0.31	1.54	0.46	0.44	3.14	0.30
ITALY	0.11	0.65	3.15	0.95	0.89	5.67	0.59
LITHUANIA	0.01	0.05	0.11	0.06	0.05	0.20	0.04
LATVIA	0.01	0.02	0.03	0.02	0.02	0.06	0.02
MALTA	0.00	0.00	0.00	0.00	0.00	0.01	0.00
NETHERLANDS	0.00	0.00	0.01	0.00	0.00	0.02	0.00
NORWAY	0.04	0.32	2.91	0.56	0.55	7.41	0.31
POLAND	0.10	0.24	0.47	0.27	0.26	0.81	0.22
PORTUGAL	0.05	0.11	0.27	0.13	0.14	0.43	0.12
ROMANIA	0.00	0.01	0.03	0.01	0.01	0.83	0.00
SWEDEN	0.01	0.03	0.29	0.05	0.05	1.04	0.03
SLOVENIA	0.03	0.06	0.11	0.06	0.06	0.15	0.05
UNITED KINGDOM	0.39	1.76	5.69	2.26	1.98	10.99	1.54
EUROPE	1.25	6.56	26.96	8.90	8.13	59.82	6.01

Table 3 shows the EAPA for the scenario considering only climate change, so assuming static population. Aggregated over Europe, EAPA is projected to rise from 102,000 under present climate conditions to more than 450,000 people annually exposed to coastal flooding (respectively 467,900 and 558,800 people for RCP4.5 and RCP8.5) by mid-century. Similarly to the damage projections the figures diverge between the two RCPs as time proceeds, and by 2100 EAPA could rise to 1.3 million people under RCP4.5 and to 2.1 million people under RCP8.5 (Table 3).

When including spatial projections of population change the total EAPA for Europe in 2050 is projected to rise to 540,430, 532,750 and 741,570 under RCP4.5-SSP1, RCP8.5-SSP3, and RCP8.5-SSP5, respectively (Figure 9). This will further grow to 1.53, 1.52, and 3.65 million people towards the end of the century. Similar to EAD, the projected increase in EAPA accelerates from mid-century, but at a slower rate afterwards following the trend discerned under population scenarios. The countries with the highest absolute increase in EAPA are the UK, Italy and France (643,000, 225,000, and 220,000, respectively).

Table 3. Expected Annual Number of People Affected (EAPA, in thousands) from coastal flooding per country for the baseline, and for 2050, 2100 and 2˚warming under RCP4.5 and RCP8.5. Damages are expressed in million € (2010 values) and reflect the effects of only climate change (static economic analysis) for a moderate ice-sheet behaviour case.

	BASELINE	**RCP4.5**			**RCP8.5**		
	2000	2050	2100	2˚C	2050	2100	2˚C
BELGIUM	0.2	1.8	5.1	2.2	1.2	9.4	1.1
BULGARIA	0.6	1.5	2.6	1.6	1.5	3.6	1.4
CYPRUS	3.0	9.4	11.6	9.7	9.8	12.7	9.2
GERMANY	1.3	7.8	27.4	9.7	8.8	65.7	7.7
DENMARK	0.8	5.8	46.7	9.5	6.4	103.9	4.7
ESTONIA	0.1	0.3	0.4	0.3	0.3	0.6	0.3
SPAIN	7.5	51.1	147.5	65.1	64.3	187.9	51.3
FINLAND	0.4	0.9	2.3	1.1	1.4	17.1	1.1

FRANCE	3.3	25.1	105.3	35.4	34.0	191.5	22.8
GREECE	10.2	58.8	123.9	68.3	66.7	167.8	54.5
CROATIA	11.9	40.8	100.1	48.9	47.7	139.4	38.1
IRELAND	3.1	17.5	57.9	22.9	22.8	88.5	17.3
ITALY	12.6	71.8	198.1	92.0	90.7	265.4	66.8
LITHUANIA	1.3	3.4	7.5	3.9	3.6	12.3	3.2
LATVIA	0.2	0.5	1.1	0.6	0.6	1.7	0.5
MALTA	0.0	0.1	0.2	0.1	0.1	0.2	0.1
NETHERLANDS	0.0	0.1	0.5	0.2	0.1	0.9	0.1
NORWAY	1.6	12.4	95.3	23.1	23.5	175.4	13.0
POLAND	9.6	17.8	28.8	19.5	18.4	41.0	16.9
PORTUGAL	2.5	6.0	11.8	6.8	6.9	17.0	6.1
ROMANIA	0.4	0.9	3.0	1.2	1.0	6.0	0.8
SWEDEN	0.4	1.6	15.5	2.8	2.3	36.8	1.6
SLOVENIA	2.4	3.8	4.8	3.9	3.9	5.4	3.6
UNITED KINGDOM	28.2	128.7	332.5	157.7	142.9	527.9	114.0
EUROPE	101.9	467.9	1329.9	586.3	558.8	2078.1	436.0

Breaking down the contributions of the ESL components shows that future coastal flood risk mainly relates to extreme weather conditions, which are driving >97.5% of the future estimated impacts (Figure 10). RSLR is projected to locally surpass coastal protection structures and have direct effects only after 2060, contributing up to 2.5% of the mean EAD and EAPA, towards the end of the century (Figure 10). This number is lower than the residual from considering or not climate variability in waves and storm surge, accounting for 4.9%-11% of the estimated impacts. However, RSLR has a strong indirect effect by increasing the absolute magnitude of extreme events, and therefore acts as the main driver of increasing flood risk. This is shown by the fact that RSLR combined with stationary climate extremes can explain 87%-96% of the total impacts (Table 4). Climate controls on waves/storm surges play a less important role, since dynamic projections of climate extremes under the absence of RSLR can in average explain 24% of the projected total impacts in 2050, a number decreasing to 4.6%-7% towards the end of the century, when RSLR gathers pace (Table 4).

Figure 10. Contributions to EAD (a,b) and EAPA (c,d) from the different ESL components aggregated for Europe: RSLR (blue), baseline climate extremes component (red), wave contribution (green), dynamic variations of climate extremes (purple), and aggregated total. Black error plots express inter-model variability. Note that values correspond to static economic analysis.

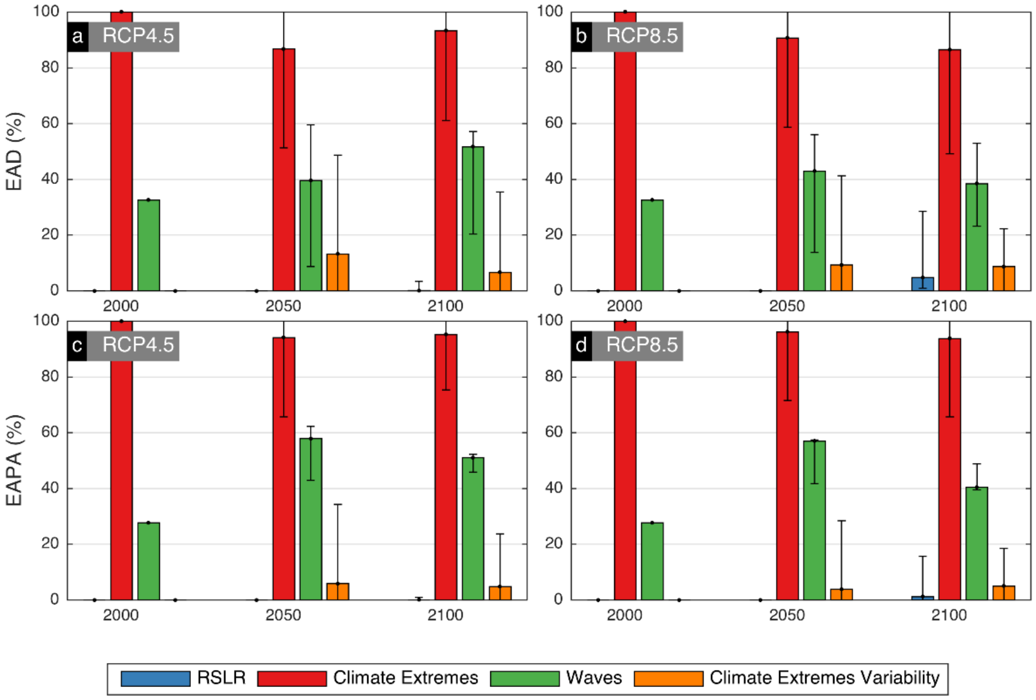


Table 4. Percentage of the total EAD and EAPA explained from considering RSLR combined with static climate extremes (Static CE), no RSLR combined with dynamic climate extremes (No RSLR), and without considering wave ESL contributions (No waves), under RCP4.5-SSP1, RCP8.5-SSP3, and RCP8.5-SSP5, in 2050 and 2100.

		BASELINE			**2050**			**2100**		
		Static CE	No RSLR	No waves	Static CE	No RSLR	No waves	Static CE	No RSLR	No waves
EAD	RCP4.5	100	100	67.4	86.8	27.9	60.4	93.4	6.3	48.3
	RCP8.5	100	100	67.4	90.7	19.9	57.1	91.3	2.9	61.5
	Mean	**100**	**100**	**67.4**	**88.74**	**23.9**	**58.7**	**92.36**	**4.6**	**54.9**
EAPA	RCP4.5	100	100	72.3	94.1	25.9	42.1	95.2	10.2	49.0
	RCP8.5	100	100	72.3	96.1	21.1	43.0	95.0	6.1	59.6
	Mean	**100**	**100**	**72.3**	**95.12**	**23.5**	**42.6**	**95.11**	**8.2**	**54.3**

4 Conclusions

The work carried out constitutes a significant step forward in the current state of the art of coastal impact assessment in view of climate change, especially for continental scale studies. There have been substantial improvements in all the components of the impact assessment calculation chain, which are discussed hereinafter, along with current knowledge gaps/limitations, followed by potential improvements/solutions.

The safety and resilience of European coastal societies depends on the effectiveness of natural and man-made coastal flood protection, i.e. the capacity to act as a buffer and absorb ocean energy through complex wave shoaling and breaking processes (Vousdoukas et al., 2012). RSLR-driven intensification of ESLs will push existing coastal protection structures beyond their design limits (Sierra and Casas-Prat, 2014), rendering a large part of Europe's coastal zones exposed to intermittent flood hazard. For most part of Europe the present day 100-year extreme sea level event is expected to occur on an annual basis by 2100. As a consequence, direct impacts are projected to increase by an order of magnitude after 2070, and even by two orders of magnitude under the *Fossil Fuel Development* SSP5.

The projected intensification of risks is one of the most prominent among other natural hazards (Forzieri et al., 2016), with implications which are unprecedented and unpredictable. The present findings accent the urgent need for implementing long-term coastal adaptation strategies; which if not timely could imply massive population movements (Hauer et al., 2016). Present investments in coastal protection of low lying areas like the Netherlands, which spend 1.2-1.6 billion Euro per annum in their Delta Programme (Delta Committee, 2008), shows that this may inflict huge costs. Recent evidence further shows significant future global investments and maintenance costs of protecting coasts by dikes, varying between US$ 12-71 billion per annum in 2100 (Hinkel et al., 2014).

It is likely that the present analysis tends to underestimate several aspects of coastal risk. First of all the reported impacts are only direct, while indirect ones can be even higher. Recent findings imply that RSLR can exceed the presently considered range (DeConto and Pollard, 2016; Hinkel et al., 2015), rendering the present projections on the conservative side. Processes that lead to impacts such as dyke failure and coastal erosion are neglected, as their consideration remains a challenge given the complex processes as well as temporal and spatial scales involved. Similarly challenging is the assessment of compound flooding events driven by joint, river and coastal flooding; which are not presently considered. All the above comprise potential directions for future research, along with the cost-benefit analysis of potential adaptation solutions.

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List of abbreviations and definitions

ESL	Extreme Sea Levels
MSL	Mean Sea Level
RSLR	Relative Sea Level Rise
SLR	Sea Level Rise

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