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Coastal Migration due to 21st Century Sea-Level Rise

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Key Points:

- We provide an estimate of 21st century global coastal migration due to sea-level rise (SLR) taking into account local coastal protection
- Using multiple climate and socio-economic scenarios we estimate 21st century coastal migration to 17–72 million people
- Considering coastal retreat as an option in coastal adaptation decision making lowers 21st century cost of SLR by factors 2 to 4

Supporting Information:

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

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Abstract

Rising mean and extreme sea-levels and induced increased coastal flooding are expected to lead to massive coastal migration if coasts are not protected. Using a wide range of sea-level rise (SLR) scenarios, socioeconomic pathways and discount rate assumptions, 21st century coastal migration is assessed at global scale assuming local cost-benefit optimal protection decisions for about 12,000 coastal segments with homogeneous coastal and socioeconomic characteristics. Costs considered include investment and maintenance cost for protection, migration cost in the case of no protection, and expected annual damage to assets by extreme sea-level events that over-top existing protection. Robust decisions in favor of protection over all scenarios are found for about 3% of the global coastline, covering 78% of global coastal population and 92% of global coastal floodplain assets. For the remaining 97% of global coastline cumulative 21st century land loss ranges from 60,000 to 415,000 km^2 and coastal migration ranges from 17 to 72 million people. Big countries with long uninhabited coastlines suffer the biggest land losses. In absolute terms big countries in South and South-east Asia account for the highest coastal migration, while in relative terms small island nations suffer most. Global cost of 21st century SLR can be lowered by factor two to four if local cost-benefit decisions also consider, next to protection, coastal migration as an adaptation option.

Plain Language Summary

This study provides the first estimate of 21st century global coastal migration due to sea-level rise (SLR), considering the feedbacks between coastal protection and migration. 21st century coastal mean SLR of 33–170 cm combined with five socio-economic scenarios is projected to lead to global coastal land loss of 60,000–415,000 km^2 and associated migration of 17–72 million people assuming cost-benefit optimal local protection decisions. Considering coastal retreat as an option in local coastal adaptation decision making lowers 21st century cost of SLR by factor 2 to 4 compared to decision making that only considers protection as an option.

1. Introduction

Migration due to environmental factors could be a growing phenomenon of the 21st century (Myers, 2002). There are already significant migration streams today, mainly driven by urbanization processes, and climate change could intensify migration (Adger et al., 2020). In the coming decades population that is exposed to the impacts of anthropogenic climate change is projected to increase dramatically (IPCC, 2018). Increase in average temperature, changes in precipitation patterns and rising sea levels will probably lead to more and extreme weather events, such as heat waves, droughts, and floods, and as a consequence one response is for people to adapt to these events and their impacts through migration (Pachauri et al., 2014).

In recent years, a growing body of literature has investigated the influence of climate change on migration (Cattaneo et al., 2019). Generally, this literature emphasizes that migration is a complex phenomenon driven by many push and pull factors and that migration is often only indirectly linked to environmental hazards while social factors play a bigger role (Black et al., 2011; Findlay, 2011; Martin et al., 2014; Millock, 2015). The economic aspects of migration (including costs of benefits for source and destination countries) have been discussed extensively (Bodvarsson & Van den Berg, 2013; Jean & Jimenez, 2007; OECD, 2013).

Within this literature on climate change and migration, sea-level rise (SLR) and coastal migration has gained a lot of attraction from the beginning (Myers, 1993, 2002; Schneider & Chen, 1980). Often there is a specific focus, for instance on river deltas (de Campos et al., 2020; Ericson et al., 2006; Lázár et al., 2020; Milliman et al., 1989), on least developed countries (Nicholls & Leatherman, 1995), on post-disaster migration

(DeWaard et al., 2015; Gray & Mueller, 2012) or on small island states (Arenstam Gibbons & Nicholls, 2006; Speelman et al., 2017).

More recently, coastal retreat and assessments of the associated continental and global scale number of people forced to migrate due to future SLR have received increased attention in the literature and media, with accelerated SLR and increased coastal flooding potentially displacing millions of people from coastal areas (Cattaneo et al., 2019; Hauer, 2017; Hauer et al., 2019).

Indeed mean and extreme sea-levels are projected to rise substantially during the 21st century, with a recently observed acceleration (Nerem et al., 2018). The recently released Special Report on the Ocean and Cryosphere in a Changing Climate (SROCC) of the Intergovernmental Panel on Climate Change (IPCC) projects that there is a 66% chance that global-mean sea level will rise by 0.6–1.1 m by 2100 if greenhouse gas emissions continue to rise unabated (i.e., RCP8.5) and still by 0.3–0.6 m in 2100 if emissions are reduced to meet the goal of the Paris Agreement to limit global warming "well below 2°C" (i.e., RCP2.6) (Oppenheimer & Glavovic, 2019), with large uncertainties and a fat tail on ice sheet contributions (DeConto & Pollard, 2016). Such substantial SLR will trigger different human responses ranging from coastal protection to retreating from the coastal floodplain, and the latter will lead to migration of coastal population.

The available continental to global scales assessments of coastal migration due to rising mean and extreme sea-levels (Desmet et al., 2018; Hauer, 2017; Nicholls et al., 2011; Rigaud et al., 2018), however, generally exhibit one major limitation: they have not taken into account the effects of coastal protection on migration. The only available studies that took into account the effect of coastal protection on migration have been conducted at coarse world-reginal scales with the Integrated Assessment Model FUND (Nicholls et al., 2008; Tol, 2002). These studies however, do not consider multiple scenarios for SLR and socio-economic development. Furthermore its decision modeling is rather simple by only applying a threshold for population density.

Not considering coastal adaptation significantly overestimates the number of people forced to migrate, as the enduring lack of coastal protection is one of main drivers of coastal migration. People that are well protected do not migrate, as illustrated by the millions of people that are currently living below mean high tides, for instance in the Netherlands or other densely populated delta regions such as New Orleans, Tokyo and Shanghai (Oppenheimer & Glavovic, 2019). Today there is little migration from such places (Hino et al., 2017) and even if limits to coastal protection may be encountered in some places, the general trend is likely to continue into the future as coastal protection has been shown to be very effective and cost-efficient in reducing impacts in cities (Aerts & Botzen, 2012; Hinkel et al., 2018; Lempert et al., 2013) and at global scales (Diaz, 2016; Fankhauser, 1995; Hinkel et al., 2014; Lincke & Hinkel, 2018; Nicholls et al., 2008; Tiggeloven et al., 2020; Tol, 2007).

We address this limitation and provide the first estimate of 21st century global coastal migration taking local protection decisions into account. We model migration due to SLR as the consequence of two plausible retreat scenarios: (i) *autonomous migration*, which assumes that coastal residents migrate when the land they live on is lost and *managed relocation*, which assumes that migration takes place earlier due to its proactive initiation and supervision by governments. To sample a wide range of relevant uncertainties, each retreat scenario is combined with five SLR scenarios reaching 33–170 cm in 2100 (RCP2.6 low ice melt, RCP2.6 high ice melt, RCP8.5 low ice melt, RCP8.5 high ice melt and high-end), the five socioeconomic pathways (SSP) and five social discount rates from 0% to 6%. For the resulting 250 scenarios, we report on the land loss and number of people expected to migrate, what proportion of the coast is protected and retreated, and by how much coastal retreat reduces the total cost of SLR as compared to simulations that do not include migration. Finally, we analyze the robustness of local results in terms of the percentage of coastline with robust decisions over most or all scenarios. Thus, a global result of the analysis is the proportion of world's coast that is protected or retreated under a very wide range of possible futures, defined here by the 250 scenario-combinations.

2. Methods

2.1. Protection, Retreat, and Migration

We model coastal protection and coastal retreat decisions jointly as a consequence of local cost-benefit analysis (CBA) on about 12,000 coastline segments homogeneous in coastal and socioeconomic characteristics (Vafeidis et al., 2008).

By using CBA, we do not want to suggest that one should use CBA do make decisions on where to protect or retreat. The limitations of applying CBA are well known and have been discussed extensively in climate change literature (Chambwera et al., 2014; Dennig, 2018; Kunreuther et al., 2014; Markanday et al., 2019) In particular, it is near to impossible to unambiguously monetize the many intangible values constituting the costs and benefits of protection and retreat decisions including migration (Barkin, 1967) or ecosystem services (Turner et al., 2007). And even if this would be possible, other decision criteria beyond benefit-cost-ratios or net present values (NPVs), such as environmental justice theory (Ajibade, 2019), could also be applied.

Conversely, here we apply CBA as a descriptive model of plausible government behavior in the face of coastal risks and we argue that this is a good model for several reasons. First, CBA is currently applied to coastal protection decisions in some of the countries facing the highest coastal risks today, such as the Netherlands (Van der Most et al., 2014) and the United Kingdom (Defra, 2011). Second, it is plausible that CBA will be more widely applied in the future given that coastal damage and adaptation costs under 21st century SLR can amount to several percent of GDP (Hinkel et al., 2014; Tol, 2007), which means that there is an increasing existential need to economize on adaptation expenditure. This need is already apparent today as adaption deficits are growing due to increasing costs and decreasing government spending due to high government debt and austerity policies being put in place (Bisaro & Hinkel, 2018). Finally, and associated to this, an increasing number of policy frameworks are calling for a risk-based approaches to adaptation, such as for example, found in European Water Framework Directive (European Parliament, 2000) and the 2019 strategic development plan of the Maldives (Republic of Maldives president's office, 2018).

Our CBA minimizes the NPV of the total cost of SLR, defined here as discounted sum of protection cost (cost for upgrading and maintaining coastal protection), migration cost and residual damage cost, which is caused by floods that over-top existing protection. See supplementary material for a mathematical account of this optimization. The procedure is applied separately for each coastline segment taking into coastal exposure evolving with socioeconomic development and SLR. The resulting cost-optimal response strategy can either be protection with a cost-optimal protection level or no protection which implies retreat from the coast.

Migration is then modeled as the consequence of two plausible retreat scenarios that differ in the flood probability threshold at which retreat is initiated. Determining this threshold empirically is difficult because there is hardly any empirical evidence to draw upon (Oppenheimer & Glavovic, 2019). Hence, we explore the implication of this uncertain threshold using two retreat scenarios plus an additional sensitivity analysis.

In our *autonomous migration* scenario coastal residents migrate in an individual basis when the land they live on is lost, assuming that there is no government effort to initiate and coordinating retreat earlier. We follow the assumption that land is lost if it lies below the 1-in-1 year flood return level (Nicholls et al., 2011), which means that land is inundated in average once per year and thus generally not usable for buildings and infrastructure. Hence the population stays as long as possible—until the land is finally uninhabitable. This scenario resembles what is called voluntary migration, but associating voluntariness to some forms of migration can and has been debated (Adger et al., 2014), particularly in the context of SLR making land uninhabitable (Oppenheimer & Glavovic, 2019). Here, we follow (Hino et al., 2017) and use autonomous migration, as this form of human mobility usually occurs as a result of autonomous retreat (Hino et al., 2017) The high flood probability threshold used in this scenario reflects the empirical finding that there is often an unwillingness to migrate, even under constant threat (Esteban et al., 2020; Hauer et al., 2019). The 1-in-1 year flood return level threshold models this unwillingness in that the individual decision to migrate is delayed as long as possible. Only when the land becomes regularly inundated (1-in-1 year flood return level can be seen as a proxy for spring high tides) people leave.

In our *managed relocation* scenario, coastal residents migrate already if they live below the 1-in-10 years flood return level, reflecting that the loss of land due to gradual SLR is foreseeable and migration can take place before the land is swallowed by the sea. This resembles that retreat is which refers to migration initiated, supervised and/or implemented by governments (Hino et al., 2017). The lower flood probability threshold used in managed relocation scenario reflects that such a retreat is usually more proactive. We do not cover what is called displacement as we do not do event-based modeling of coastal floods.

In the managed relocation scenario, the abandoned land is not lost earlier as compared to the autonomous migration scenario, reflecting that the land below the 1-in-10 years flood level can still be used temporarily for purpose that do not require long-lived infrastructure such as, for example, agriculture (Tol et al., 2016).

In order to compare our results with those of earlier flood risk studies that did not consider retreat, we also include a *no retreat* scenario.

2.2. Migration Cost

Migration is costed as 3.0 times local GDP per capita per migrant, which is roughly the value of the assets on the lost land (for each resident 2.8 times local GDP per capita (Hallegatte et al., 2013) plus 7% deconstruction cost (Diaz, 2016). This assumes that assets subject to abandonment have to be renewed completely. While some authors have argued that because SLR is a slow and gradual process, assets have depreciated their entire value once they are swallowed by the sea (Tol et al., 2016; Yohe & Tol, 2002), but little empirical evidence is available on this. Furthermore, we assume that both in the case of reactive as well as planned relocation, that the social planer compensates or buys out homeowners, which has been observed today. For example, in the aftermath of the coastal flooding brought by Xynthia, the French Government offered to fully compensate all home-owners, based on the value of the real estate prior to the storm and most homeowners accepted within a year (Lumbroso & Vinet, 2011). Finally, the migration cost used lies within the range of migration cost used in the few global studies available, as well as empirically established cost estimates in some case studies ([Diaz, 2016]; [Hinkel et al., 2013]; [McNamara & Des Combes, 2015]; [Regeneris Consulting, 2011]; [State of Louisiana, 2015]; ([Tol, 1995]; Table S3).

2.3. Flood Damages

The methods for assessing global coastal flood damages follow earlier work from Hinkel et al. (Hinkel et al., 2014). These authors calculate the impact of coastal extreme event flooding in terms of the mathematical expectation of flood damages (expected annual damages) under a given protection level for the 12,148 coastline segments defined in the DINAS-COAST database (Vafeidis et al., 2008). Coastal segments represent parts of the coast with homogeneous biophysical and socioeconomic characteristics. People affected by coastal floods and expected annual flood damages are calculated by combining elevation-based population and asset exposure with flood depths caused by extreme events and applying a depth-damage function. Expected annual flood damages are computed as the mathematical expectation of damages based on extreme event distributions. Affected population is not translated into economic damages.

Extreme water level distributions are taken from the GTSR database (Muis et al., 2016) and are assumed to uniformly increase with SLR, following 20th century observations (Menendez & Woodworth, 2011). Current protection levels are taken from a stylized protection model (Sadoff et al., 2015) complemented with protection levels for the biggest 136 coastal cities (Hallegatte et al., 2013). As in earlier work (Lincke & Hinkel, 2018) land with a population density below 30 people per km^2 is considered as unpopulated land. Protection level zero is assumed for unpopulated land. In unprotected areas it is assumed that nobody lives below the 1-in-1-years water level. Cost for construction of protection infrastructure are based on national unit cost for dikes (Hinkel et al., 2014) and the annual maintenance cost for protection infrastructure is one percent ot its capital cost.

Table 1
Coast Length, Floodplain Area, Population and Assets in Different Classes of Percentage of Scenarios Where Protection has a Positive Net-Present value

Percentage of scenarios with NPV > 0	Length of coast (km)	Length of coast (%)	Floodplain area (km^2)	Floodplain area (%)	Floodplain population (mill.)	Floodplain population (%)	Floodplain assets (bill. US$)	Floodplain assets(%)
0%	618,000	89.4	440,000	63.5	5.6	3.7	156	1.1
1%–33%	19,600	2.8	29,800	4.3	5.4	3.6	108	0.8
34%–67%	14,300	2.1	26,100	3.8	6.5	4.3	214	1.4
67%–99%	15,900	2.3	26,600	3.8	15.1	10	629	4.4
100%	23,300	3.4	170,000	24.6	118.1	78.4	13,200	92.3

Note: All values refer to 2015.

2.4. Scenarios

21st century SLR impacts, expected flood damages, protection costs and coastal migration are assessed for combinations of five SLR scenarios, five socioeconomic scenarios, five discount rates and two retreat scenarios. Four regional SLR scenarios (Hinkel et al., 2014) (the 5th and 95th percentile of RCP2.6 using the HadGEM-ES2 model and the 5th and 95th percentile of RCP8.5 using the HadGEM-ES2 model) are complemented with a fifth high-end regional sea-level scenario (Jevrejeva et al., 2016) in order to sample also the low-probability, high impact tail of possible 21st century SLR. The climate induced coastal mean SLR of these scenarios covers a range of 0.3–1.7 m over the 21st century (Table S1). While under the RCP2.6 scenarios sea-levels rise roughly linear until 2100, under the RCP8.5 scenarios sea-levels accelerate significantly in the second half of 21st century (Figure S3). For local relative sea-level change climate-induced SLR is complemented with glacial-isostatic adjustment (Peltier, 2004) and delta subsidence for coastal segments associated with river deltas.

As socioeconomic scenarios for population and assets projections we use the five Shared SSP version 9 (Figure S4) provided by the SSP database (IIASA, 2012; O'Neill et al., 2014). For discounting future costs we use five rates from 0% to 6% (in 1.5% steps) in order to cover the full range of discount rates put forward from both positivist and ethical perspectives in the literature on intra-generational discounting of climate change benefits and costs (Weisbach & Sunstein, 2008; Weitzman, 2007).

Land loss due to permanent inundation is modeled using flood frequency (R. Nicholls et al., 2011). Unprotected land that falls below the 1-in-1 year frequency of flooding is considered as lost. In the autonomous migration scenario, the population living on the lost land is subject to (forced) migration. In the planned relocation scenario, population migrated before the land is lost. Flood frequency is used to model the retreated area. Unprotected land the falls below the 1-in-10 year frequency of flooding is considered to be subject to planned retreat and the affected population migrates. Migrating population and associated assets are moved out of the coastal zone and not subject to further flooding.

3. Results

3.1. Global

From the point of view of CBA, coastal protection is found to be favored over retreat (including both, autonomous migration and planned relocation) in all scenario combinations for 3.4% of the world's coastline (Table 1), corresponding to 25% of the global 1-in-100-year floodplain, 78% of global floodplain population, and 92% of the global floodplain assets in 2015. For the remaining 96.6% of the world's coastline, proceeding without protection and accepting the resulting land loss and coastal migration is the preferred option in at least one scenario combination.

Global land loss during 21st century adds up to 60,000 km^2 to 415,000 km^2 and the resulting migration to 17–72 million people or 0.23%–0.97% of the global population in 2015 (Figure 1). While large uncertainty from socioeconomic scenarios and discount rates exists for forced migration, land loss depends only weakly

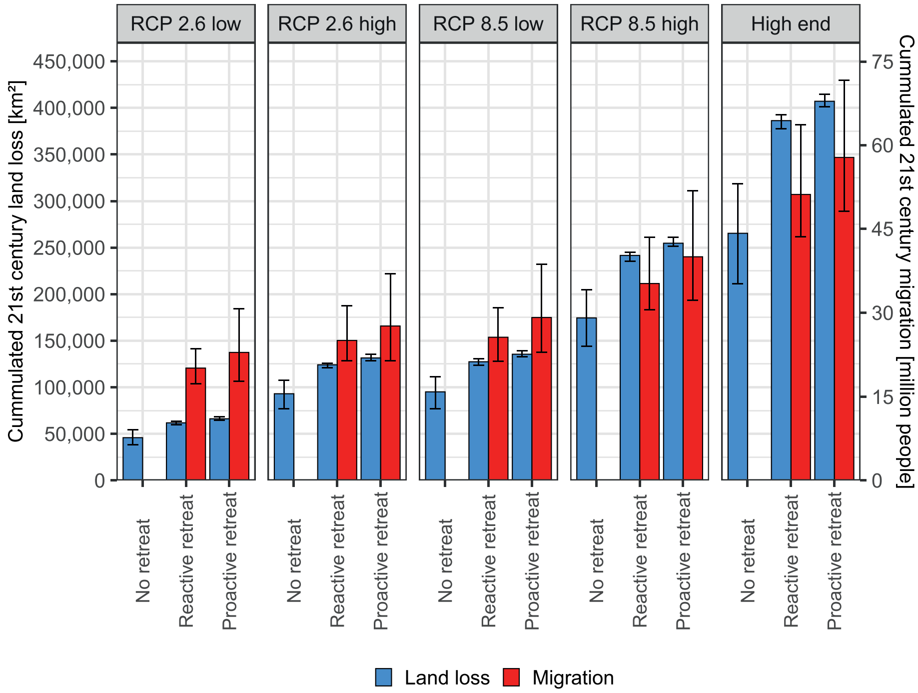

Figure 1. Global land loss and migration cumulative over the 21st century under different retreat assumptions and the five sea-level rise (SLR) scenarios used in this study. The bars show averages over all shared socioeconomic pathway (SSP) scenarios and discount rates, the error bars show the associated uncertainty range.

on these two dimensions of uncertainty (Figures 1 and S2), which reflects that most of the lost land is very sparsely populated. In fact, unpopulated land is also lost under the no retreat scenarios. Applying a linear regression on land loss and SLR values over all scenarios and all intermediate time steps we find the model

$$landloss(km^2) = 251{,}543.8\left(\frac{km^2}{m}\right) * sl\ change(m) + 2959.7(km^2) \tag{1}$$

with $r^2 = 0.996$ (see Figure S1) to predict 21st century global land loss based on global SLR under local cost-benefit optimal protection. The positive intersection value reflects that there is land below sea-level which would already be lost, if it would not be protected today.

Contrary to land loss, global 21st century coastal migration increases with SLR, but also with decreasing wealth. Higher wealth implies higher asset values associated with population. Thus migration cost gets higher with increasing wealth while protection cost remain constant, preferring protection over migration.

Further, higher discounting of future cost leads to lower coastal migration, especially in combination with the planned relocation scenario (Figure S2). As protection cost growth slowly with SLR (Figure S6) and expected annual damages growth faster with SLR (due to the depth-damage relation), avoided damages by any coastal protection growth faster than protection cost. Thus, higher discount rates lead to higher protection levels, more protected coastline and less coastal migration. Also, the cost of planned relocation is higher than the cost of autonomous migration (as more population and assets need to be migrated in the planned case) while expected annual damages are lower under planned relocation (as less population and assets remain in the coastal zone). As expected annual damages growth faster with SLR (due to the depth-damage relation) higher discount rates prefer planned relocation over autonomous migration.

3.2. Country-Level

The 3.4% of coastline for which protection was found to be robust over all scenario combinations can be found mainly in Europe and in the highly developed Asian countries China and Japan, which is due to

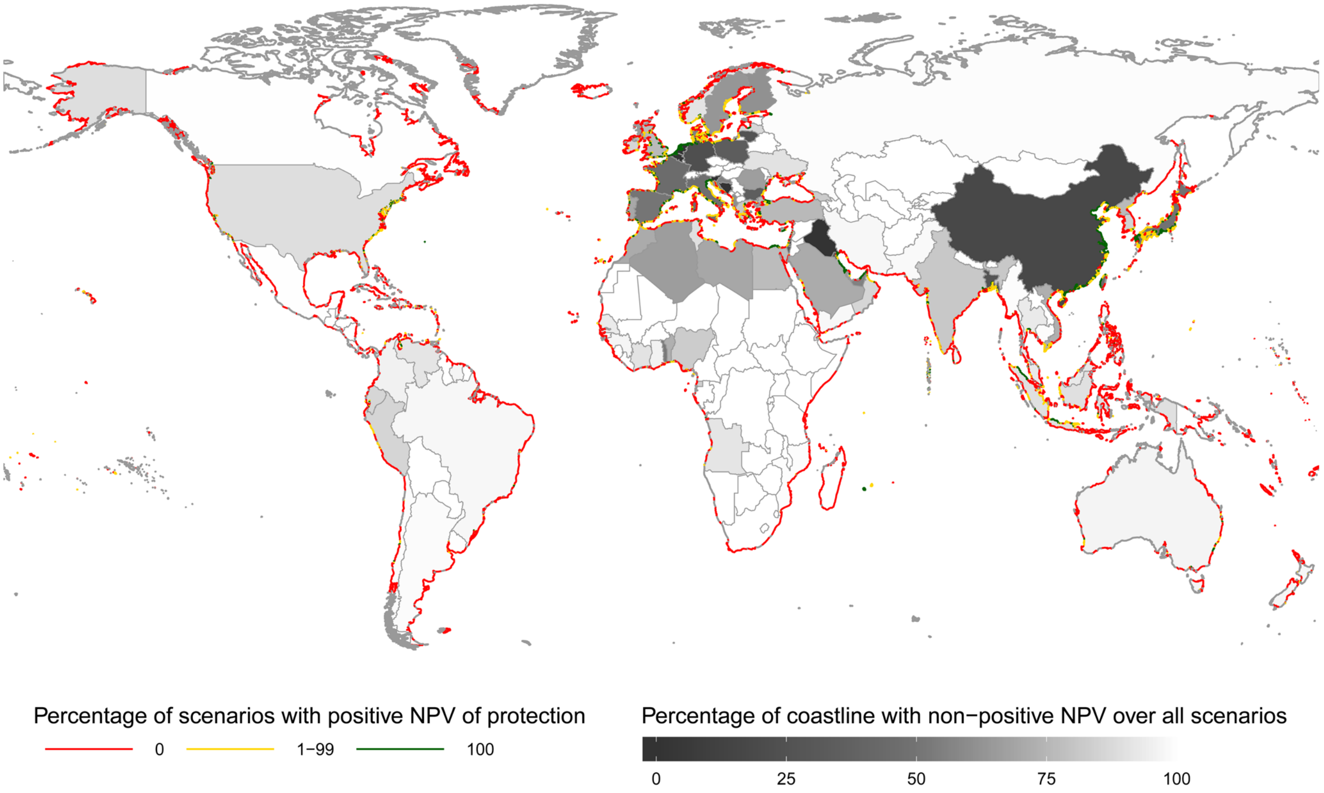

Figure 2. Robust local protection and retreat responses due to sea-level rise (SLR). The color shows the percentage of scenarios in which protection has a positive net-present value (NPV) taking into account costs associated with both protection and retreat. Gray coastline indicates uninhabited parts of the coast that have a negative NPV of protection over all scenarios, but no migration. Countries are colored according to the percentage of coastline that is not protected over all scenarios. The lighter a country is colored, the more of its coastline is subject to retreat under every scenario.

their high level of coastal urbanization and the high existing protection standards (Figure 2). In addition, urbanized areas at the US coast and a few locations with high population densities, such as the Nile delta or the big cities in Australia, have robust results in favor of protection and hence do not suffer from land loss and migration.

The cumulative 21st century SLR induced land loss due to local retreat is highest for the big northern countries Canada, Russia, and the USA (Table 2). These countries have very long sparsely populated northern coastlines, which are not protected under any scenario combination. Australia also loses a significant amount of land reflecting that the Australian coast outside of the urban agglomerations is very sparsely populated and will thus not be protected. The big land loss for these four countries does, however, not account for large migration. Instead, the cumulative 21st century migration due to the SLR induced land loss is highest for densely populated countries in South and South-east Asia (Tables 2 and S1). While in India and Vietnam the coastal mega cities like Mumbai, Chennai, Kolkata, Ho Chi Min City and the urban agglomeration in the north including Hanoi and Hai Phong are protected under any scenario combination, the rural area outside these urban centers is not protected under every scenario combination and accounts for significant migration.

For eight countries the entire coastline is protected under every scenario (Table S1). Most of these countries have short coastlines that are highly urbanized (i.e., Belgium, Gibraltar, Macau, and Monaco).

The highest relative effects (for both, land loss and migration) are obtained for Small Island States with large proportions of low-lying land (Table 3). Countries with low, mainly rural population concentrated at the coast, specifically Small Island Developing States such as the Pitcairn Islands, Marshall Islands, Kiribati, Tuvalu aud Nauru have the highest migration relative to the 2015 population (Table 3). The big differences in the uncertainty ranges for relative migration between countries reflect the robustness of protection

Table 2

Cumulative Land Loss and Forced Migration During 21st Century for the Ten Most Affected countries

Rank	Country	Median	Min-max range
	Land loss (km^2)		
1	Russia	28,600	13,600–56,600
2	Canada	23,400	8,000–43,900
3	USA	15,200	8,100–39,000
4	India	8,300	3,800–20,600
5	Brazil	7,200	2,500–25,700
6	Greenland	6,400	0–24,600
7	Australia	6,200	3,200–24,800
8	Viet Nam	4,900	200–16,200
9	Mexico	3,800	2,300–13,100
10	Indonesia	3,500	700–21,400
	Migration (10^6 people)		
1	Viet Nam	5.7	1.2–12.0
2	India	5.4	3.0–14.5
3	Indonesia	1.4	0.8–4.5
4	Bangladesh	1.2	0.2–8.0
5	Philippines	1.0	0.6–2.5
6	Brazil	0.9	0.5–1.8
7	Myanmar	0.9	0.4–3.0
8	China	0.8	0.2–3.3
9	South Korea	0.7	0.5–1.3
10	Japan	0.6	0.2–2.3

Note: The median column shows the median value over all scenarios, the min-max range column the minimum and maximum over all scenarios. Countries are selected and ordered according to the median value.

decisions. For some countries (i.e., Pitcairn Island) the protection decisions are robust over all scenarios. Hence, the uncertainty range only represents the uncertainty of migration caused by socioeconomic development and SLR. For other countries (i.e., Marshall Islands) the uncertainty range also includes the uncertainty over protection decisions. For small island states these decisions are often in the range from protect everywhere to protect nowhere, showing that these island states are also very sensitive to the choice of the discount rate.

3.3. The Effect of Migration on Total Cost of Sea-Level Rise

Comparing the retreat scenarios with the no retreat scenario shows that considering the option of coastal retreat and migration within local decisions can significantly reduce the total cost of 21st century SLR (sum of protection, maintenance, migration, and residual flood damage cost) as compared to only considering coastal protection as an option (Figure 3).

Taking the retreat option into account lowers the length of coast for which a robust protection result is obtained. This is because the NPV of protection can be bigger than the NPV of no protection without retreat but lower than the NPV of no protection with retreat. In the latter case, the migration of people and assets lowers the expected annual damages by floods. Globally, 112,000–117,000 km of coast inhabited by 14–24 million people in 2015 are protected under every scenario if retreat is not an option but not protected under every scenario if retreat is taken into account (Table S3).

Both observations are based on the same effect. When considering protection as the only adaptation option (i.e., no retreat scenario), this population of 24 million people would be protected, because the flood damage cost is higher than the cost of protection. If the retreat option is introduced, however, flood damage costs are reduced through migration, which brings the sum of retreat and remaining flood damage below the cost of protection for the bespoke 24 million people. Consequently, the population that is protected under every scenario is lower if the retreat-option is available, which in turn reduces the discounted total cost of 21st century SLR to 28%–52% of the cost under the corresponding scenario without migration (Figure 3).

Migration accounts for the highest share of total SLR cost under high SLR, while under low SLR, protection cost is the highest share (Figure 3). With migration taken into account, damage cost do not strongly depend on SLR, but rather on socioeconomic development (Figure S5), because the latter process determines how many people will be living in the coastal floodplain and hence how many may migrate. In contrast, protection costs rise with rising sea-levels but are almost independent from socioeconomic development. Migration cost rise with both—SLR and socioeconomic growth (Figure S5).

3.4. Sensitivity Analysis

Our assessment of coastal migration involves two major uncertain parameters that are difficult to empirically estimate. The first parameter is the per capita cost of migration. In our analysis, a per capita migration cost of three times the local GDP per capita was used, assuming that capital assets on the land lost need to be deconstructed and fully replaced (See Methods). Per capita cost in the few available numbers from case studies and economic models range between 1.2 and 9.5 (Table S4), whereby 9.5 is a bit of an outlier. These numbers are, however, difficult to compare due to different underlying assumptions and cost components. To explore the sensitivity of our results to these assumptions, the analysis was repeated with per capita migration cost of two and four which covers the core range of migration cost used in studies listed in Table S4.

Table 3

Relative Effect of 21st Century SLR on Land Loss and Migration for the Ten Countries With the Highest Relative Effect. All Values Refer to the 2015 Values as Baseline. The Land Loss/Migration Column Shows the Median Value Over All Scenarios, the Range Column the Minimum and Maximum Over All Scenarios. Countries are Selected and Ordered According to the Median Value.

	Land loss (% of land area)		
Rank	Country	Median	Min-max range
1	Marshall Islands	5.6	2.3–25.4
2	Kiribati	4.9	2.8–25.1
3	Bahamas	4.0	1.9–20.9
4	British Virgin Islands	3.4	0.9–10.3
5	Tuvalu	3.0	1.6–10.9
6	British Indian Ocean Territory	2.5	1.3–9.7
7	Gambia	2.1	0.9–10.2
8	French Polynesia	2.1	1.2–9.9
9	Saint Pierre and Miquelon	1.7	0.8–4.5
10	Cocos Islands	1.6	0.9–12.1
	Migration (% of population)		
1	Pitcairn Islands	86.4	86.3–89.3
2	Marshall Islands	70.7	11.4–86.8
3	Kiribati	59.3	56.1–62-6
4	Tuvalu	45.0	43.1–47.3
5	Nauru	36.1	35.9–37.3
6	Saint Pierre and Miquelon	34.6	4.7–37.1
7	Norfolk Island	28.6	28.6–29.2
8	Wallis and Futuna	27.7	0.0–86.6
9	Cook Islands	25.2	6.8–26.9
10	Cocos Islands	23.0	22.8–25.5

The second parameter is the retreat threshold specifying the probability of flooding at which forced or managed retreat is carried out. In the literature, there is little information to base this threshold upon. While this uncertainty is partly included in our analysis by distinguishing between autonomous migration (below the 1-in-1 year water level) and planned relocation (below the 1-in-10 year water level), planned relocation could also be initiated earlier. To analyze how an even more proactive form of planned relocation would influence results, all simulations have been repeated with a retreat threshold of the 1-in-100 year water level.

The sensitivity of the results to changes in both parameters has been assessed using a one-driver-at-a-time (OAT) approach, varying only the parameter of interest while keeping all other parameters constant. Lower per capita migration cost clearly favors retreat over protection and thus leads to higher land loss and migration (Figure S7). Lowering per capita migration cost from 3 to 2 times GDP per capita, raises land loss by 0.9%–7.9% (5th to 95th quantile: 1.4%–4.9%) across all scenarios and associated migration by 8.5%–34.9%. (5th to 95th quantile: 11.7%–27.2%). Consequently, raising per capita migration cost from 3 to 4 times GDP per capita, lowers land loss by up to 0.7%–4.1% (5th to 95th quantile: 0.9%–2.9%) across all scenarios and associated migration by 5.4%–20.4% (5th to 95th quantile: 7.5%–17.1%). Variations in the retreat threshold do not influence the results in such a clear direction (Figures S8). While increasing the planned relocation threshold from the 1-in-10 years flood level to the 1-in-100 years flood level leads to up to 4.7% more cumulative global land loss (5th to 95th quantile: 0.3%–4.1%) across all scenarios, global coastal migration is altered by between −9.4% and +26.7% (5th to 95th quantile: −5.2%–23.1%).

4. Discussion

Our results show that studies that do not take coastal protection into account overestimate land loss and the number of SLR migrants significantly. For example, without considering coastal protection Nicholls et al. (Nicholls et al., 2011) estimates that about 900 to 1,800 thousand km^2 of land will be lost under 0.5–2.0 m of SLR, leading to 70–190 million people migrating from coastal areas during the 21st century. Under comparable SLR scenarios, our study finds that only about 60–420 thousand km^2 land will be lost, leading to about 20–70 million migrants. Similarly, the 13.1 million people estimated to migrate out of the coastal zone in the US, which was assessed without considering upgrades to coastal protection by (Hauer, 2017), is an order of magnitude higher than the estimates presented here (Table S2).

Comparing to local studies that have considered both protection and migration, we find similar ranges. Country-level projections for Bangladesh estimate coastal migration of 1.5–7.4 million people in the 21st century (Lázár et al., 2020), which is in line without estimate (0.2–8.0 million, see Table S1). The lower bound of Lazar et al. (2020) is higher than ours, because the authors also include socio-economic factors such as compromised quality of life (household can only afford to pay its food expenses and nothing else) and rice yield shortages in their migration-model. As these factors are can also occur in protected areas, there is migration also under their protection scenario.

One limitation of our approach is that we model flood risk at the level of whole probability distributions and hence cannot represent single extreme events. In practice, coastal migration is, however, often driven by large single events such as Hurricane Katrina (Hallegatte et al., 2013). Representing single events would require a different modeling approach requiring information on spatial and temporal autocorrelation of extremes as well as large numbers of model runs, both of which has so far not been practiced at broad scales.

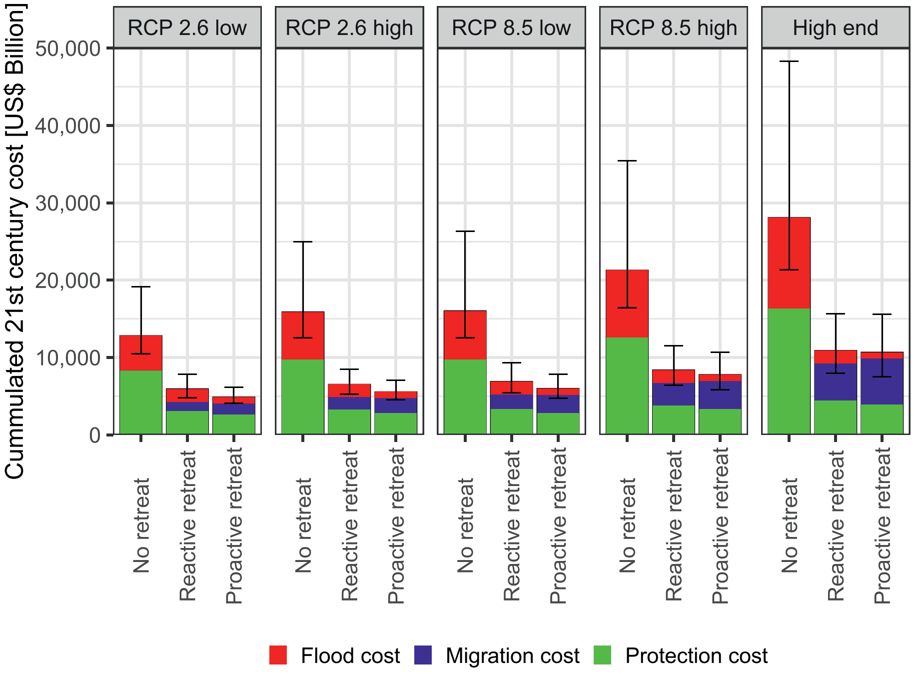

Figure 3. Cumulative not discounted 21st century sea-level rise (SLR) cost and its components under the SLR and retreat scenarios used in this study compared to a *no retreat* scenario. The bars show the average of the components over all scenarios, while the error bar shows the minimum and maximum of the total cost over all scenarios.

The modeling of single events would also need to include decisions on recovery versus abondement, which is difficult to model. The former includes back-migration of population, as empirically observed after many extreme events (Cutter et al., 2014; DeWaard et al., 2015), the latter has for instance been observed after the 2004 tsunami for several islands of the Maldives (UNEP, 2005). In any case, our autonomous migration scenario can be seen as a lower bound of migration due to disasters, because by the time SLR leads to a person living below the threshold of the 1-in-1 year extreme event, the person would have probably been hit by an extreme event and migrated before.

Further limitations arise due to inaccuracy in the underlying global datasets, including the digital elevation data, population datasets, surge data, etc., which means that the absolute numbers are meant to be indicative. However, our analysis over multiple SRL- and socio-economic scenarios shows that for a large share of the global coast (92.8%) there is a robust protection response in either direction (89.4% retreat and 3.4% protect). As the multiple SLR and socio-economic scenarios cover a wide range of possible futures with wide ranges of population and asset exposures, it is likely that locations with a robust protection response over all scenarios would have the same protection response when different data sets (for instance a different digital elevation model) would be used. Thus the insights on the share of coast that is protected or not protected under all scenarios is an important result, and also the share of coastal floodplain population and assets that would either be protected or not be protected under every future considered are important insights.

The results of this study show what the world would look like if all local decision-makers are only following cost benefit analysis. This does neither mean that we suggest that cost benefit analysis should necessarily be applied to informs decisions, nor that we see cost benefit analysis as an isolated dimension of coastal decision making. There are many other frameworks that can be applied for decision making and which framework to use is essentially a normative decision of coastal societies. While many of these frameworks comprise cost benefit analysis as one of many criteria, other dimensions such as location-specific social, ecological and cultural consequences should be considered in local coastal decision making. In some cases, the choice of options is limited, for example, small island nations with no significant elevated area (Maldives, Kiribati) could not choose to migrate their population within the country even if this would be the outcome of an cost benefit analysis. The question of where the population from islands that cannot be protected and are eventually abandoned is a key issue in the climate change debate (and beyond the scope of our analysis). There is also empirical evidence that in some cases people continue to live in places that are inundated regularly, for example in elevated homes (Esteban et al., 2020). In that sense, our threshold of the 1-in-1 frequency may locally be more aggressive than practice.

One advantage of modeling future adaptation pathways using CBA is that this method takes into account that protection levels rise with rising exposure and affluence of coastal societies, which is consistent with 20th century observations (Hinkel et al., 2014). However, recent literature also points out that coastal protection and retreat may raise financing issues (Bisaro & Hinkel, 2018) and social conflicts that impede the implementation of coastal adaptation measures even if they are beneficial from an economic cost-benefit point of view (Bisaro & Hinkel, 2016; Hinkel et al., 2018). This points toward the need for future work investigating the link between costs and benefits of coastal adaptation on the one hand and financing instruments that can be applied to mobilize resource for implementing adaptation on the other hand.

The results of this study strengthen the conclusion of IPCC SROCC that the world is likely to see bifurcating coastal futures. On the one hand, the grand majority of coastal inhabitants, which lives in densely populated and urban coastal areas, is likely to (continue to) protect themselves even under high-end SLR (Esteban et al., 2020). On the other hand, poorer rural areas will struggle to maintain safe human settlements and are likely to eventually retreat from the coast. For the latter areas it is important to manage retreat and migration in a way that ensures acceptance of affected communities. More proactive retreat approaches such as managed realignment (Turner et al., 2007) or setback zones (Rochette et al., 2010) could be a way to achieve acceptance and also may lower cost and impacts of SLR significantly. As migration cannot always be within country borders, international issues might arise.

5. Conclusion

In this study, we provide the first extensive (multi-scenario) analysis of 21st century coastal migration that takes into account local coastal protection. We find that across five SLR, five socio-economic, five discount rates and two retreat scenarios local least cost-benefit decision leads to a robust response (meaning the same response over all scenarios) for 92.8% of the global coast. While for 3.4% of the coast this robust response is to protect the coastline, for 89.4% of the coast the robust response is to retreat. For the coast that is not protected 21st century land loss is projector to be 60,000 to 415,000 km^2 with a resulting migration of 17–72 million people.

Our study shows that even under low SLR there will probably be migration from coastal areas in this century. As CBA will part of coastal protection decisions in one way or another, countries need to be prepare that not all coastal population can be protected and that migration will be one of the consequences for the population of unprotected coastal areas.

Future research should take into account more advanced methods for decision making. As CBA is often criticized, especially in environmental context, better decision models that include more location-specific social, ecological, and cultural dimensions are needed. Applying such models could show more alternative coastal futures.

Conflict of Interest

The authors declare no conflict of interest.

Data Availability Statement

Data sets for this research are available in the repository https://github.com/daniellincke/DIVA\text{_}paper\text{_}migration and under the Zenodo record 4459151 (DOI: 10.5281/zenodo.4459151).

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