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Understanding the Drivers of Coastal Flood Exposure and Risk From 1860 to 2100

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Key Points:

- 20th century coastal exposure and risk is almost completely attributable to socie-econmoic development
- For 21st century this changes: climate induced sea-level rise can become the main driver of coastal exposure and risk in the 21st century
- Coastal adaptation is a crucial driver for coastal risk - global mitigation policy needs to be complemented by local coastal management

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Global coastal flood exposure (population and assets) has been growing since the beginning of the industrial age and is likely to continue to grow through 21st century. Three main drivers are responsible: (a) climate-related mean sea-level change, (b) vertical land movement contributing to relative sea-level rise, and (c) socio-economic development. This paper attributes growing coastal exposure and flood risk from 1860 to 2100 to these three drivers. For historic flood exposure (1860–2005) we find that the roughly six-fold increase in population exposure and 53-fold increase in asset exposure are almost completely explained by socio-economic development (>97% for population and >99% for assets). For future exposure (2005–2100), assuming a middle-of-the-road regionalized socio-economic scenario (SSP2) without coastal migration and sea-level rise according to RCP2.6 and RCP6.0, climate-change induced sea-level rise will become the most important driver for the growth in population exposure, while growth in asset exposure will still be mainly determined by socio-economic development.

Plain Language Summary This study provides the first analysis of historical (1860–2005) and future (2005–2100) coastal flood exposure and flood risk and the attribution of both to the three main drivers: socio-economic development, climate-related sea-level change and geologic sea-level change. From 1860 to 2005 coastal population has grown roughly by factor 6 and coastal assets roughly by factor 53 and this growth has almost completely be driven by socio-economic development. From 2005 to 2100 further growth is expected, where the actual factor depend on the chosen scenario. However, this future growth is much more driven by climate-induced sea-level rise then the historical growth. For coastal risk adaptation measures have to be taken into account and it shows that adaptation is a crucial factor. With adaptation taken into account the increase in coastal risk is lower than the increase in coastal exposure, in general with higher attribution to the climate driver.

1. Introduction

Coastal flood exposure (defined as the population and the assets located within the 100-year floodplain) and related risk (which depends on exposure and is defined as expected annual population flooded and expected annual asset damage) are dynamic in time. The dynamics reflects changes in socio-economic (population and capital) and climatic (sealevel and storm surge heights) condititions that alter the flood system componenets. These are the hazard (given by the probability distribution of extreme water levels which changes with sea-level rise), exposure (given by the population and assets in the floodplain which change with socio-economic development) and vulnerability (given by the coastal protection measures which also change with socio-economic development) (Oppenheimer et al., 2019). Taking a global and long-term perspective there are two main drivers of coastal flood risk: (a) socio-economic development (SED) leading to an increase (or decrease) of coastal exposure due to population and asset growth (or decline) in coastal areas, and (b) relative sea-level change. Relative sea-level change can be further distinguished by its cause and thus be divided into (a) climate-induced sea-level change and (b) vertical land movements due to geological processes. Climate-induced sea-level change includes both, sea-level change due to natural (interannual) climate variability and sea-level rise (SLR) due to human-induced climate change. Geological processes include subsidence in sedimentary coastal lowlands where large populations are often concentrated (Nicholls et al., 2021). It is widely accepted that these drivers have substantially increased coastal flood exposure since the beginning of the 20th century. SED has led to tremendous increase in coastal population and assets, while sea levels have risen and expanded potential flood plains (e.g., de Moel et al., 2011). The absolute and relative magnitude of these effects at a global scale is, however, unknown. Looking to the future, a range of projections indicate that these increasing exposure trends could continue across a range of possible scenarios (e.g., Hallegatte et al., 2013; Hinkel et al., 2014; Jongman et al., 2012; Nicholls, 2002). For coastal flood risk, however, it is less clear whether the increasing trends might continue, mainly because coastal adaptation is an additional determinant of coastal flood risk and adaptive capacity might increase with technological and economic development. While without any further adaptation coastal flood risk could increase several orders of magnitude, with successful adaptation coastal flood risk could even decrease compared to today (Diaz, 2016; Hinkel et al., 2014; Jevrejeva et al., 2018; Oppenheimer et al., 2019).

The attribution of changes in flood exposure and flood risk to these different drivers is not only an important academic exercise, but also provides important insights for global climate policy. The fractions of exposure and risk attributable to climate change are for example needed to determine the "additionality" of climate finance, as required in the Copenhagen Accords (Donner et al., 2016). Further, such information may ultimately play a decisive role in emerging cases of climate litigation (Peel & Osofsky, 2020).

The attribution of the increased intensity or frequency of individual weather extreme events to anthropogenic climate change research matured over the last decade to estimate change in magnitude or probability attributable to climate change on a case-by-case basis (Hulme, 2014; NAS, 2016; Stott et al., 2016; Trenberth et al., 2015). For SLR, for example, attribution has been considered for historic coastal flood events such as for hurricane Katrina (Irish et al., 2014) or superstorm Sandy (Lin et al., 2016), or for specific locations such as New York City (Kemp & Horton, 2013). The attribution of increased damages of individual weather extreme events (e.g., coastal floods) to climate change, however, is a currently evolving field of research (Strauss et al., 2021). For the attribution of increased coastal flood risk, which integrates across all possible extreme events, however, there is up to now only one study available (Tiggeloven et al., 2020). This study attributes future (21st century) cost of SLR to climate change and SED. However, it does not include a comparison with the situation at the beginning of industrial age nor an analysis of coastal exposure.

This paper is the first extensive global assessment of attributing drivers of coastal exposure and risk since the beginning of the industrial age (taken as 1860) to 2100. Its main innovation is that it is a globally aggregated assessment, attributing risk and exposure to different drivers as compared to (Strauss et al., 2021) who focus on a specific event. Therefore the term attribution is used in this study as a general concept that means determining the role of a set of drivers (that may or may not include human influences) to a particular process. In contrast studies that focus on a specific event usually refer to attribution in a more specific sense referring to a causal relationship between humans and climate. Further, our study combines for the first time historical estimates of changing coastal conditions with future scenarios to assess coastal population and coastal assets.

For both, changes in exposure and risk are attributed to socio-economic, climatic and geologic drivers. The analysis is based on the ISIMIP simulation protocol round 2b (Frieler et al., 2017) and addresses two research questions:

1. What are the effects of industrial age change of bio-physical and socio-economic coastal conditions on current and future coastal flood exposure and flood risk?
2. How much of current and future coastal flood exposure and risk can be attributed to climate change, and how much might climate change and related SLR increase flood exposure and risk over the 21st century? And how do other factors contribute?

2. Methods

The analysis uses the framework of the Dynamic Interactive Vulnerability Assessment (DIVA) model which has been applied to problems such as coastal erosion (Hinkel et al., 2013), coastal flooding (Hinkel et al., 2014), coastal wetland change (Schuerch et al., 2018), subsidence and relative sea-level rise (Nicholls et al., 2021) and coastal migration (Lincke & Hinkel, 2021) among others. The underlying structure is a data set of coastal floodplains based on 12,148 coastal segments which divide the world's coast (excluding Antarctica) into lengths that are homogeneous with respect to bio-physical and socio-economic characteristics (Vafeidis et al., 2008). All input data such as SLR, SED, extreme water levels, subsidence rates, etc., are mapped to these segments and all outputs are computed for these segments (and then aggregated).

Elevation exposure is obtained from the Multi-Error-Removed Improved-Terrain Digital Elevation Model (Merit-DEM) data (Yamazaki et al., 2017) which originates from the Shuttle Radar Topography Mission (Rabus et al., 2003). While known erros in such a DEM affects the absolute impact numbers and the DEM is a major source of uncertainty (e.g., Hinkel et al., 2021), the relative impacts (changes in exposure and risk) are much less sensitive to the DEM used. Current population exposure is obtained by overlaying elevation exposure with the Gridded Population of the World (GPW) population data (Center for International Earth Science Information Network - CIESIN - Columbia University, 2018). Coastal population is translated into coastal assets by applying sub-national GDP per capita rates (Vafeidis et al., 2008) to the population data, followed by applying an assets-to-GDP ratio of 2.8 (Hallegatte et al., 2013). Historic population and asset baselines (for 1860) are derived from current population and asset values by inversely applying the growth rates of historical socio-economic scenarios (Geiger, 2018).

Exposure is defined in terms of the population and the assets located within the 100-year floodplain. Following Hinkel et al. (2014) risk is defined as expected annual number of people flooded (EAP), and expected annual coastal flood damages (EAD)., In this setting flood risk depends on exposure, areas without exposure cannot have any risk. Previous, current and future coastal protection levels are modelled after Sadoff et al. (2015) who complemented the protection levels for the biggest 136 coastal cities of Hallegatte et al. (2013), with expert judgment for segments not associated with these cities (see Table S1 in the Supporting Information S1). Following Lincke and Hinkel (2018), a population density lower than 30 people per km^2 in the 100-year floodplain is considered sparsely populated land which is never protected and therefore a protection level of zero is assumed. While there are certainly locations where land could be protected due to economic assets that are not tied to population or because of other (e.g., strategic) considerations, such cases are not resolved in our model.

Extreme water level distributions are taken from the Global Tide and Surge Reanalysis (GTSR) database (Muis et al., 2016) and are assumed to uniformly change with sea-level changes, following 20th century observations (Menendez & Woodworth, 2011). This means that additional changes in extreme water levels due to changing wind and pressure fields are not modelled. DIVA is forced by local relative sea-level rise combining climate-change-induced mean sea level rise and non-climatic vertical land motion (Gregory et al., 2019). Local sea-level change due to glacial isostatic adjustment caused by ice loading and unloading are taken from the ICE-6G_C (VM5a) model (Peltier et al., 2015). For the 117 deltas in the DIVA delta database, which comprise the world's most significant deltas, natural delta subsidence is taken from Nicholls et al. (2021). In the analysis, we do not consider uncertainty in the delta subsidence and glacial isostatic adjustment which are assumed to occur at a constant rate over the period of analysis. Additional human-induced subsidence is not considered as while it is presently large in some important cases, neither historic or future changes are known to any precision (Shirzaei et al., 2021; Syvitski, 2008; Syvitski et al., 2009; Wu et al., 2022). Historic mean SLR data for the industrial age and early 21st century SLR simulations are taken the ISIMIP input data archive (https://www.isimip.org/gettingstarted/availability-input-data-isimip2b/; Figure 1).

The SLR data set is described in Frieler et al. (2017) and consists of a historical part (1900–2005) without regional information and a future part (2005–2100), which is regionally resolved and dependent on the RCP scenario. For the historical period we use reconstructed global SLR (Kopp et al., 2016) as a proxy for regional mean SLR. This implies that there is no regional pattern for SLR over the historical period. For the future period (2005–2100), two climate scenarios are considered: RCP2.6 which is commonly considered to represent a world that meets the 1.5°C target from the Paris agreement, and RCP 6.0 that is considered to represent a likely world given current policies (Hausfather & Peters, 2020). The input data for the future period provides a regional pattern of mean climate-driven SLR including uncertainty, constructed from the components of thermal expansion, glacier melt and Greenland and Antarctic ice sheet loss, using the pattern of oceanic changes directly from the GCMs and fingerprints (Bamber & Riva, 2010) to scale the global glacier and ice sheet contributions. We use the four ISIMIP2b GCMs GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR and MIROC5 to cover differences in climate model responses. Global glacier and ice sheet contributions are derived through semi-empirical relations for each component (Mengel et al., 2016). We provide the uncertainty of future sea level rise from the uncertain parameters of the semi-empirical relations in the form of quantiles. For historic socio-economic changes, we use historic country-level population and GDP growth scenarios based on observations and extrapolation (Geiger, 2018; Klein Goldewijk et al., 2017) provided by the ISIMIP input data archive (Figure 2). These are harmonized with future projections according to the Shared Socio-economic Pathways, so that the absolute numbers in 2005 fit.

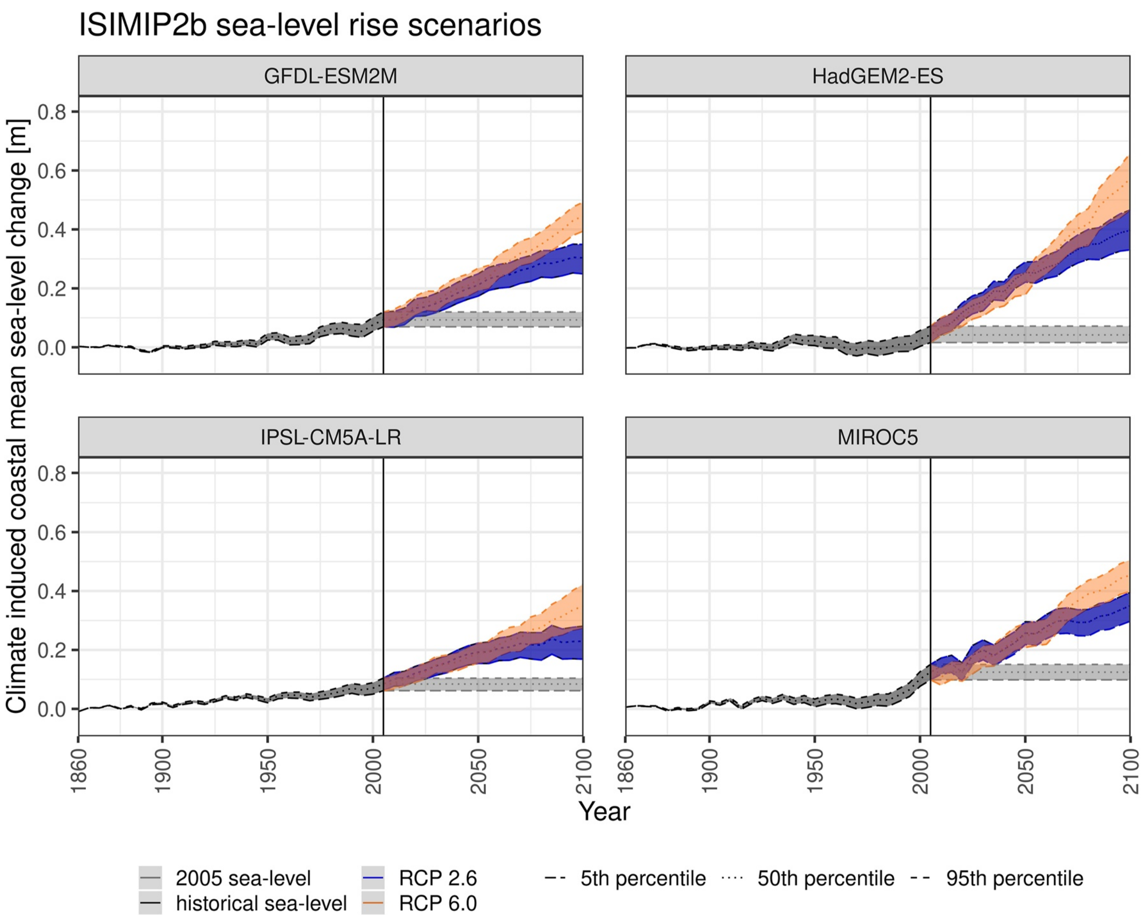

Figure 1. Historic (from 1860) and 21st century SLR scenarios used in this study. Data is taken from the ISIMIP input data archive (https://www.isimip.org/gettingstarted/availability-input-data-isimip2b/).

Urbanisation is a major feature of the coastal zone, both historically and this trend is very likely to continue in the coming decades (Nicholls, 1995; Nicholls et al., 2008; Seto et al., 2011). To capture this we use regionalized population growth projections (Merkens et al., 2018) based on the middle-of-the-road Shared Socio-economic Pathway SSP2 (IIASA, 2012; Kriegler et al., 2014; O'Neill et al., 2014) as required from the ISIMIP2b protocol

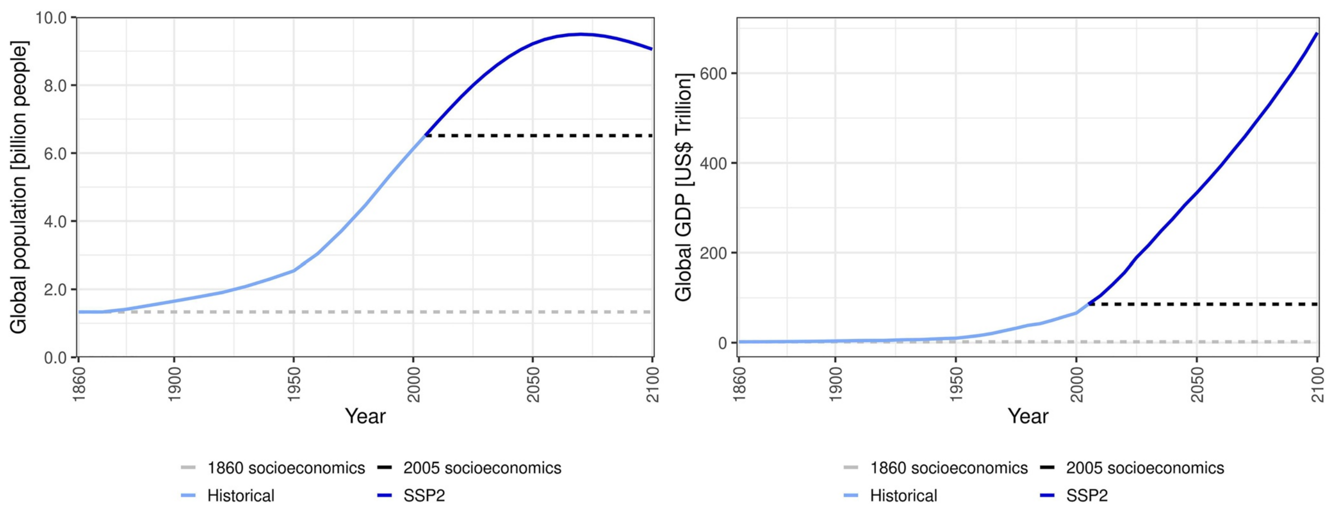

Figure 2. Historic and 21st century socio-economic scenarios used in this study. Taken from IIASA and from (Geiger, 2018).

(Frieler et al., 2017). In addition, simulations with future socio-economics according to the extreme scenarios SSP3 (high population growth, low GDP per capita growth) and SSP5 (low population growth, high GDP per capita growth) are conducted to analyze the sensitivity of the results to these inputs. Following common practice, socio-economic development is modeled independently from existing protection (although in our model of protection, socio-economic development is usually accompanied by a construction/upgrade of coastal protection, as elaborated below).

One specific challenge in assessing coastal flood risk is that this requires information on the coastal protection measures in place. As no suitable global data on historic protection levels is available, we model this with a stylized protection model, which computes design water levels against which to protect based on GDP per capita and coastal population (see Supporting Information S1). For future flood risk, two future adaptation scenarios are considered: (a) a "no adaptation" scenario that assumes no further protection upgrade from 2005 onwards (although existing protection is maintained until permanently overtopped), and (b) a more realistic assumption, applying the stylized adaptation model to future GDP per capita and population densities (labeled as an "adaptation" scenario). In this scenario, protection upgrades can be arbitrarily small and are applied in every time step.

We report both global and regional results to illustrate the regional differences. For this, the 23 coastal regions defined by Future Earth Coast (formerly Land Ocean Interactions in the Coastal Zone [LOICZ]) and originally introduced in Hoozemans et al. (1993) are used.

As noted above, three drivers are considered, (a) climate-induced SLR (clim); (b) geologically induced sea-level change (geo), and (c) socio-economic development (soc). We compute the contributions of each driver to the indicators coastal flood exposure and coastal flood riskby enabling and disabling each driver. Thus, we use in total seven counterfactual scenarios (with at least one driver disabled) and one factual scenario (with all drivers enabled). First we determine the relative effect of each single driver on the value of the indicator (only this one driver activated). As the sum of these single driver effects does necessarily not equal one, second-order interactions, which are the additional effect of any combination of two drivers relative to the sum of the effect the two single drivers, and third-order interactions are also considered. These interactions effects are used to normalize the sum of the single driver effects to one. This method is described in detail in the Text S1 of the Supporting Information S1.

3. Results

3.1. Coastal Flood Exposure

From 1860 to 2005 coastal population exposure is estimated to have grown almost sixfold – from 35 million people in 1860 to 200 million people in 2005 (Figure 3 and Figure S13 in the Supporting Information S1) – with significant regional variations (Table 1). Globally, 97.3 percent of this growth can be explained by socio-economic drivers, 3.2 percent by climate-related SLR, while geologic-induced sea-level change contributes less than 1 percent and its net effect is negative (i.e., it is reducing exposure). There are only minor regional variations in the driver contributions, with a notable exception for the Baltic Sea coast, where geologic drivers significantly reduced exposure because of high rates of local sea-level fall due to glacial isostatic adjustment. Regions with densely populated subsiding deltas (e.g., East Asia, Southern Mediterranean) tend to have above global average contributions from geological drivers. For sparsely populated regions with small absolute changes (e.g., Southern Atlantic Small Islands) the relative contributions can be large and these results should be interpreted with caution.

Extending this analysis to 2100 using SSP2 for future socio-economic development, socio-economic driver remain dominant in the increase of coastal exposure (Table 1, Figure 3 and Figure S13 in the Supporting Information S1). Global floodplain population in 2100 ranges between 312 million people under RCP 2.6 (50th percentile) and 344 million people under RCP 6.0 (50th percentile). Socio-economic development still explains 89–91 percent of the increase compared to 1860. These numbers do not change significantly when using lower (i.e., 5th) and higher (i.e., 95th) percentiles of the SLR scenarios (Figure S1 and Table S2 in the Supporting Information S1). There is, however, an increasing trend in the fraction of exposure change that can be attributed to the climate driver. While only 3.2% of the change in population exposure from 1860 to 2005 can be attributed to the climate driver, the fraction of the change from 1860 to 2100 that can be attributed to the climate driver is larger: 9.5% (50th percentile, 5th-95th percentile: 8.8%–10.1%) under RCP2.6 and 11.5% (10.8%–12.2%) under RCP6.0

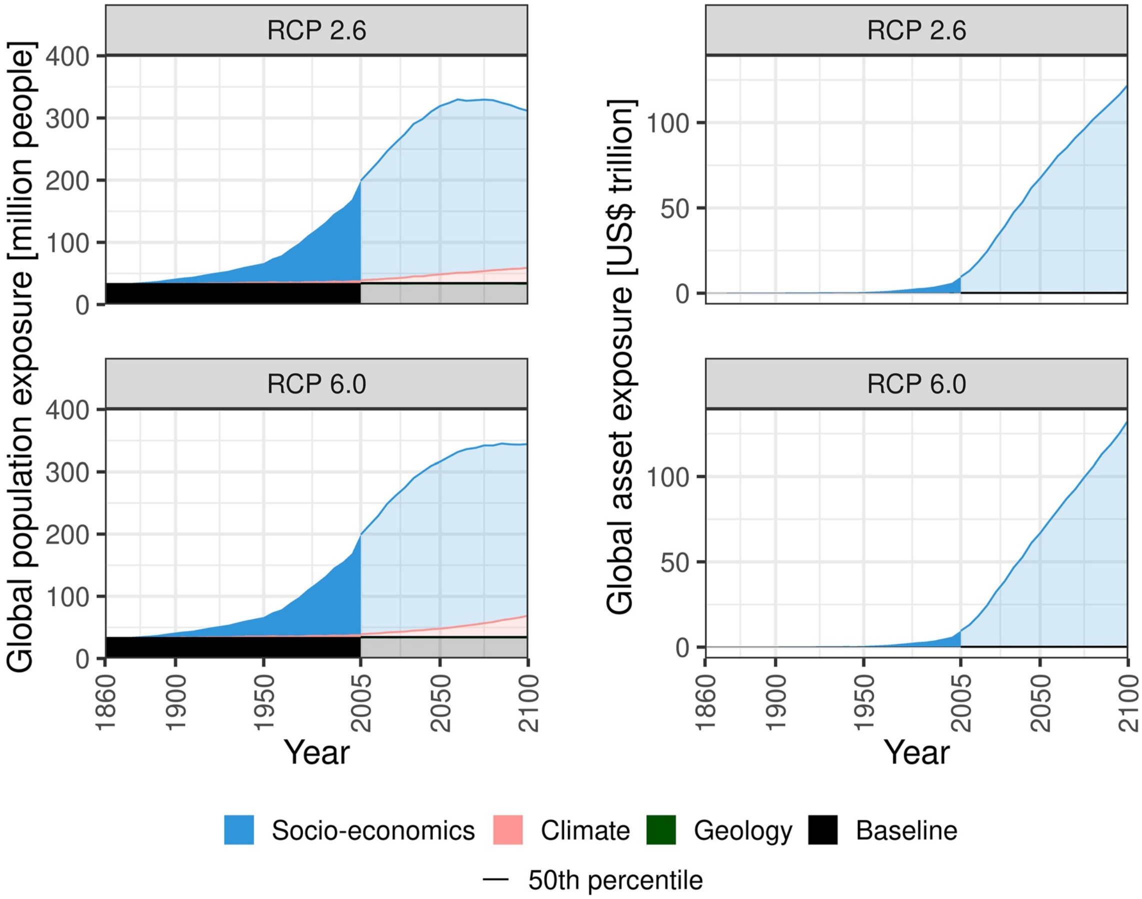

Figure 3. Population and asset exposure to the 100-year extreme water level from 1860 to 2100 under the 50th percentiles of the ensemble mean global SLR. Shaded areas show the contributions of the three drivers of socioeconomic change, climate change and geologically induced change. For global asset exposure, socio-economics is such a dominant driver that the climate and geology drivers are not even visible.

(Table 1 and Table S2 in the Supporting Information S1). Figure S2 in the Supporting Information S1 shows the increasing trend of the attribution factors over 21st century.

However, under both RCP 2.6 and RCP 6.0, climate change induced SLR is the biggest driver of the increase in global coastal population exposure change over the 21st century (2005–2100). While 47–48 percent (RCP 2.6) or 39–40 percent (RCP 6.0) of the exposure change can be explained by socio-economic drivers, 54–55 percent (RCP 2.6) or 62–63 percent (RCP 6.0) of this change is due to climate-change-induced sea-level-rise (Table S4 in the Supporting Information S1). So the base year used for the analysis has important implications for the results.

The analysis of simulations with all driver combinations shows that the interaction effects have a large influence. SLR alone increased coastal population exposure by 14–21 million from 1860 to 2100 and SED alone increased coastal population exposure by 175 million (Figures S2 and Table S6 in the Supporting Information S1). However, the additional exposure under the combination of both, SLR and SED is up to 315 million people which is much more than the sum of the two single factor contributions. The interaction effects in such an analysis are usually multiplicative instead of additive, so this is not a surprising result. While SLR increases the potentially flooded area by factor a, SED increases the exposure per area by factor b and thus these processes together increase exposure roughly by factors $a*b$. In our exposure population analysis, SLR alone increases coastal population exposure roughly by factor $a = 1.5$ (Table S6 in the Supporting Information S1), SED alone increases coastal population exposure roughly by factor $b = 6$, and the combination of both, SLR and SED increases coastal population exposure roughly by factor $a*b = 6*1.5 = 9$. These findings remain true when applying the widely used attribution method applied in other available impact studies (i.e., Strauss et al. (2021)): using the driver combination with SED and geological effects enabled and climate-change-induced SLR disabled as the "counterfactual".

Table 1
Change in Coastal Floodplain Population From 1860 to 2005 and to 2100 Globally and Per World Region, and Attribution of This Change to Socioeconomic, Climatic and Geologic Drivers

	Floodplain population					Attribution of change to drivers (soc/clim/geo)		
	1860	2005		2100		2005	2100	
World region	[Mill.]	[Mill.	(Factor)]	RCP 2.6 [Mill.]	RCP 6.0 [Mill.]		RCP 2.6	RCP 6.0
Africa Atlantic Ocean	0.81	9.16	(11.4)	36.94	41.03	96.5/1.5/2.0	97.4/1.9/0.7	96.9/2.5/0.6
Africa Indian Ocean	0.15	1.92	(12.4)	6.51	7.13	98.4/1.6/0.0	98.1/1.9/0.0	97.6/2.4/0.0
Asia Indian Ocean	7.61	37.27	(4.9)	68.95	77.32	105.4/3.3/−8.7	96.3/9.2/−5.4	93.4/11.5/−4.8
Atlantic Ocean Small Islands	0	0.01	(3.6)	0.01	0.01	95.9/2.6/1.5	89.9/8.4/1.7	87.7/10.8/1.5
Baltic Sea coast	0.32	0.73	(2.3)	0.91	1.03	112.1/2.7/−14.8	96.2/16.1/−12.4	88.3/21.7/−10.0
Caribbean islands	0.02	0.21	(10.3)	0.25	0.29	97.2/2.7/0.1	87.5/12.3/0.2	82.4/17.4/0.2
Central America Atlantic Ocean	0	0.02	(27.4)	0.08	0.1	97.7/3.2/−0.9	93.7/6.9/−0.6	90.8/9.7/−0.5
Central America Pacific Ocean	0.01	0.23	(21.4)	0.41	0.45	99.4/1.0/−0.4	97.2/3.2/−0.4	96.6/3.8/−0.4
Coasts of Russian Federation	0.09	0.37	(4.1)	0.15	0.17	88.2/7.6/4.2	−34.6/107.1/27.5	−25.2/106.9/18.3
East Asia Coast	16.53	74.27	(4.5)	73	78.47	91.7/4.3/4.0	69.3/24.1/6.6	65.9/28.2/5.9
Gulf States	0.2	4.51	(22.2)	16.85	18.17	98.5/0.7/0.8	99.0/0.8/0.3	98.8/1.0/0.2
Indian Ocean Small Islands	0.02	0.09	(3.5)	0.21	0.23	97.0/4.2/−1.2	95.3/5.6/−0.9	93.4/7.4/−0.9
North America Atlantic Ocean	0.14	1.87	(13.2)	4.05	4.5	96.7/0.9/2.4	95.2/2.8/1.9	94.2/4.0/1.8
North America Pacific Ocean	0.08	0.86	(10.8)	1.91	2	99.0/0.5/0.5	98.4/1.3/0.3	98.0/1.7/0.3
North and West Europe	4.65	15.47	(3.3)	19.76	20.55	99.8/1.5/−1.3	97.5/4.2/−1.7	96.1/5.7/−1.8
Northern Mediterranean	0.36	1.17	(3.2)	1.42	1.57	95.0/10.5/−5.5	84.2/22.7/−6.9	78.1/27.9/−6.0
Pacific Ocean large Islands	0.04	0.56	(13.0)	1.65	1.83	99.3/1.1/−0.4	98.4/1.9/−0.3	97.9/2.5/−0.3
Pacific Ocean small Islands	0.02	0.17	(7.0)	0.35	0.39	97.4/4.4/−1.8	93.8/7.8/−1.6	92.1/9.4/−1.6
South America Atlantic Ocean	0.15	2.47	(16.0)	3.62	4.12	98.9/1.9/−0.8	94.9/6.1/−1.0	93.3/7.6/−0.9
South America Pacific Ocean	0.06	1.05	(18.2)	2.12	2.21	99.1/0.5/0.4	98.5/1.2/0.3	98.3/1.4/0.3
South-east Asia Coast	3.17	40.09	(12.6)	62	71.1	99.4/1.9/−1.3	95.4/6.0/−1.5	93.8/7.6/−1.4
Southern Atlantic Small Islands	0	0	(1.4)	0	0	81.2/42.5/−23.7	56.0/71.6/−27.6	49.4/78.9/−28.2
Southern Mediterrean	0.22	6.89	(31.3)	10.88	11.9	95.9/0.7/3.4	96.2/0.7/3.0	95.9/1.2/2.9
Global	34.69	199.56	(5.8)	312.11	344.63	97.3/3.2/−0.5	90.9/9.5/−0.4	88.8/11.5/−0.4

Note. Future SED is according to SSP2 and future SLR according to the 50th percentiles of the SLR scenarios used in this study.

Following this approach, the world evolving with climate-induced SLR accounts for coastal population exposure of 199 million people, while the world evolving without climate-induced SLR accounts for coastal population exposure of 169 million people (Table S6 in the Supporting Information S1) - the amount of additional exposure that would be attributed to climate-induced SLR is thus 30 million people. It is worth pointing out that this attribution method could be applied to other drivers. Attributing the change of exposure to SED we find that in the counterfactual world (SED disabled, geologic effects climate-change-induced SLR enabled) the exposure would be 38 million people - and thus the amount of additional exposure that would be attributed to SED is 161 million people. The sum of the two single factor attributions (191 million people) is bigger than the increase in coastal population exposure itself (this is just 165 million people). This reflects that the interaction effects are counted twice using this method for attributing a change to different drivers.

The growth of exposed coastal assets since 1860 has been much larger than the growth of exposed coastal population reflecting the compounding of population growth and per capita wealth. While exposed coastal population has grown by 570 percent from 1860 to 2005, exposed coastal assets grew 5,300 percent from US$^{2014} 180 billion in 1860 to US$^{2014} 9,600 billion in 2005. This increase of exposed coastal asset values can be explained almost completely by socio-economic drivers (99.7 percent, Table 2). The growth in exposed coastal assets is projected

Table 2
Change in Coastal Floodplain Assets From 1860 to 2005 and to 2100 Globally and Per World Region, and Attribution of This Change to Socioeconomic, Climatic and Geologic Drivers

	Floodplain assets					Attribution of change to drivers (soc/clim/geo)		
	1860	2005		2100		2005	2100	
World region	[US$ 10⁹]	[US$ 10⁹]	(Factor)	[US$ 10¹²]	[US$ 10¹²]			
Location name	assets_below_h100_1860	assets_below_h100_2005	growth	assets_below_h100_2100_rcp26	assets_below_h100_2100_rcp60	attribution_2005	attribution_2100_rcp26	attribution_2100_rcp60
Africa Atlantic Ocean	1.71	16.56	(9.7)	2.07	2.27	94.6/1.7/3.7	99.9/0.1/0.0	99.9/0.1/0.0
Africa Indian Ocean	0.05	2.19	(42.9)	0.29	0.32	99.6/0.4/0.0	100.0/0.0/0.0	100.0/0.0/0.0
Asia Indian Ocean	4.52	67.9	(15.0)	3.05	3.4	101.2/0.9/−2.1	100.0/0.1/−0.1	99.9/0.1/−0.1
Atlantic Ocean Small Islands	0.01	0.54	(42.7)	0	0	99.8/0.1/0.1	99.8/0.1/0.0	99.8/0.2/0.0
Baltic Sea coast	1.04	39.53	(38.1)	0.22	0.26	100.8/0.1/−0.9	100.0/0.1/−0.2	99.9/0.2/−0.1
Caribbean islands	0.06	3.41	(60.9)	0.02	0.03	99.6/0.4/0.0	99.7/0.3/0.0	99.5/0.5/0.0
Central America Atlantic Ocean	0	0.22	(367.6)	0.01	0.01	99.9/0.2/−0.1	100.0/0.0/0.0	99.9/0.1/0.0
Central America Pacific Ocean	0.01	2.13	(290.4)	0.04	0.04	99.9/0.1/0.0	100.0/0.0/0.0	100.0/0.0/0.0
Coasts of Russian Federation	0.1	4.17	(40.9)	0.01	0.01	99.8/0.3/−0.1	99.1/0.9/0.0	98.8/1.2/0.0
East Asia Coast	13.22	1072.33	(81.1)	10.1	10.81	99.6/0.2/0.2	99.9/0.1/0.0	99.8/0.1/0.0
Gulf States	0.42	47.08	(111.1)	1.17	1.27	99.8/0.1/0.1	100.0/0.0/0.0	100.0/0.0/0.0
Indian Ocean Small Islands	0.09	1.21	(13.3)	0.02	0.02	99.5/0.7/−0.2	99.8/0.2/0.0	99.8/0.2/0.0
North America Atlantic Ocean	0.92	149.85	(163.8)	0.72	0.81	99.7/0.1/0.2	99.8/0.1/0.1	99.8/0.1/0.1
North America Pacific Ocean	0.45	63.26	(140.7)	0.34	0.36	100.0/0.0/0.0	100.0/0.0/0.0	99.9/0.0/0.0
North and West Europe	34.7	1483.93	(42.8)	6.01	6.24	100.0/0.1/−0.1	100.0/0.1/0.0	99.9/0.1/0.0
Northern Mediterranean	1.36	55.46	(40.8)	0.22	0.24	99.8/0.6/−0.4	99.7/0.4/−0.2	99.6/0.6/−0.2
Pacific Ocean large Islands	0.2	27.75	(136.4)	0.26	0.29	99.9/0.1/0.0	100.0/0.1/0.0	99.9/0.1/0.0
Pacific Ocean small Islands	0.06	3.09	(53.1)	0.04	0.04	99.7/0.5/−0.2	99.9/0.2/0.0	99.8/0.2/0.0
South America Atlantic Ocean	0.09	29.17	(324.7)	0.29	0.33	99.9/0.1/0.0	100.0/0.0/0.0	100.0/0.0/0.0
South America Pacific Ocean	0.03	8.19	(234.6)	0.17	0.18	100.0/0.0/0.0	100.0/0.0/0.0	100.0/0.0/0.0
South-east Asia Coast	1.42	313.26	(220.8)	8.76	10.05	99.9/0.1/0.0	100.0/0.0/0.0	100.0/0.0/0.0
Southern Atlantic Small Islands	0	0.02	(12.1)	0	0	99.2/1.7/−0.9	99.1/1.3/−0.4	98.9/1.6/−0.4
Southern Mediterrean	0.11	27.45	(241.2)	0.5	0.55	99.7/0.1/0.2	100.0/0.0/0.0	100.0/0.0/0.0
Global	179.55	9595.33	(53.4)	124.05	134.57	99.7/0.2/0.1	99.9/0.1/0.0	99.9/0.1/0.0

Note. Future SED is according to SSP2 and future SLR according to the 50th percentiles of the SLR scenarios used in this study. The base unit of all monetary values is $US\$_{2014}$.

to continue in the 21st century under the SSP2 scenario to $US\$^{2014}$ 124,000 billion (RCP 2.6, 50th percentile) and $US\$^{2014}$ 135,000 billion (RCP 6.0, 50th percentile) in 2100. The change from 1860 to 2100 can also be explained almost completely by socio-economic development (99.9 percent, Table 2). When considering the change for the 21st century only (2005–2100), socio-economic development remains the dominant force of the increase of coastal asset exposure (Table S5 in the Supporting Information S1, 96.4–97.4 percent). Similar to population exposure, results don't vary much when considering higher or lower percentiles of SLR as compared to the median SLR scenario (Figure S1 and Table S3 in the Supporting Information S1).

3.2. Coastal Flood Risk

The evolution of the risk metrics, EAP and EAD, differs from the evolution of exposure metrics discussed above in that a larger fraction of future risk is attributed to climate-induced SLR in the 21st century. The main reason for this difference is that risk also considers the reduction of damage due to coastal adaptation in the form

Table 3
Change in Coastal Flood Risk (Expected Annual People Flooded and Expected Annual Damages) From 1860 to 2005 Globally and Per World Region, and Attribution of This Change to Socioeconomic, Climatic and Geologic Drivers

	Expected annual people flooded				Expected annual damaged			
	1860	2005		Attribution	1860	2005		Attribution
World region	[Mill.]	[Mill.]	(Factor)	(soc/clim/geo)	[US$ 10^9]	[US$ 10^9]	(Factor)	(soc/clim/geo)
Africa Atlantic Ocean	0.17	5.31	(30.8)	71.3/14.4/14.3	0.02	1.66	(98.2)	26.6/17.3/56.1
Africa Indian Ocean	0.03	1.14	(34.6)	80.2/18.5/1.3	0	0.16	(246.9)	87.6/11.1/1.3
Asia Indian Ocean	1.33	7.01	(5.3)	94.5/26.6/−21.1	0.11	2.42	(22.8)	96.1/6.0/−2.1
Atlantic Ocean Small Islands	0	0	(7.9)	18.8/66.3/14.9	0	0.01	(60.9)	52.7/32.7/14.6
Baltic Sea coast	0.07	0.18	(2.7)	47.0/26.7/26.3	0.02	0.55	(25.9)	97.3/2.7/0.0
Caribbean islands	0	0.13	(34.0)	57.7/39.7/2.6	0	0.2	(632.3)	63.7/35.7/0.6
Central America Atlantic Ocean	0	0.02	(106.8)	78.9/22.2/−1.1	0	0.01	(6235.3)	91.0/9.1/−0.1
Central America Pacific Ocean	0	0.08	(34.3)	86.6/14.8/−1.4	0	0.07	(645.6)	98.5/1.6/−0.1
Coasts of Russian Federation	0.02	0.06	(3.3)	40.2/57.7/2.1	0	0.09	(28.0)	95.5/4.1/0.4
East Asia Coast	2.98	16.6	(5.6)	57.3/25.1/17.6	0.29	26.65	(93.5)	94.9/2.7/2.4
Gulf States	0.04	0.8	(18.2)	65.7/21.1/13.2	0.01	1.24	(185.8)	88.4/4.4/7.2
Indian Ocean Small Islands	0	0.04	(9.7)	29.6/71.5/−1.1	0	0.05	(43.9)	47.8/52.5/−0.3
North America Atlantic Ocean	0.02	0.35	(14.2)	59.3/17.5/23.2	0.01	4.16	(321.7)	93.0/2.2/4.8
North America Pacific Ocean	0.02	0.12	(7.2)	55.2/27.9/16.9	0.01	1.05	(153.0)	95.6/2.3/2.1
North and West Europe	0.96	0.27	(0.3)	157.1/−52.0/−5.1	1.29	6.49	(5.0)	92.7/6.8/0.5
Northern Mediterranean	0.07	0.23	(3.4)	11.3/89.1/−0.4	0.02	0.73	(44.5)	85.2/15.1/−0.3
Pacific Ocean large Islands	0.01	0.18	(19.8)	63.8/37.2/−1.0	0	0.75	(302.2)	89.0/11.2/−0.2
Pacific Ocean small Islands	0	0.13	(26.3)	53.9/49.1/−3.0	0	0.21	(616.8)	63.0/37.3/−0.3
South America Atlantic Ocean	0.03	0.76	(23.1)	76.8/25.6/−2.4	0	0.77	(600.9)	97.2/2.8/0.0
South America Pacific Ocean	0.01	0.78	(65.9)	87.0/4.7/8.3	0	1.2	(1980.1)	97.6/0.7/1.7
South-east Asia Coast	0.65	11.22	(17.3)	79.8/22.6/−2.4	0.03	7.46	(267.4)	96.7/3.1/0.2
Southern Atlantic Small Islands	0	0	(4.3)	11.7/115.1/−26.8	0	0	(62.2)	58.6/45.0/−3.6
Southern Mediterrean	0.04	5.11	(130.1)	70.5/6.6/22.9	0	4.62	(6383.9)	83.2/2.2/14.6
Global	5.82	31.01	(5.3)	61.6/35.9/2.5	4.29	117.14	(27.3)	92.5/4.7/2.8

of protection, and increasing flood depths across the floodplain as sea levels rise, while exposure does not. More specifically, coastal protection does not only increase with SLR, but also with socio-economic development, because wealthier societies are more risk averse and can afford higher protection standards. As a result, socio-economic development in protected areas does not necessarily increase coastal risk in terms of expected annual losses.

Historically, EAP has increased from 5.8 million people in 1860 to 31 million (factor 5.3) in 2005 and the EAD have increased from US$ 4.3 billion in 1860 to 117 billion (factor 27) in 2005 (Table 3, Figure 4, and Figure S12 in the Supporting Information S1). The increase of expected annual damages is less than the increase in asset exposure which reflects that much of the socio-economic development took place in locations with existing high exposure that are well protected in our adaptation model. Most of the increase in risk occurs in rural areas where population growth is smaller than in urban areas and protection is absent or of lower standard. The main contributor to the change in risk is socio-economic development for both population risk and asset risk, but the contribution from the other drivers is much higher than for exposure. This is again due to coastal protection: socio-economic development in protected areas only increases coastal risk slightly.

While under the no adaptation scenario EAP increases up to about 230 million people and EAD up to about US$ 25 trillion by 2100, the adaptation scenario reduces these numbers by an order of magnitude: up to 15 million people and US$ 1.7 trillion by 2100, respectively (Figure 5, Table 4, and Tables S8-S11 in the Supporting

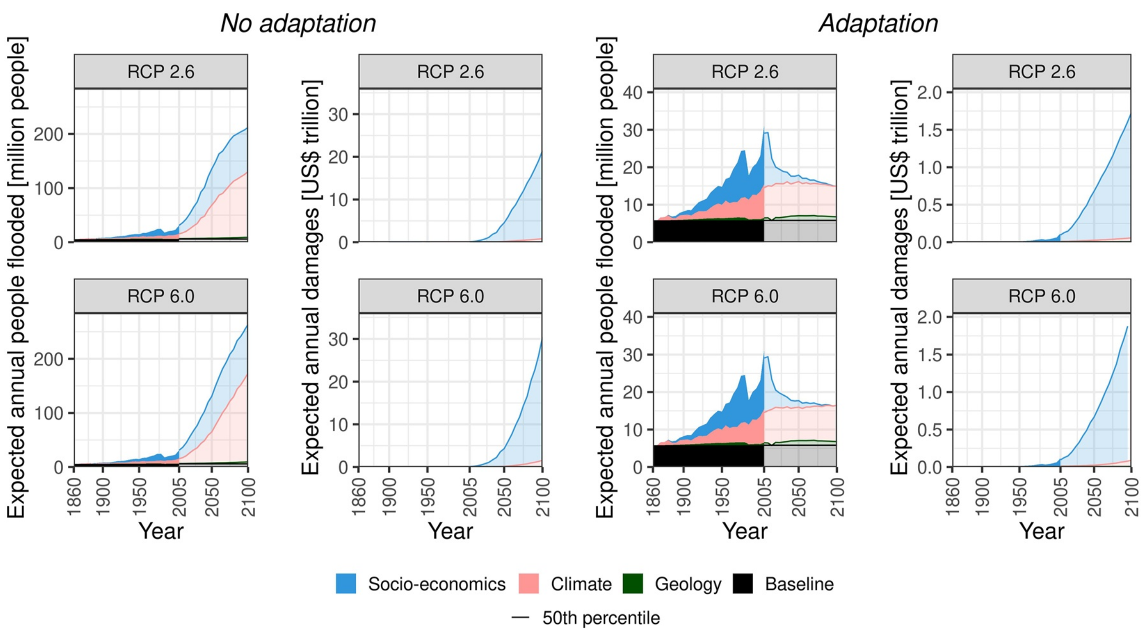

Figure 4. Expected annual number of people flooded and expected annual sea flood damages from 1860 to 2100 and the attribution to the contributing drivers relative to the 1860 baseline. Future SED is according to SSP2 and future SLR according to the 50th percentiles of the SLR scenarios used in this study.

Information S1). Further EAP is lower in 2100 than in 2005, which illustrates that the overall effect of socioeconomic development leading to higher protection in the model standards outweighs the effect of sea-level rise in our model. The peak in EAP around 1970 is due to the step function of the stylized adaptation model and shows that significant areas crossed socio-economic thresholds in terms of increasing GDP per capital and population density leading to higher protection standards. Another such peak occurred arround 2010. Empirically there is evidence that adaptation standards have indeed improved around the world during those periods (e.g., Jonkman et al., 2013; Xian et al., 2018). For example, in North-western Europe a significant increase in coastal protection occurred between 1960 and 1980 (van den Hurk et al., 2022). The North Sea floods of 1953 and 1962 initiated

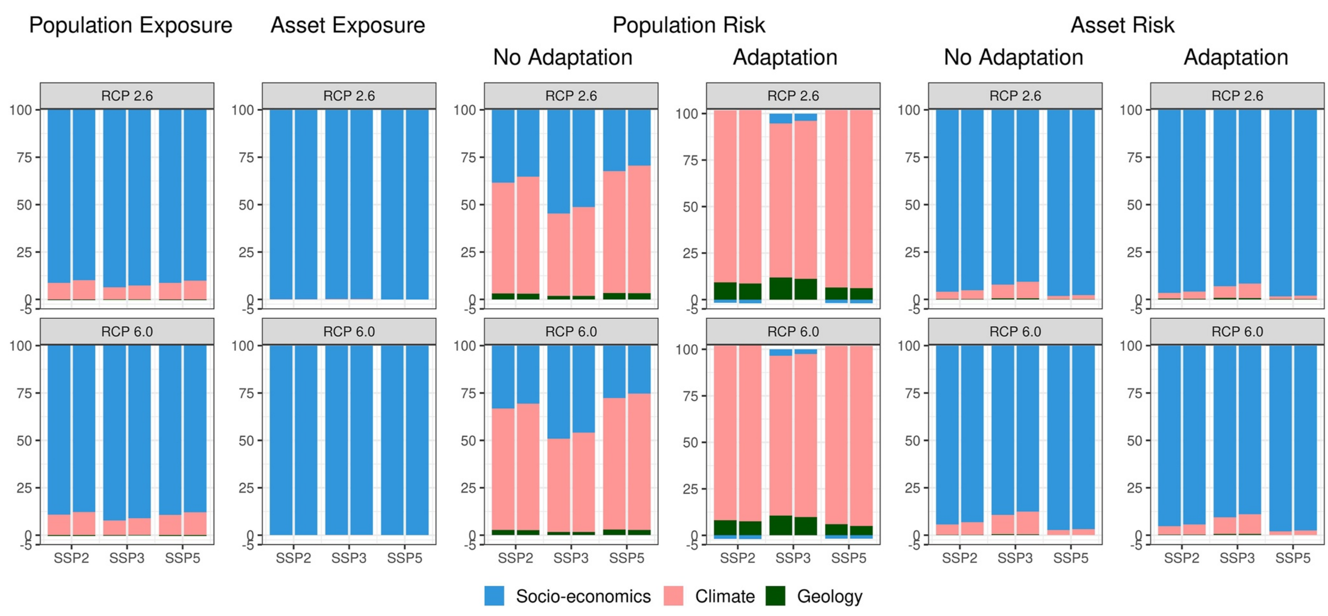

Figure 5. Relative contribution to change in global coastal exposure and risk from 1860 to 2100 for different SSPs. In each panel the first bar for each SSP shows the mean values for the 5th percentile SLR scenarios of the four GCMs (per RCP), and the second the same for the 95th percentile.

Table 4
Change in Coastal Flood Risk (Expected Annual People Flooded and Expected Annual Damages).

		No adaptation		Adaptation	
Population risk					
		[Mill.]	Attribution (soc/clim/geo)	[Mill.]	Attribution (soc/clim/geo)
1860		5.8		5.8	
2005		31.0	61.6/35.9/2.5	31.0	61.6/35.9/2.5
2100	RCP2.6	187	36.7/60.3/3.0	13.7	−1.9/92.8/9.0
2100	RCP6.0	234	31.8/65.5/2.7	15.0	−2.0/94.1/7.8
Asset risk					
		[US$ 10^9]	Attribution (soc/clim/geo)	[US$ 10^9]	Attribution (soc/clim/geo)
1860		4.3		4.3	
2005		117.1	92.5/4.7/2.8	117.1	92.5/4.7/2.8
2100	RCP2.6	18,200	95.4/4.4/0.2	1,420	96.1/3.5/0.4
2100	RCP6.0	25,600	93.7/6.1/0.2	1,690	94.8/4.9/0.3

Note. From 1860 to 2005 and 2100 globally under the adaptation and the no adaptation scenario and attribution of this change to socioeconomic, climatic and geologic drivers. All values refer to SSP2 and the 50th quantile of the SLR scenarios.

significant coastal protection projects such as the Delta plan in the Netherlands, the Sigma plan in Belgium and the Thames barrier in the UK, lowering damages in subsequent storms (e.g., Haigh et al., 2016).

Compared to the exposure analysis before, much more of the change in risk can be attributed to climate-change-induced SLR. This reflects that most socio-economic development occurs in locations that are well protected. While in 2005 36 percent of the increase in EAP since 1860 can be attributed to climate-change-induced SLR (Table 3), 62 percent can be attributed to socio-economic development (under both, the no adaptation and the adaptation scenario, as they only diverge after 2005). However, from 1860 to 2100, climate-change-induced SLR explains 60–65 percent of EAP growth under the no adaptation scenario and 93–94 percent under the adaptation scenario, respectively. For EAD, socio-economic development remains the major driver with 93–95 percent of the increase of EAD attributable to socio-economic development (over both adaptation scenarios). Interestingly, the contribution of socio-economic development to the increase of EAP from 1860 to 2100 is negative in the adaptation scenario, which again highlights that risk reduction due to increasing protection following increasing affluence outweighs the effect of increasing exposure due to SLR and SED (see Figure S8 and Table S12 in the Supporting Information S1).

3.3. Sensitivity of Results to Changes in Socio-Economic Scenarios

As SED induced growth of coastal population and asset exposure is very dominant in the analysis of exposure and asset risk, we extended our analysis to other SSPs to explore the sensitivity of our results against the change of the SSP. We used SSP3 and SSP5 in addition to SSP2, as these two SSPs represent the extreme cases of the socio-economic scenario-space. SSP3 represents the highest global population and the lowest global GDP scenario, while SSP5 represents the highest global GDP scenario combined with a low global population scenario.

Figure 5 shows the results of the calculation for different scenarios. Clearly, across the range of SSP scenarios the main features of the results persist. For population exposure and risk the attribution to socio-economic development is slightly higher for SSP3 than for SSP2 reflecting the much higher global (and coastal). population under the latter SSP. For asset exposure and risk SSP5 leads to a slightly higher attribution to socio-economic drivers compared to SSP2, because the former has a higher global (and coastal) assets than the other SSPs. Exact numbers can be found in Table S16 of the Supporting Information S1.

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4. Discussion

In line with previous findings, our analysis emphasizes that SED is the main driver of historic and near-future coastal flood exposure (Lichter et al., 2011; Neumann et al., 2015; Pielke & Sarewitz, 2005). This is especially true for coastal asset exposure, for which SED is by far the most important driver due to the exponential growth of GDP assumed by the socio-economic scenarios.

Comparing our results to the only other available global sea-level rise attribution study (Tiggeloven et al., 2020) is difficult due to differing assumptions made and methods used. Tiggeloven et al. attribute the total cost of SLR (the net present value of protection cost and damages) under an benefit-cost optimal adaptation scenario, considering four drivers: climate change (sea-level rise), optimizing current protection standards, socioeconomic change and geological effects. The latter does not include glacial isostatic adjustment, but rather the high-resolution subsidence rates taken from the SUB-CR model by Kooi and Erkens. (2020). Here, we could not use these data for our purposes as they do not cover the past. Finally, the attribution calculation of Tiggeloven et al. does not consider interaction between drivers.

Compared to studies available that have attributed single events to climate-change induced sea-level rise, we find lower attributions. For example, Strauss et al. (2021) attributes 7.5%–22.5% (5th-95th percentile) of the economic damages and 5.3%–17.1% of the affected population in the Tri-State area around New York due to superstorm Sandy to SLR. This is higher than the 4.7% of current (2005) global coastal flood risk that we found here (see Table 4). However, our results refer to long-term global average while the results of Strauss et al. (2021) refer to one particular extreme event. This implies that our aggregated global analysis a lot of the details such a particular event study vanish in the global averages.

The reason why these event attribution studies find a higher attribution to climate-change-induced sea-level rise is that these studies consider SLR as the only driver, while we also consider geological processes and socio-economic development. The attribution is higher because the single-driver attribution also assigns contributions from hidden interaction effects with other drivers to SLR. This is especially problematic for coastal flood risk, because the interaction effects between climate and socio-economic drivers are large. Hence, attributing changes in flood risk to a single climate driver leads to a significant overestimation of the effect of climate change.

Our paper thus provides important insights for attribution studies. First, the results of an attribution study depend on the drivers considered. The drivers that should be considered depend on the research question. If the influence of climate on the biophysical parameters of an event are of interest it is sufficient to consider climate change alone as a driver as other drivers do not have an effect on these parameters. In areas where geological uplift/subsidence are large this must also be considered in terms of relative sea-level rise. However, if the damages of an event are of interest, socio-economic development also has to be considered in order to estimate what damages might have been avoided through avoiding further development in coastal floodplains.

A second insight relevant specifically for the debate of climate justice is that the baselines chosen for the different drivers have significant influence on the results. For instance, as shown in our study only about roughly 10 percent of the population exposure change from 1860 to 2100 can be attributed to climate change, while roughly 90 percent can be attributed to socio-economic development. However, changing the baseline of both drivers to 2005 and only attributing the exposure change from 2005 to 2100 to the drivers leads to dramatically different results: in the latter case roughly 50–60 percent of the change can be attributed to climate change and roughly 40–50 percent to socio-economic development. For attribution studies in general this means that the baselines have to be chosen carefully. While an objective choice can be made for the baseline for climate-induced sea-level rise (i.e., preindustrial sea-level), the socio-economic baseline is a normative decision that depends on the purpose of attribution. If attribution is to be used for compensating losses, it would make sense to choose a socio-economic baseline that provides incentives to steer future socio-economic development away from the coast in order to avoid the moral hazard of people developing further in the flood plain because they know they will be compensated in the case a flood occurs (Rowell & Connelly, 2012). Hence, a meaningful baseline date to use would be the date when a compensation scheme is established, excluding all further socio-economic development after this date from the compensation for climate related losses. However, there are also places like small island nations (e.g., the Maldives or Kiribati) that do not have the choice to steer their development away from the coast. Further, developing and least developed countries might be trapped in their current situation if development of their coastal zones is restricted.

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Due to some limitations and necessary simplifications in the representation of the underlying physical and economic processes, the results provide a first-order indication of the contribution of the different drivers. One set of limitations is associated with capturing past and future coastal protection. This effect needs to be considered when assessing flood damages, as even global data on current (e.g., Hallegatte et al., 2013; Scussolini et al., 2016) local coastal protection infrastructure, their protection standards and their quality is limited, while historical data back to 1860 is almost totally lacking. Our stylized adaptation model is a reasonable first-order attempt to fill these gaps by building on available data, but this model cannot capture the complex dynamics of the local evolution of protection. For example, the installation or substantial improvement in coastal protection and wider flood management infrastructure is often sparked by single extreme events causing catastrophic coastal flooding such as occurred in the Netherlands and London in 1953, Hamburg in 1962, and Venice in 1966. Furthermore, not only defense height, but also quality plays a role, because the major reason for the flooding of the Netherlands in 1953, New Orleans during Hurricane Katrina in 2005 and areas in western France in Xynthia in 2010 was the breaching of dike (or levee) systems (Gerritsen, 2005; Lumbroso & Vinet, 2011; van Heerden, 2007).

Another important limitation of our study is that we do not consider human-induced subsidence in large coastal cities built on deltaic and alluvial plains. While this can have a significant effect on global coastal exposure (Nicholls et al., 2021), it is presently difficult to assess this effect both for the past and the future. Historical data is limited to a few cities (Kaneko & Toyota, 2011) and deltas (Nicholls et al., 2021) datasets, but there is no global coverage, let alone temporal coverage as rates of subsidence varied with time. Projecting subsidence into the future is also difficult, because human-induced subsidence can be managed or enhanced and hence change significantly within short time frames (Kaneko & Toyota, 2011). However, based on recent results (Nicholls et al., 2021) it can be assumed that the contribution from the geological driver (including human-induced subsidence) is in reality significantly larger than in our study. Proactive and reactive coastal migration is not considered in this study, although these non-linear processes can could occur, especially in the future, and could influence our results. However, we have followed a standard approach and not considered these interactions in our results. While these migration processes can have large influence on our results on local level, through the aggregation to higher levels (e.g., national) these effects cancel out to a large extend, because extremes do not happen everywhere at the same time. As quantitatively the major driver of coastal retreat is the lack of coastal protection (Lincke & Hinkel, 2021) which is likely not to happen in densely populated areas. Thus the influence of coastal migration on global results will be rather small.

It is important to ask how the analysis could be improved and developed as the needs for attribution outlined at the beginning of the paper will almost certainly continue and grow with time. As reflected above, the main constraint is the availability and quality of data for the historic period (1860–2005). Hence, all the historic datasets used in this analysis could be improved with various efforts. Better and more downscaled historic socio-economic data including development of coastal urban areas could help to analyze where and when socio-economic development at the coast was decoupled from socio-economic development in non-coastal areas. Inclusion of human-induced subsidence (historic and future) could make explicit how much it contributes to current and future exposure and risk – recent analysis has shown that it is a major component of current relative sea-level rise. In order to better understand what drives coastal risk, improved historic protection estimates, in addition to future changes, would be helpful. During the 20th century a lot of coastal exposure was created by land claim (e.g., as observed in Singapore and Dubai) which is a significant process that greatly affects the location of people and assets in relation to coastal flood hazard (Nicholls et al., 2006). Land claim has occurred in almost all coastal cities to some degree (e.g., Seasholes, 2003) and is widespread today in Asia (e.g., Martín-Antón et al., 2016; Sengupta et al., 2018). While this is challenging to assess, this process is also almost certainly an important historic driver at global scales and by implication will remain so in the future.

Finally, our method only allows to attribute future changes to the presence or absence of a driver. With such an attribution assessment the driver is fixed to one scenario and the attribution numbers are different for each scenario combination. Thus our results do not take into account how likely the different scenarios are (e.g., RCP2.6 vs. RCP6.0, or SSP3 vs. SSP5) are.

5. Conclusions

We present a first global attribution study of the increase in coastal flood exposure and risk from 1860 to 2100 due to three key drivers: (a) climate-change-induced SLR, (b) geologic-induced sea-level change, and (c) socio-economic development, using historical data from 1860 to 2005 and scenarios thereafter to 2100. We find that the 6-fold increase in population exposure and the 55-fold increase in asset exposure from 1860 to 2005 is almost completely explained by socioeconomic development (>97% for population and >99% for assets). Beyond 2005, climate-change-induced sea-level change will become the dominant driver of population exposure towards the end of the 21st century, if no substantial mitigation action is taken. In contrast, for the increase in exposed assets, socio-economic development will remain the dominant driver during the 21st century. As coastal societies are expected to continue to develop and increase their adaptation capabilities, and at the same time population might stabilise, population risk will almost completely be determined by climate at the end of the century. The increase in risk for assets will still be mainly driven by socio-economic development, as asset values continue to grow exponentially in the socio-economic scenarios used.

There are important adaptation policy conclusions to be drawn from our study. First, the socio-economic contribution to future coastal exposure can be influenced by societies themselves, and hence controlling this needs to be part of the adaptation portfolio addressing SLR. Development can be steered away from the shoreline/coastal floodplain to less vulnerable areas, for instance by implementing setback zones and shoreline management plans (Lincke et al., 2020; Nicholls et al., 2014). These policies are also effective against coastal erosion, which is not explicitly considered here but is of global concern (Hinkel et al., 2013; Vousdoukas, Mentaschi, et al., 2020; Vousdoukas, Ranasinghe, et al., 2020). Second, societies need to adapt to the unavoidable impacts of sea-level rise, which will be significant under all scenarios (Oppenheimer et al., 2019). In addition to steering future development away from the coast, this might involve removing existing infrastructure from the coast via managed retreat, at least at some locations.

A third adaptation policy conclusion emerges concerning the different ways of attributing changes in exposure and risk and their wider implications. Attributing a change completely to one driver and ignoring all other drivers leads to significant overestimations of its effect due to hidden interaction effects with other drivers. This is an important issue, in particular for the key question of compensation for climate change losses (Burger et al., 2020; Minnerop & Otto, 2020), and selecting which method to use to attribute impacts and damages from extreme events. Following current practise and attributing all impacts and damages only to the climate driver might lead to the moral hazard of encouraging societies to further develop their coastlines and thus increase coastal exposure and risk despite sea levels continuing to rise.

In all cases, climate mitigation policy is critical. As shown in this paper, meeting the targets of the Paris Agreement (i.e., RCP2.6) can reduce coastal population exposure in 2100 by 30–35 million people compared to a business-as-usual RCP6.0 world. However, due to the long response time of sea-level to climate change and to already committed future sea-level rise (Mengel et al., 2018), coastal adaptation remains a policy objective in order to protect the inevitable exposed population and assets. Our analysis has shown that successful coastal adaptation can reduce coastal flood risk even if coastal exposure is increasing. Thus, a triadic policy combining climate change mitigation, coastal management that steers future development away from the coastal floodplain/shoreline and coastal protection for the most valuable areas will be a more effective response to managing coastal flooding than any of these responses alone.

Data Availability Statement

As this paper is part of the ISIMIP framework all data is available via the ISIMIP portal. Input data can be found under https://www.isimip.org/gettingstarted/input-data-bias-correction/ and output data under https://www.%20isimip.org/outputdata/.

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