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A global analysis of erosion of sandy beaches and sea-level rise: An application of DIVA

Jochen Hinkel [a,*], Robert J. Nicholls [b], Richard S.J. Tol [c,d], Zheng B. Wang [e,f], Jacqueline M. Hamilton [g], Gerben Boot [f], Athanasios T. Vafeidis [h], Loraine McFadden [i], Andrey Ganopolski [j], Richard J.T. Klein [k,l]

[a] Global Climate Forum (GCF), Neue Promenade 6, 10178 Berlin, Germany
[b] Faculty of Engineering, Environment and Tyndall Centre for Climate Change Research, University of Southampton, Southampton, United Kingdom
[c] Department of Economics, University of Sussex, Falmer, United Kingdom
[d] Institute for Environmental Studies, Department of Spatial Economics, Vrije Universiteit, Amsterdam, The Netherlands
[e] Faculty of Civil Engineering and Geosciences, Delft University of Technology, The Netherlands
[f] Deltares, Delft, The Netherlands
[g] Research Unit Sustainability and Global Change, Centre for Marine and Atmospheric Studies, University of Hamburg, Hamburg, Germany
[h] Institute of Geography, Christian-Albrechts University Kiel, Kiel, Germany
[i] Flood Hazard Research Centre, Middlesex University, Enfield, United Kingdom
[j] Potsdam Institute for Climate Impact Research (PIK), 14412 Potsdam, Germany
[k] Stockholm Environment Institute, Stockholm, Sweden
[l] Centre for Climate Science and Policy Research, Department of Thematic Studies, Linköping University, Linköping, Sweden

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A B S T R A C T

This paper presents a first assessment of the global effects of climate-induced sea-level rise on the erosion of sandy beaches, and its consequent impacts in the form of land loss and forced migration of people. We consider direct erosion on open sandy coasts and indirect erosion near selected tidal inlets and estuaries, using six global mean sea-level scenarios (in the range of 0.2–0.8 m) and six SRES socio-economic development scenarios for the 21st century. Impacts are assessed both without and with adaptation in the form of shore and beach nourishment, based on cost-benefit analysis that includes the benefits of maintaining sandy beaches for tourism. Without nourishment, global land loss would amount to about 6000–17,000 km^2 during the 21st century, leading to 1.6–5.3 million people being forced to migrate and migration costs of US$ 300–1000 billion (not discounted). Optimal beach and shore nourishment would cost about US$ 65–220 billion (not discounted) during the 21st century and would reduce land loss by 8–14%, forced migration by 56–68% and the cost of forced migration by 77–84% (not discounted). The global share of erodible coast that is nourished increases from about 4% in 2000 to 18–33% in 2100, with beach nourishment being 3–4 times more frequent than shore nourishment, reflecting the importance of tourism benefits. In absolute terms, with or without nourishment, large countries with long shorelines appear to have the largest costs, but in relative terms, small island states appear most impacted by erosion. Considerable uncertainty remains due to the limited availability of basic coastal geomorphological data and models on a global scale. Future work should also further explore the effects of beach tourism, including considering sub-national distributions of beach tourists.

1. Introduction

Sea-level rise and associated extreme water levels will lead to a range of impacts including temporary flooding, permanent submergence of low lying areas, increased coastal erosion, wetland change and loss, salinity intrusion into coastal aquifers and the lower reaches of rivers (Nicholls et al., 2007). Coastal flooding, submergence and erosion are distinct, but related processes (Nicholls, 2010). Flooding and submergence relate to rising relative water levels without any change in absolute elevation, while erosion is a morphodynamic process produced by the removal of sediment, due to waves, currents and other hydrodynamic processes. In this paper, the focus is the erosion of sandy beaches. Beach erosion can occur at a range of timescales (Stive et al., 2002, 2009). Individual storms will generally lead to rapid short-term erosion, followed by rapid short-term accretion and the net change is often negligible. If sediment deficiencies persist, more chronic long-term erosion can result. This paper addresses such chronic long-term erosion due to sea-level rise.

Long-term erosion of beaches (and other soft coasts) is already a widespread phenomenon at the regional and global scale (Bird, 1985;

* Corresponding author. Tel.: +49 30 2060738 20; fax: +49 30 2060738 33.
E-mail address: hinkel@globalclimateforum.org (J. Hinkel).

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Nicholls et al., 2007; Eurosion, 2004). The drivers of these changes are widely debated with a combination of natural erosion trends on some coasts, exacerbated by a widespread reduction in sediment supply due to human agency (e.g., Bird, 1985). Historic sea-level rise over the last 100 years (e.g., Church and White, 2011) has also been linked to these changes (e.g., Vellinga and Leatherman, 1989; Zhang et al., 2004), and sea-level change is one component altering coastal sediment budget at all locations. Looking to the future and the likelihood of accelerated sea-level rise due to human-induced climate change, there is a consensus that this process will exacerbate coastal erosion with adverse physical and socio-economic impacts on the world's beaches and adjoining coasts (Zhang et al., 2004; Church et al, 2010).

Despite the anticipated exacerbation of coastal erosion due to sea-level rise, global assessments of sea-level rise impacts have almost exclusively focused on the impacts of temporary flooding or permanent submergence of land. As far as we are aware, there is no global analysis of coastal erosion due to sea-level rise. This paper presents such an analysis. Its goals are twofold: (1) present methods to evaluate coastal erosion; and (2) analyse the potential implications of erosion for the world's coasts over the 21st century under plausible climate and socio-economic scenarios, including adaptation via nourishment. This includes the magnitude of land loss and its socio-economic costs and consequences, adaptation costs, and identifying regions and countries that appear particularly vulnerable to erosion. The analysis builds on earlier global assessments of other impacts of sea-level rise such as coastal flooding and wetland loss (e.g., Hoozemans et al., 1993; Nicholls, 2004). The method presented was developed and consolidated as part of the DIVA[1] model (DINAS-COAST Consortium, 2006; Hinkel and Klein, 2009).

The analysis focuses on the average erosion of sandy beaches and the adjacent land due to sea-level rise. Other coastal erosion such as along muddy coasts and cliffs is not considered. Further, this analysis only considers the consequences of sea-level rise. Other erosion processes on sandy beaches such as alongshore transport, falling sediment budgets due to coastal defences and dams on rivers (e.g. Syvitski et al., 2009) are not considered. Hence, we only report a *component* of beach erosion rather than the total erosion that will occur during the 21st century due to all drivers.

Erosion of sandy beaches is estimated due to the combination of the direct effect of profile translation and the indirect effect of tidal inlets, where appropriate. The direct effect is estimated using the Bruun Rule to estimate average erosion rates per segment. The Bruun Rule has generated considerable debate in the literature both favourable and unfavourable (e.g., Cooper and Pilkey, 2004; Zhang et al., 2004). Our application scale is consistent with the broad scale validation of the concept by Zhang et al. (2004). Zhang et al. (2004) also showed that the Bruun Rule is problematic in the vicinity of inlets as there are important indirect erosion effects of sea-level rise (see also Stive, 2004; Ranasinghe et al., 2012a). For this reason, this indirect effect is also considered and estimated for about 200 major tidal basin complexes using an adapted version of the ASMITA model (Stive and Wang, 2003). Hence, we have developed and applied a simple first-order erosion model that is applicable on a broad-scale perspective. We see this as a first attempt at this type of model. More sophisticated treatments might be developed in the future following the concepts of Cowell et al. (2003) and Ranasinghe et al. (2012a,b), but the challenges of such applications at broad scale should not be underestimated.

The remainder of the paper is organized as follows: Section 2 describes the model, data and scenarios, Section 3 presents results, Section 4 discusses them and Section 5 concludes.

[1] DIVA (Dynamic Interactive Vulnerability Assessment) was developed by the DINAS-COAST (Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Climate Change and Sea-Level Rise) Consortium.

2. Methodology

2.1. The DIVA model and database

DIVA is an integrated, global model of coastal systems that assesses biophysical and socio-economic consequences of sea-level rise and socio-economic development taking into account coastal erosion, coastal flooding, wetland change and salinity intrusion (http://www.diva-model.net; DINAS-COAST Consortium, 2006; Hinkel and Klein, 2009). An important innovation is the explicit incorporation of a range of adaptation options, including beach or shore nourishment as a response to erosion. The DIVA data model divides the world's coast into 12,148 variable length coastal segments, and associates up to 100 data values with each segment (Vafeidis et al., 2008). DIVA is driven by climatic and socio-economic scenarios, comprising temperature (for coastal tourism), sea level, land use, coastal population and GDP. Only the aspects of DIVA dealing with erosion are considered in this paper.

For the erosion assessment, a number of processes are assessed in each coastal segment. First we assess potential land loss per segment in response to sea-level rise as the sum of land loss due to direct and indirect erosion (see below). Then, the socio-economic impacts are considered, including the number of people that are forced to migrate due to land loss and the associated welfare costs. Finally, adaptation options are applied according to different strategies.

2.2. Estimating direct erosion due to sea-level rise

For each segment that contains sandy beaches, direct erosion due to sea-level rise is estimated. Indicative average estimates of the direct erosional effect of sea-level rise on sandy coasts are developed for each coastal segment following Bruun (1962) — see also Mimura and Nobuoka (1995), Zhang et al. (2004), Ranasinghe and Stive (2009) and Nicholls (2010). This describes how an equilibrium profile responds to relative sea-level rise in a two-dimensional sense. The so-called Bruun Rule considers near-shore slope and material composition (e.g., Hands, 1983).

$$R = G * S * l/h \tag{1}$$

where R is the horizontal recession due to sea-level rise; G is the composition of the eroded material expressed as the reciprocal of fraction of beach-grade material; S is relative sea-level rise; l is the active profile width above the depth of closure; and h is the active profile height above the depth of closure.

As l/h is typically about 100 (e.g., Nicholls, 1998), and in the absence of appropriate data G is assumed to be 1 (all eroded material is sand), then Eq. (1) can be simplified to

$$R = 100 * S. \tag{2}$$

Eq. (2) is the form used in DIVA. In coastal segments where sea-level fall is predicted, no calculations are made.

The value of l/h is uncertain and deviations from 100 will lead to greater or less retreat depending on the actual nearshore coastal slope (Ranasinghe and Stive, 2009). If we take the approach of Nicholls et al. (1995) to evaluate the uncertainty in this value, l/h national average values range from 110 to 170, 100 to 2100 and 80 to 122 for Senegal, Argentina and Venezuela, respectively (Nicholls, 1998). Cowell et al. (2006) recommend a similar approach to evaluate this uncertainty. However, we do not have the data to estimate l/h around the world's coasts. Similarly if $G > 1$ (i.e. not all the material is sand), the recession rates would be higher than reported here. This effect is counteracted if the beach is backed by harder less erodible material, in which case erosion would remove the beach and leave a more rocky coastline. Again we do not have the data to estimate how widely this will occur.

To translate R into the loss of sand volume due to direct erosion (direct sand loss), the appropriate length and height of the beach are required. The beach length is expressed via the segment length (z) and the Erosion Factor (E_f), which estimates the proportion of z that is composed of sandy beaches (Vafeidis et al., 2008). At the global scale, E_f is difficult to estimate: it is derived from a composite range of data sources which were combined as explained in Appendix A. In DIVA, the global shoreline is about 1,000,000 km, while the erodible sandy shoreline is about 110,000 km or about 11%, compared to other estimates such as Bird (1985) which are 20%. This suggests that DIVA may be underestimating the length of sandy coast, and hence the scope for beach erosion. The active profile height (h) is estimated using the tidal range and wave height classes defined by Davies (1972) as explained in Appendix B.

Hence the direct potential sand loss per segment (V_d) is estimated as:

$$V_d = z * R * E_f * h. \tag{3}$$

2.3. Estimating indirect erosion due to sea-level rise

For segments linked to tidal basins, indirect erosion due to sea-level rise is also estimated. Tidal basins import sediment under rising sea levels, as they try to maintain a dynamic equilibrium. This requires a sediment flux from the nearby open coast into the tidal basin, resulting in an additional local *indirect erosion* of the adjacent open coast (Stive, 2004). We compute this indirect erosion based on a simplified version of the ASMITA[2] model (Bijsterbosch, 2003; Stive and Wang, 2003), designed in a generic form that is applicable globally (see Appendix C). The ASMITA model applies to an individual tidal basin system, which is conceptualised into three morphological elements: (1) the tidal flats in the basin, (2) the channels in the basin and (3) the associated ebb-tidal delta. These three elements can exchange sediment with each other, and the ebb-tidal delta can also exchange sediment with the adjoining coasts (the "outside world"). A basic assumption is that the system will be in morphological equilibrium if undisturbed (no relative sea-level change and/or no human interference) for a long time. Then the volume of each of the three elements is related to the tidal conditions and morphologic characteristics:

$$\begin{aligned} V_{fe} &= f_1(A_b, H) \\ V_{ce} &= f_2(P) \\ V_{de} &= f_3(P) \end{aligned} \tag{4}$$

where:

V_{fe}	Equilibrium (sediment) volume of tidal flats in the basin
V_{ce}	Equilibrium (wet) volume of channels in the basin
V_{de}	Equilibrium (sediment) volume of ebb-tidal delta
A_b	Area of the tidal basin
H	Tidal range
P	Tidal prism

The ASMITA model combines these empirical relations for morphological equilibrium and the formulations for sediment transport processes in order to simulate the changes of the volumes of the three elements when the system is perturbed by relative sea-level rise. The resulting model assumes that the basin is in dynamic equilibrium with the segment-specific rate of relative sea-level rise in the base year. Under these conditions, the basin has a constant demand for sand under a constant rate of sea-level rise. The sediment demand grows under accelerating sea-level rise and hence the indirect erosion grows through the 21st century under the scenarios analysed here.

A sample of 200 of the largest (and hence most influential) tidal basin complexes around the world's coast was selected and analysed based on the 2-minute Gridded Global Relief Data (ETOPO2 v1) data and the Times Atlas of the World (see Appendix C). 54 out of 166 coastal countries considered have tidal basin complexes. The basic parameters are the area of the tidal basin and the number of tidal inlets that link the tidal basin to the neighbouring open sea. The other parameters that are required to implement ASMITA are taken from the well-studied Wadden Sea tidal basin in the Netherlands (Van Goor et al., 2003; Kragtwijk et al., 2004; Wang et al., 2007). Each tidal basin is linked to its neighbouring coastal segment where any erosion occurs. While there are only 200 segments with tidal basins complexes, the erosion in these areas is a large part of the global erosion due to sea-level rise as discussed in the Results below.

2.4. Socio-economic impacts

Two main socio-economic impacts of erosion are evaluated: dryland loss and forced migration of the people living there. Values are attached to these impacts. All economic costs are in 1995 US dollars.

Dryland loss refers to the loss of habitable land. The dominant land use class per segment (see Climate and socio-economic scenarios) is used to value these losses. Generally, this is agricultural or lower value land classes (e.g., nature areas, forests or tundra). In these cases, it is assumed that should land for more valuable uses such as housing or industry be lost due to erosion, then those activities would relocate elsewhere at the expense of the dominant agricultural or lower value land.

The number of people forced to migrate is calculated as the product of the land area eroded and the average population density per segment — that is, we assume that the population is spread evenly over the area. Following Tol (1995), emigration is valued at three times per capita income. This is a guesstimate. It is equivalent to the net present value, using a 5% discount rate, of a 15% wage increase. Barrett and Goggin (2010) find a migration wage premium of 7% for returnees to Ireland, Cutilloa and Ceccarellia (2012) a 21% wage premium for migrants within Italy. A migration value of 300% annual income is therefore not implausible, but perhaps on the low side as forced migration would be more detrimental to welfare than the voluntary migration observed in the labour literature. Future research should seek better estimates. The cost of rebuilding houses and infrastructure at different locations is not considered. Erosion due to sea-level rise is a slow process and the losses can be anticipated (Yohe et al., 1996, 2011). That is, buildings and infrastructure are fully depreciated before being swallowed by the sea.

While tourism revenues are considered in the analysis of nourishment decisions (see below), the impact of sea level rise on tourism is not considered, because DIVA includes only the coastal zone. In order to assess tourism impacts a tourism model would need data on the interior as well (Hamilton et al, 2005a,b). Furthermore, sea level rise has little impact on coastal tourism because the presence of tourists means that, in most cases, it is worthwhile to protect the coast (see Bigano et al., 2008, and below).

2.5. Beach and shore nourishment

DIVA also considers beach and shore nourishment, i.e. the replacement of eroded sand (Dean, 2002). In beach nourishment, the sand is placed directly on the intertidal beach, while in shore nourishment the sand is placed below low tide where the sand will progressively feed onshore due to wave action, following current Dutch practice (van Koningsveld et al., 2008). Based on expert judgement and information of Deltares, six unit costs for nourishment are considered depending on the availability of sand and the type of nourishment (Table 1).

[2] ASMITA — Aggregated Scale Morphological Interaction between a Tidal basin and the Adjacent coast.

Table 1
Unit nourishment costs in 1995 US dollars.

Erosion factor (E_f) (and hence inferred sand supply)	Shore nourishment (for other beaches) (US\$/m^3)	Beach nourishment (for tourist beaches) (US\$/m^3)
>0.5 (sand supply abundant)	3	6
0.2 to 0.5	6	9
<0.2 (sand supply limited)	9	12

Shore nourishment is cheaper than beach nourishment and effective in slowing erosion, but it is less effective at sustaining the attractiveness of a beach for tourism, because the benefits on the dry beach are not felt immediately. Secondly, the distance the sand has to be transported is important and this is inferred using E_f as an index of sediment availability. Nourishment costs are assumed to be universal, as the technology is generic and dredging companies are multinationals. Nourishment costs are assumed to be constant over time. We also recognise that shore nourishment may be ineffective or very slow to produce benefits in fetch-limit seas where waves are less effective at moving material onshore under calm conditions due to their short period (e.g. Komar, 1998). We consider this factor via a sensitivity analysis where shore nourishment is removed as an option in selected fetch limited seas.

Nourishment options may be applied following different adaptation strategies. In this analysis, two strategies are considered: (1) no nourishment and (2) optimal nourishment based on cost-benefit analysis (CBA) as explained below. In the no nourishment strategy, DIVA computes the impacts as described above.

For optimal nourishment, the benefits of nourishment depend on the damage avoided in terms of land loss, forced migration and tourism. Because both the costs and benefits are assumed to be linear functions of the amount of nourishment, areas are either fully protected (so that no damage is done) or not at all. For areas with coastal tourism, beach nourishment is the preferred adaptation option. It is applied if the combined benefits in terms of land loss, migration and tourism are sufficient. If the costs of beach nourishment cannot be justified by its benefits, then shore nourishment is evaluated to avoid land loss and forced migration.

The level of tourism and tourism revenues are calculated using the Hamburg Tourism Model (HTM) (version 1), which is an econometric model of international tourism flows at a national scale (Hamilton et al., 2005a,b). In HTM, the number of tourists increases with population and income; tourists prefer holidays at a temperature of 25 °C. Hence, as countries become increasingly wealthy and populous the number of tourists increases, while global warming can change optimum tourist locations. If the warmest month is below 15 °C, there is no beach-related tourism. Above this temperature, the national economic value of coastal tourism is estimated as 16% of HTM's predicted national tourism revenues, based on the assumptions that 65% of tourists are coastal, and 25% of their expenditure is profit. We assume that coastal tourism is focussed along the sandy beaches in a strip 1 km wide. As these are national estimates, we cannot resolve sub-national characteristics of this distribution.

The assessment of the optimal level of nourishment is straight forward as all the key relationships are linear within each segment: (1) the marginal benefits of nourishment to counteract the total potential erosion estimated above are constant: i.e. for every cubic metre of additional sand supply, the same additional land area is protected from erosion; (2) land values are constant (in the area eroded); and (3) the costs of nourishment are linear in the amount of sand applied, so that the marginal costs of nourishment are constant. This implies that optimal nourishment is a corner solution. If the unit cost of nourishment exceeds the marginal benefit (i.e., the value of the land area protected from erosion per cubic metre of sand supplied), then no nourishment occurs in a segment. If the marginal cost is less than the marginal benefit, then nourishment will fully offset erosion in a segment.

2.6. Climate and socio-economic scenarios

Eight sets of scenarios based on the IPCC SRES storylines are explored (Nakicenovic and Swart, 2000). The socio-economic component of the scenarios was derived from the IMAGE 2.2 17-region implementation of the SRES scenarios (IMAGE Team, 2002), since the IMAGE model has a greater regional breakdown than comparable models, and includes land-use scenarios. The regional growth rates for population and GDP are assumed to apply homogeneously to the countries within the associated region with the exception of GDP for rich countries in poor regions (namely Hong Kong, Singapore, Macao, Taiwan and several Caribbean countries). Fig. 1 shows global GDP and population for these scenarios.

The climate and sea-level rise scenarios were derived with CLIMBER-2 — a climate model of intermediate complexity (Petoukhov et al., 2000). For each SRES emission scenario, a low, medium and high gridded air temperature and global-mean sea-level rise scenario was produced by assuming the three different climate sensitivities of 1.5 K (low), 3 K (medium) and 4.5 K (high). Here we focus on the medium climate sensitivity, with the exception of the A1B storyline where we consider all three climate sensitivities (Fig. 1). The range of 21st century global mean sea-level covered by these scenarios is 22 to 80 cm, which is consistent with the range published in the Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (Meehl et al., 2007) and thus excludes potential higher contribution of the ice sheets of Greenland and Antarctica to global mean sea-level rise due to an acceleration of ice sheet flow (e.g., Rahmstorf, 2007). Due to the slow response of the ocean to global warming, differences between the global-mean sea-level rise scenarios for the same climate sensitivity only become significant after the middle of the 21st century.

DIVA downscales the climate-induced sea-level rise scenarios by combining them with segment-level estimates of local vertical land

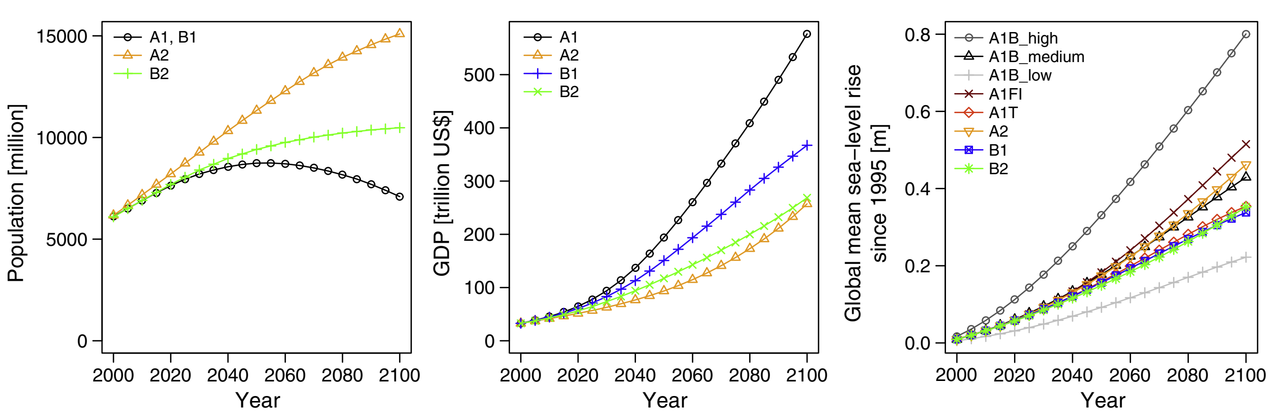

Fig. 1. Global population (left), GDP (middle) and mean sea-level rise (right) for the eight scenarios used in this paper.

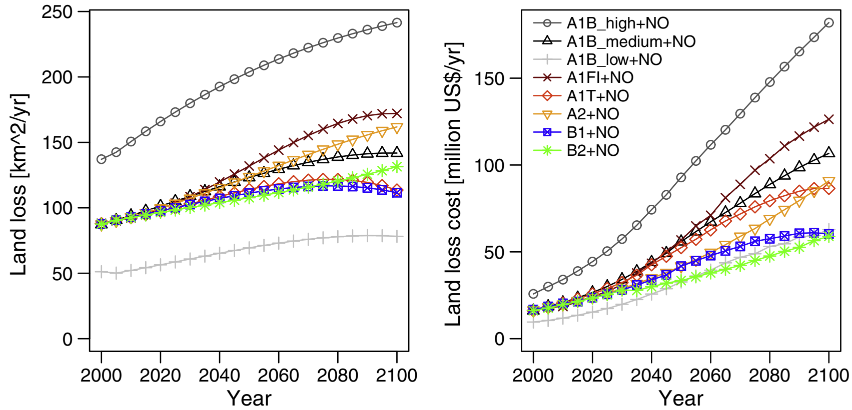

Fig. 2. Global annual land loss (left) and global annual cost of land loss (right) due to coastal erosion without nourishment.

movement based on glacial isostatic adjustment (Vafeidis et al., 2008). Additionally, where segments occupy deltas, we assumed, based on expert judgement, an additional 2 mm/year subsidence due to natural sediment compaction. The resulting relative sea-level rise is lower than the global average for some uplifting regions such as Fennoscandia and higher than the global average in subsiding deltas. Human-induced subsidence may be much greater on susceptible coasts, most especially in deltas (e.g., Nicholls, 2010), but this is not considered in DIVA due to a lack of consistent information.

Each set of scenarios is run without nourishment (symbolized as + NO) and with optimal (cost-benefit) nourishment (symbolized as + CBA) as described above.

3. Results

3.1. Land loss without nourishment

The most immediate impact of erosion is the loss of land. Without nourishment and assuming medium climate sensitivity, between 112 and 172 km^2 land will be lost annually due to erosion in 2100 under the six SRES sea-level rise scenarios (Fig. 2). Land loss decelerates notably towards the end of the century in all scenarios but A2 and B2 due to the linear relationship between the direct erosion recession rate and the rate of global sea-level rise (Eq. (2)) with the latter rate decreasing towards the end of the century in all scenarios but A2 and B2. When considering only low, medium and high A1B sea-level rise scenarios, the range increases to between 78 and 242 km^2 per year in 2100. Hence, the uncertainty about climate sensitivity has a greater effect on the uncertainty about erosion at the global scale than the uncertainty about socio-economic development and associated emission pathways. The rank order of land loss attained under the different SRES scenarios follows the rank order of the corresponding rise in sea level: A1FI is the highest, and B1 is the lowest. Cumulatively, between 6000 and 17,000 km^2 land is projected to be lost over the 21st century under the scenarios considered here.

The cost of land loss lies between US $59 and $126 million per year in 2100 across the six medium scenarios, compared to US $63 and $182 million per year across the three A1B scenarios, respectively (Fig. 2). The rank order for costs of land loss attained under the different SRES scenarios differs from the rank order of the rise in sea level, because the unit value of land also varies with SRES scenario (reflecting different socio-economic development).

The five countries most affected by land loss under A1B medium in 2100 are the United States, Australia, Mexico, Russian Federation and Brazil. These countries all have a long coastline and a relative high share of sandy beaches. Four of these countries are amongst the five countries ranking highest in terms of their total length of sandy beaches: Australia (13,200 km), U.S.A. (12,800 km), Brazil (6100 km), Denmark (4600 km) and Mexico (4900 km). In terms of absolute costs, the five countries most affected in 2100 under the A1B medium scenario are the U.S.A., Japan, Germany, Denmark and the Netherlands (Fig. 3). In terms of relative costs (to national GDP), Kiribati, The Marshall Islands and Tuvalu are most affected, losing more than 0.01% of national GDP under the A1B medium scenario in 2100 (Fig. 3).

Globally, indirect erosion accounts for about 70–73% of total erosion at the beginning of the century under all scenarios without nourishment and falls to 50–64% by the end of the century. The share of direct erosion increases over the century because direct erosion is linear in sea-level

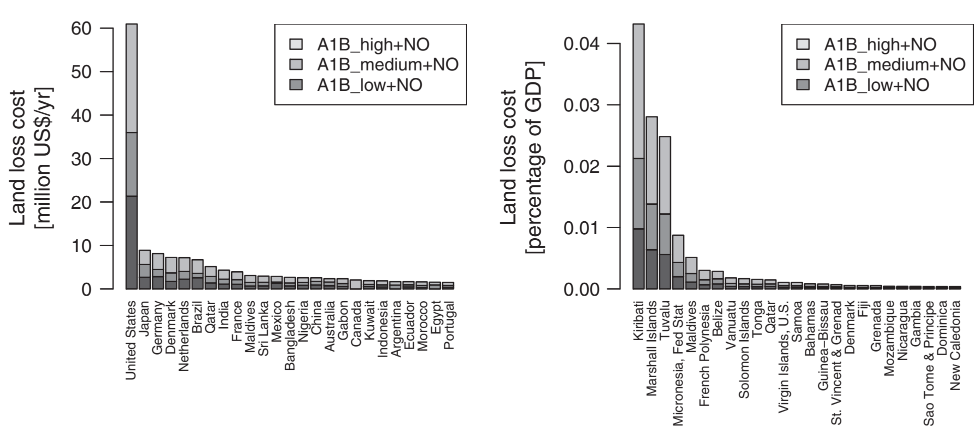

Fig. 3. Annual cost of land loss for the 25 most affected countries in absolute terms (left) and relative to GDP (right) in 2100 for the A1B scenario with low, medium and high sea-level rise and without nourishment.

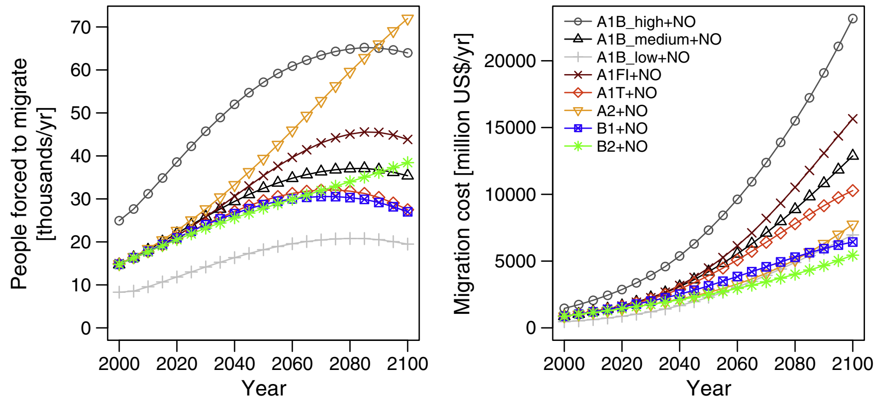

Fig. 4. Global annual number of people forced to migrate due to coastal erosion (left) and global annual cost of forced migration (right) without nourishment.

rise and hence directly reacts to the accelerating rates of sea-level rise, whereas indirect erosion reacts with a delay, because the tidal basin systems only gradually adjust towards new dynamic equilibria when sea-level accelerates. On a country level, the share of total land loss caused by indirect erosion is logically high for those countries that have tidal basins. In 2100 and under A1B medium, this shares lies above 90% for Qatar, Cameroon, Belize, Romania, Panama, Oman, Angola; Costa Rica, Canada and Ecuador.

3.2. Forced migration without nourishment

The second major impact of erosion is forced displacement of the residents living on the eroded land. Without nourishment, about 25,000 to 70,000 people per year are expected to be forced to migrate in 2100 across the six medium SRES scenarios, compared with 19,000 to 64,000 people per year under the low, medium and high A1B scenarios (Fig. 4). Across the SRES scenarios, the highest impacts are under the A2 scenario, reflecting that this has the largest population and one of the highest rises in sea level (Fig. 1). Cumulatively, between 1.6 and 5.3 million people are forced to migrate due to increased erosion in the 21st century across all the scenarios.

The cost of forced migration is about two orders of magnitude higher than the cost of land loss (Fig. 4). Cumulatively, forced migration is expected to cost between US$ 300 and 1000 billion for the scenarios considered here. For the medium sea-level rise scenarios, costs are highest under the A1FI scenario as people are much wealthier than in an A2 world. The countries with the highest migration costs in 2100 under the A1B medium scenario are the U.S., Japan and The Maldives, with the costs in the U.S.A. being about half the global cost (Fig. 5). In terms of cost relative to national GDP, the Maldives, the Marshall Islands and Kiribati rank highest with around 0.5% of national GDP in 2100 required for population relocation under the A1B medium scenario.

3.3. Impacts with nourishment

If we apply nourishment following the CBA approach, impacts are increasingly reduced during the 21st century, reflecting that the benefit of nourishment increases with increasing land values due to socio-economic development (Fig. 6). The socio-economic benefits in terms of avoided forced migration and avoided costs are much larger than the pure physical benefits, reflecting the cost-benefit approach taken and that much of the coastal population is concentrated in a few places (Small and Nicholls, 2003). Cumulatively over the 21st century, CBA reduces land loss by 8–14%, cost of land loss by 39–52% (not discounted), forced migration by 56–68% and the cost of forced migration by 77–84% (not discounted). This illustrates the CBA mechanism: valuable land is disproportionally protected, and wealthy people are preferentially protected. The lowest reductions are under the B2 scenario reflecting the low GDP growth and moderate increase in population exposure.

In 2100, global annual nourishment costs are estimated to be US $1.4 to $5.3 billion per year across the low, mid and high A1B scenarios and US$ 1.4 to 3.2 billion per year across the mid SRES scenarios. The undiscounted cumulative costs for the 21st century lies between US$ 64 and 221 billion for the scenarios considered here. Costs are lowest under B2 and A2 and highest under A1. On a country level for the A1B medium scenario, nourishment costs in 2100 are highest in absolute terms for the U.S.A., Japan, Qatar, the Netherlands and China at above US$ 0.1 billion per year per country. In relative terms (to GDP), Qatar

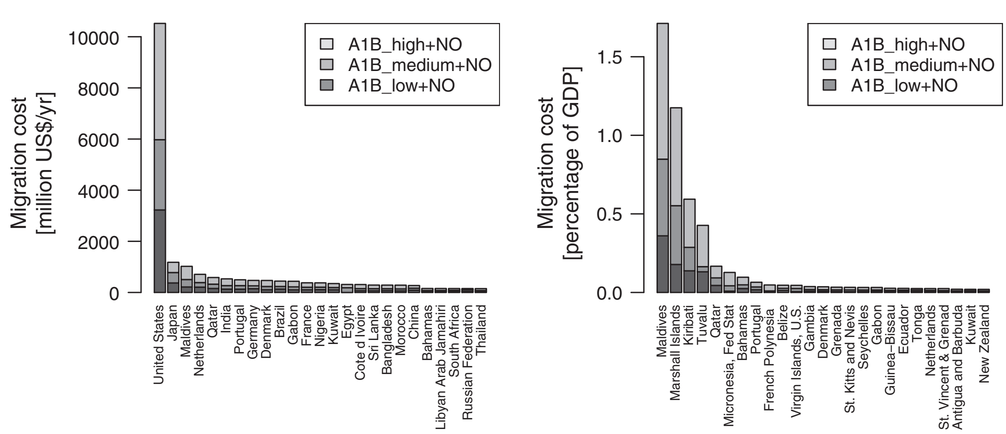

Fig. 5. Annual cost of forced migration for the 25 most affected countries in absolute terms (left) and relative to GDP (right) in 2100 for the A1B scenario with low, medium and high sea-level rise and without nourishment.

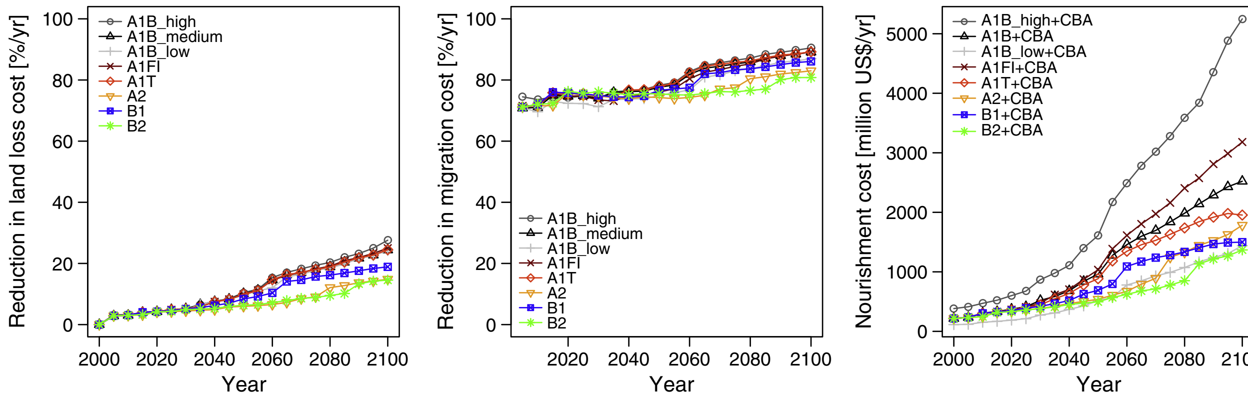

Fig. 6. Reduction in global annual land loss cost (left) and migration cost (middle) through optimal nourishment and associated nourishment cost (right).

(0.06% of GDP), The Maldives (0.04% of GDP), the Virgin Islands (0.03% of GDP) and Ecuador (0.02% of GDP) have the highest national costs.

The change in tourist arrivals affects these results in two ways. Climate change pushes the border where beach tourism is attractive further north and the number of segments where tourists are present increases. Second, socio-economic development increases the number of tourist arrivals and the revenues attained from tourism. Under the CBA strategy, this leads to an increasing number of segments receiving nourishment.

The global share of erodible coast that is nourished increases from about 3% in 2000 to 18–33% in 2100 under all scenarios. The lowest share nourished in 2100 is under the A2 and B2 scenarios, again reflecting the lower land values and hence lower benefits of protection under these low-income scenarios. In 2000, this share is split equally between beach and shore nourishment, whereas in 2100 the share of beach nourishment is 3–4 times that of shore nourishment. This illustrates the importance of taking into account tourism benefits in the nourishment decision.

The effect of excluding shore nourishment in potentially fetch-limited seas is relatively small. In a sensitivity analysis, we exuded shore nourishment in the Baltic Sea, Red Sea, Mediterranean, Black Sea, Caribbean, Gulf of Mexico, Persian Gulf, Sea of Japan, Java Sea and Banda Sea. This lead to nourishment not being cost efficient any more in some coastal segments, which increased cumulative land loss by about 1%, cumulative migration by about 4% and decreased cumulated (not discounted) nourishment costs by about 4% for the A1B medium scenario and the 21st century. The effect is relatively small because in many of those regions tourists are present and beach nourishment is applied in any case.

4. Discussion

A range of physical impacts and economic costs have been estimated using two simple erosion formulations coupled to an adaptation cost-benefit model, providing, for the first time, indicative results of global aggregate impacts of sea-level rise on the erosion of sandy beaches and adaptation needs. Absolute costs appear large, but in relation to the national economies of the most threatened countries (such as U.S.A.), they are relatively small and manageable. However, they do indicate strategic challenges that coastal management will need to address over the next century. In relative terms, small island nations appear particularly vulnerable to erosion as the costs are large relative to their national economies. Hence, this work reinforces the conclusion in earlier analyses that these are amongst the most vulnerable nations to sea-level rise (cf. Hoozemans et al., 1993; Nicholls, 2004; Nicholls and Tol, 2006). This analysis did not consider global mean sea-level rises beyond the range given in AR4 that could result from an accelerated contribution of the ice sheets of Greenland and Antarctica. Future work needs to do this. Given that direct erosion is linear in sea-level rise we would expect no great surprise in terms of direct physical impacts (i.e. land lost), but in terms of socio-economic impacts the interplay between local socio-economic development, tourism and local relative sea-level would need to be investigated further.

The limitations of the analysis also need to be appreciated and include the following issues. The description of erosion processes through the Bruun Rule is limited and controversial (e.g., Cooper and Pilkey, 2004; Pilkey and Cooper, 2004; Stive, 2004). The Bruun Rule has rightfully been rejected as a predictive model to be used for planning and management at local scales (Pilkey and Cooper, 2004). One basic and unrealistic assumption underlying the Bruun Rule is the absence of alongshore sediment transport. A further limitation of the Bruun Rule is the difficulty to estimate the depth of closure due to a lack of data (e.g., Ranasinghe and Stive, 2009). On the other hand, there are also arguments that can be made in favour of applying the Bruun Rule for a global scale analysis. While local estimates of land loss may be incomplete because they miss important components of the sediment budget (e.g., alongshore sediment transport), global estimates are expected to be more accurate because they average across large areas. Zhang et al. (2004), for example, find agreement between the Bruun rule and observed erosion trends for the U.S. East Coast. Furthermore, a global assessment needs to apply stylized models such as the Bruun rule, as complex morphodynamic models cannot be applied at broad continental and global scales.

Further limitations include that the underlying data on the world's coast is limited and the difficulty in defining the location of the sandy shorelines of interest to this study. As well as continuous sandy beaches, pocket beaches need to be considered, as these are often important for tourism. This raises questions on the extent of erosion, which has been considered unlimited in this analysis. The extent of erosion is, for example, often limited in many coastal situations such as on barrier islands (e.g., US East Coast), or where a beach is backed by rocks, while DIVA assumes erosion can continue indefinitely. The scope for migration within national borders may also be limited, in particular for Small Island states and densely populated countries.

Future work may improve the current analysis in several directions. One major innovation of this paper is the inclusion of adaptation and tourism in the assessment of coastal erosion due to sea-level rise. The treatment of tourism, however, is generalized to a national scale and this may be further developed on sub-national scales (as in Hamilton and Tol, 2007). The cost-benefit analysis could be improved by taking into account the interactions with other impacts such as coastal flooding and the consideration of defence benefits of nourishment. More analysis of the costs of beach nourishment could also be included, as higher nourishment costs would reduce the extent of nourishment. The resolution of the coast-line could be improved for geographic regions for which better data is available and additional tidal basin systems could be included as a great share of erosion is indirect erosion. Finally, data can be improved, especially on inlets and distribution of sandy beaches. This might include a more focussed analysis on areas with the best data such as the USA or Europe which would help to improve the analysis methods and to understand to what extend better data could improve the analysis. Hence there is significant scope for improvement which the authors are pursuing, and what is presented should be considered as interim results that illustrate a workable methodology for this type of analysis.

5. Conclusions

This paper assesses the global effects of climate-induced sea-level rise and erosion of sandy beaches, including possible nourishment responses. It has been developed as a component of the DIVA (Dynamic Interactive Vulnerability Assessment) Model of coastal impacts and adaptation. It considers both direct erosion effects on open sandy coasts and indirect erosion effects near selected tidal basins and estuaries, the potential socio-economic implications of the resulting land loss, and the potential for adaptation using nourishment, including a consideration of the economic value of coastal tourism.

Across the SRES scenarios considered, large areas of land could be lost if there is no adaptation. Cumulatively over the 21st century about 6000–17,000 km^2 land area may be lost across the globe due to sea-level rise induced erosion, leading to 1.6–5.3 million people being forced to migrate with an associated migration costs of US$ 300–1000 billion (not discounted). Optimal beach and shore nourishment based on cost-benefit analysis would cost about US$ 65–220 billion (not discounted) during the 21st century and would reduce land loss by 8–14%, cost of land loss by 39–52% (not discounted), forced migration by 56–68% and the cost of forced migration by 77–84% (not discounted) under the scenarios considered here. In absolute terms, with or without nourishment, large countries with long shorelines appear to have the largest costs, but in relative terms, small islands appear most threatened by erosion.

These results contribute to the ongoing attempts to quantify the impacts of climate change on a global level and they add estimates for one impact that has so far not been quantified globally. The results may also be used for comparison between different world regions and nations (e.g., Nicholls, 2010), but not for coastal management analyses where more complex morphodynamic methods are necessary (e.g., Dickson et al., 2007; Nicholls et al., 2011). The analysis also shows the need for improved basic coastal geomorphic data at a global scale. We hope that this paper will stimulate more attention on acquiring the underlying data – which can be improved significantly – and further algorithm development in terms of physical changes, adaptation responses and socio-economic processes such as tourism.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.gloplacha.2013.09.002.

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