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ORIGINAL ARTICLE

Sea-level rise impacts on Africa and the effects of mitigation and adaptation: an application of DIVA

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Abstract This paper assesses sea-level rise impacts on Africa at continental and national scales including the benefits of mitigation and of applying adaptation measures, considering four scenarios of global mean sea-level rises from 64 to 126 cm in the period of 1995–2100. We find that in 2100, 16–27 million people are expected to be flooded per year, and annual damage costs range between US$ 5 and US$ 9 billion, if no adaptation takes place. Mitigation reduces impacts by 11–36%. Adaptation in the form of building dikes to protect against coastal flooding and nourishing beaches to protect against coastal erosion reduces the number of people flooded by two orders of magnitude and cuts damage costs in half by 2100. Following such a protection strategy would require substantial investment. First, Africa's current adaptation deficit with respect to coastal flooding would need to be addressed. DIVA suggests that a capital investment of US$ 300 billion is required to build dikes adapted to the current surge regime and US$ 3 billion per year for maintenance. In addition, between US$ 2 and US$ 6 billion per year needs to be spent on protecting against future sea-level rise and socio-economic development by 2100. This suggests that protection is not effective from a monetary perspective but may still be desirable when also taking into account the avoided social impact. We conclude that this issue requires further investigation including sub-national scale studies that look at impacts and adaptation in conjunction with the development agenda and consider a wider range of adaptation options and strategies.

Keywords Adaptation · Africa · Climate change impacts · Mitigation · Sea-level rise

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Introduction

The impacts of sea-level rise have been studied less intensely in developing than developed countries. Yet, poorer countries—in particular areas where there is dense population—may be worst hit by climate change as they have a lower ability to prepare, adapt and respond (IPCC 2007; UN-HABITAT 2008). The continent of Africa represents such a vulnerable region as shown in many previous climate change assessments, such as water resources, agriculture or health (e.g. Boko et al. 2007).

Many coastal African countries are vulnerable to sea-level rise, particularly where large growing cities with a high population density are situated in the coastal zone (Nicholls et al. 2008; UN-HABITAT 2008). With most African coastal countries undergoing rapid population growth, urbanisation, coastward migration and associated socio-economic growth, dramatic coastal change is occurring (e.g. Stanley and Warne 1993; Boko et al. 2007). This includes a rapid increase in exposure of people and assets to sea-level variability and long-term rise (Zinyowera et al. 1998; Desanker et al. 2001; Nicholls et al. 2008). Local factors, such as natural and artificial land subsidence, can worsen the situation, especially in deltaic areas (Ericson et al. 2006; Syvitski et al. 2009).

While parts of Africa are vulnerable to sea-level rise, there is to date no continental-wide study that provides comparable results for all African countries. Africa has been considered in the context of global assessments such as deltas and relative sea-level rise (Ericson et al. 2006), coastal flooding and wetland loss due to global sea-level rise (e.g. Nicholls 2004) and port cities and exposure to coastal flooding (Nicholls et al. 2008). At national and sub-national level, as discussed later, only a few countries are well studied (e.g. Egypt, and particularly the Nile delta), whereas for many others, there is little information available (e.g. Liberia, Sierra Leone, Sudan, Sao Tome & Principe). Furthermore, the few studies that are available are difficult to compare and synthesise due to a lack of consistent data and underlying assumptions (de la Vega-Leinert et al. 2000).

To fill this gap, an analysis of Africa with the DIVA model[1] has been performed. 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 (both direct and indirect), coastal flooding (including rivers), wetland change and salinity intrusion into deltas and estuaries as well as adaptation in terms of raising dikes and nourishing beaches (http://www.diva-model.net).

This assessment studies the effects of mitigation by comparing impacts of a no-mitigation scenario leading to about 4°C temperature increase in 2100 compared with pre-industrial levels and a sea-level rise of 64 cm in the period 1995–2100, with an ambitious mitigation scenario leading to 2°C increase in 2100 compared with pre-industrial levels and a sea-level rise of 42 cm in the period 1995–2100. These sea-level rise estimates are rather 'conservative' as they are in a range similar to the estimates given in the Fourth Assessment Report (AR4) of the Intergovernmental Panel of Climate Change (IPCC), which do not consider potential higher sea-level rises resulting from a rapid melting of the ice-sheets of Greenland and Antarctica. Thus, we also explore the effects of higher sea-level rise by considering a projection based on Rahmstorf (2007) leading to 126 cm rise from 1995 to 2100. Finally, we study the effects of adaptation by comparing simulations that do not include adaptation with those that do include common protection options in form of raising dikes and nourishing beaches. Impacts are compared through the twenty-first century based on the following parameters: (1) people flooded, (2) people forced to migrate, (3) damage costs and (4) adaptation costs.

The remainder of the paper is organised as follows. Section Africa and sea-level rise contains a brief description of Africa's coastal zone and sea-level rise impacts based on available literature and national reviews for selected countries. Section Methodology details the DIVA methodology and describes the scenarios and simulations considered in this analysis. Results are presented in Sect. Results and discussed in Sect. Discussion. Finally, Sect. Conclusion concludes.

Africa and sea-level rise

As the poorest continent, Africa already faces many challenges. Conflicts, limited economies, high population growth, famine and disease place enormous pressures on the continent, and the low adaptive capacity makes the population vulnerable to change per se (Boko et al. 2007). Climate change is thus expected to exacerbate many of the already existing challenges. While sea-level rise is not viewed as the most important threat to African nations, its impacts can be far reaching as large and growing amounts of wealth and high population densities and growth rates are concentrated in the coastal zone (Dasgupta et al. 2009; Small and Nicholls 2003; McGranahan et al. 2007).

Continental Africa comprises 48 countries, 33 of which have coastlines. Additionally, seven adjacent island nations and territories are considered in this assessment, bringing the total number of nations assessed in this paper to 40 (Table 1). The continent's coastline is estimated to be more than 38,000 km in length.

Africa is bounded in the north by the Mediterranean Sea, the Atlantic Ocean to the west, Indian Ocean towards the east and south east of the continent, and the Red Sea to the north-east, connecting to the Mediterranean via the Suez Canal. The coastal zone (defined as the land up to 10 m above sea level) varies in width from a few 100 m (Red Sea and the mountainous coastal areas) to more than 100 km (in the Niger and Nile deltas) (Zinyowera et al. 1998).

The coastal zone along the Mediterranean Sea, though narrow, contains large cities such as Benghazi and Tripoli (population > 3 million inhabitants), Alexandria (population > 3.5 million inhabitants) and Algiers (population > 3 million inhabitants) (e.g. Nicholls et al. 2008). Coastal cities are of high economic value due to commercial, industrial, residential and recreational activities and have a high population density (Ibe and Awosika 1991). The coastal zone along the Atlantic Ocean (extending from

[1] Here the DIVA model version 3.2.0 is used together with the DIVA database version 1.8.0.

Table 1 The 40 African coastal territories considered in this study and their coastal length from the DIVA database

Coastal countries	Coastal length (km)	Islands surrounding the African continent	Coastal length (km)
Algeria	1,375	Cape Verde	724
Angola	1,712	Comoros	340
Benin	122	Madagascar	5,055
Cameroon	548	Mauritius	839
Congo	164	Reunion (France)	201
Congo, Democratic Republic of	130	Sao Tome & Principe	170
Cote d'Ivoire	1,034	Seychelles	151
Djibouti	311		
Egypt	3,224		
Equatorial Guinea	421		
Eritrea	1,214		
Gabon	1,453		
Gambia	446		
Ghana	714		
Guinea	547		
Guinea-Bissau	1,227		
Kenya	584		
Liberia	559		
Libyan Arab Jamahiriya	1,932		
Mauritania	222		
Morocco	1,871		
Mozambique	3,114		
Namibia	1,520		
Nigeria	1,571		
Senegal	1,053		
Sierra Leone	689		
Somalia	3,073		
South Africa	3,079		
Sudan	631		
Tanzania, United Republic of	1,390		
Togo	50		
Tunisia	1,358		
Western Sahara	1,032		
Total length	38,370		7,480

Morocco to Namibia) is characterised as sandy and muddy low-lying areas with beach elevations ranging from 2 to 3 m above sea level, and containing four major drainage basins. The eastern coastal zone (ranging from the Egyptian Red Sea to South Africa) is relatively smooth and low-lying, with a few exceptions such as the rivers of Zambezi and Limpopo. The eastern coastal zone region is heavily populated due to its fast growing industrial infrastructure and comprises an estimated 13% of the region's population due to rapid development of fishing, sea ports, tourism and other industries. The island states are characterised with areas of volcanic origin, with narrow coastal plains, which are even almost absent in some areas (e.g. the Seychelles). However, extensive coastal plains associated with major rivers are present in Madagascar (Ibe and Awosika 1991).

Africa's largest drainage basins include the Congo (Democratic Republic of Congo), Nile (Central and North East Africa, discharging in Egypt), Niger (West Africa, discharging in Nigeria) and Zambezi (Central Southern Africa discharging in Mozambique) covering a drainage area of 12 million km^2 (Milliman et al. 1995). Northern Africa has a Mediterranean climate with hot dry summers and warm wet winters. Towards the central part of the continent, the climate is more tropical and can experience periods of heavy rainfall and dry seasons. Southern Africa experiences sub-tropical conditions.

Historic data (>50 years) of continuous sea-level rise in Africa are fairly limited compared with other global regions (Woodworth et al. 2007; PSMSL 2007; Menendez and Woodworth 2010). This hinders the assessment of coastal impacts and vulnerability, as it is unknown how sea-levels have changed with respect to other global areas, and there are little quantitative data concerning local up-lift and subsidence. Given the geological nature of Africa's coast, the latter effect is expected to be small except in the vicinity of deltas where both natural and human-induced subsidence may play an important role (Ericson et al. 2006; Syvitski et al. 2009). The deficiency of data has been addressed by the implementation of new tide gauges in recent decades.

Africa has a population of 1 billion people (2009 estimate, Earth Trends 2009), and a land area of about 30 million km^2 (Vörösmarty et al. 2000). Of Africans, 28% live within 100 km of the coast (excluding small islands), despite this only representing 11% of the land area (Singh et al. 1999). The continent has around 320 coastal cities with more than 1,00,000 inhabitants, and nearly 56 million people presently live in low elevation coastal zones (defined as land up to 10 m above sea level). Of these, 60% live in coastal urban areas (UN-HABITAT 2008), where there are high concentrations of residential, industrial, commercial, agricultural, transportation, tourist, educational and military facilities (Ibe and Awosika 1991). These urban areas are expected to grow substantially during this century (Singh et al. 1999) and thus are a main focus for sea-level rise impacts and adaptation needs. Elsewhere coastal population density is low.

Sea levels are expected to rise around Africa, and expected impacts of climate change and sea-level rise include flooding, salt water intrusion, loss of beaches and recreational activities including tourism, loss of infrastructure, changes to river flows and outputs on the coast, reduced productivity of coastal fisheries and coral bleaching (Elasha et al. 2006). Previous studies indicate that many coastal African countries are highly vulnerable to climate change and sea-level rise, leading to increased rates of coastal erosion and flooding of low-lying coasts (Ibe and Awosika 1991; de la Vega-Leinert et al. 2000). This could endanger large areas and place significant populations at risk. The impacts of climate-induced sea-level rise, which in some places such as deltas may be accentuated by local subsidence, could exacerbate existing problems through increased coastal erosion, more persistent flooding, wetland loss, increased salinisation of aquifer and groundwater, which all would impose significant impacts on African communities and economies (Ibe and Awosika 1991; Desanker et al. 2001).

Dasgupta et al. (2009) ranked 84 developing countries for population potentially exposed to a 1-m sea-level rise (considering existing condition at the time of study and assuming no defences). Egypt, Mauritania, Tunisia and Benin are in the top ten most effected countries. Ericson et al. (2006) considered six major African deltas and relative sea-level rise as part of a global study. They estimated that about 1.4 million people could be displaced by present rates of relative sea-level rise from 2000 to 2050, with over 90% of these in the Nile delta. Syvitski et al. (2009) identified the Nile and Niger deltas as being the most threatened of the African deltas due to subsidence and human interference, with the Limpopo and Congo deltas being least threatened.

Previous studies showed that with a mean global sea-level rise of only 0.38 m combined with population growth scenarios and no protection upgrade, the average number of people that experience annual coastal flooding in Africa could increase from 1 million/year in 1990 to 70 million/year in the 2080s (Nicholls et al. 1999). UN-HABITAT (2008) also suggests that many of the major coastal cities around the continent will be affected by rising sea levels, and the impacts could be severe due to the lack of preparedness and adaptation via adequate drainage, embankments and soft engineering to withstand extreme weather conditions. A study on impacts of storm surges in coastal areas also revealed that about 30 million people around the African Atlantic and Indian Ocean coasts live within the flood hazard zone (i.e. the potentially exposed population), out of which about 2 million people per year could potentially be flooded in the 2020s (Nicholls 2006). Many agricultural areas are located in the coastal zone, and these too would be threatened by flooding and salinisation, having impacts for food supplies and industrial products, such as wood or oil (Nyong 2005). Depending on the magnitude of the losses, this could have knock-on socio-economic impacts for the whole country or region. Nicholls (2006) identified Mozambique, Tanzania and Madagascar as being particularly vulnerable countries to increased flooding, as they experience tropical storms and these may intensify (Meehl et al. 2007).

Nicholls et al. (2008) estimated the exposure of the world largest port cities to coastal flooding due to storm surges. Globally, they identified 136 port cities (with 19 in Africa) with a population greater than 1 million people. They found that Africa is ranked as the third and fourth highest continent in terms of port city's population exposure (more than 2.6 million people in the coastal floodplain in 2005) and asset exposure (about US$ 42 billion of assets in the floodplain in 2005), respectively. Given the low wealth and poor development of flood management in Africa, this existing exposure is of concern. Alexandria (Egypt) and Abidjan (Cote d'Ivoire) are ranked in the top twenty list of world port cities for population exposure to coastal flooding in 2005. Taking high-end scenarios of socio-economic, climate and non-climate trends, in the 2070s, the total population and assets exposed in the nineteen African port cities grow to 13.3 million people and US$ 998 billion of assets, respectively. Three cities contain the bulk of this exposure: Alexandria (Egypt), Lagos (Nigeria) and Abidjan (Cote d'Ivoire). In contrast, other large port cities have relatively small exposure, such as Cape Town (South Africa), Dar es Salaam (Tanzania; see Kebede and Nicholls 2011), Tripoli (Libya) and Luanda (Angola) reflecting the steeper nature of the coasts at these cities. The study also reveals that from 2005 to the 2070s, smaller cities (in terms of population and wealth) such as Mogadishu (Somalia) and Luanda (Angola) could experience a rapid increase in population and asset exposure posing significant challenges for local communities to adapt to these changes.

A number of national and sub-national studies have also provided estimates of impacts, adaptation and vulnerability to sea-level rise around the Africa coast. Examples of country-level studies include Egypt, in particular the Nile delta (El-Raey 1997; El-Raey et al. 1999; Frihy 2003), Gambia (Jallow et al. 1996, 1999; Hinkel 2010), Morocco (Snoussi et al. 2009), Senegal (Dennis et al. 1995; Hinkel 2010), Nigeria (French et al. 1995) as well as National Communications to the United Nations Framework Convention on Climate Change. City studies have been conducted for Alexandria (El Raey et al. 1995), Accra (Appeaning Addo et al. 2008), Dar es Salaam (Kebede and Nicholls 2011) and Mombasa, Kenya (Kebede et al. 2011). Comparison between studies is, however, difficult due to the variety of methods and socio-economic and sea-level scenarios used as well as in parameters considered (de la Vega-Leinert et al. 2000).

This review shows a continent that is changing rapidly with a growing population and economy and strong trends of urbanisation. However, the continent remains poor and, for example, rapidly expanding coastal cities have little or no formal flood management. Furthermore, delta areas such as the Nile are changing rapidly primarily due to human interference. Hence, Africa's coast will look quite different in 50 years. Climate change and sea-level rise are additional problems that could cause significant impacts, especially if there is no preparation for these changes. The lack of data on Africa's coast is especially striking, and this is a major barrier to better analysis. Missing data include information on present rates of sea-level change and coastal geomorphology through to good data on socio-economic trends. Good coastal environmental management depends on this type of information, and it should be a priority to improve collection and management. This suggests a need for national, regional and international efforts to collect data, including through remote sensing techniques.

Methodology

This paper applies the model DIVA (Dynamic Interactive Vulnerability Assessment), which is an integrated model of coastal systems that assesses biophysical and socio-economic impacts of sea-level rise and socio-economic development (www.diva-model.net). DIVA is based on a data model that 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. 2005, 2008). The first version of the DIVA model was developed as part of the DIVA Tool in the EC-funded project DINAS-COAST (Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Climate Change and Sea-Level Rise; DINAS-COAST Consortium 2006; Hinkel and Klein 2009). Here, the DIVA model version 3.2.0 is used together with the DIVA database version 1.8.0.

DIVA combines global sea-level rise scenarios due to global warming with estimates of local vertical land movement. These local components vary from segment to segment and are taken from the global model of glacial isostatic adjustment of Peltier (2000a, b). For segments that occur at deltas, we assumed an additional 2 mm/year subsidence due to natural sediment compaction. Subsidence may be much greater in deltas and susceptible cities due to human agency, e.g., Nicholls (1995), Ericson et al. (2006), Syvitski et al. (2009), but this has not been considered in this analysis due to a lack of consistent information.

Based on the relative sea-level rise, DIVA assesses three types of biophysical impacts: (1) dry land loss due to coastal erosion, (2) coastal flooding and (3) salinity intrusion in deltas and estuaries. The flooding of the coastal zone caused by sea-level rise and associated storm surges is assessed for both sea and river floods (the backwater effect) and taking into account the effects of dikes. Extreme water levels produced during storm surges are displaced upwards with the rising sea level, following twentieth century observations of extreme sea-level rise (e.g. Zhang et al. 2000; Woodworth and Blackman 2004; Menendez and Woodworth 2010). Based on these flood frequencies, as well as on land elevations, population densities, dikes and relative sea level, the expected number of people flooded annually (people flooded, hereafter) is estimated over time. In a similar way, the expected monetary value of damage caused by sea and river floods is estimated based on a damage function logistic in flood depth (Tol et al., in preparation).

We run DIVA with and without applying protection options. In the *no adaptation strategy (NO)*, impacts are assessed following the traditional impact assessment approach without applying any adaptation options. In the

Table 2 Overview of the ten simulations considered in this paper

Scenarios	Temperature rise in 2100 compared to pre-industrial (°C)	Global mean sea-level rise in 2100 compared to the level of 1995 (cm)	Simulation without adaptation	Simulation with adaptation
No sea-level rise scenario (NOSLR)	0	0	NOSLR+NO	NOSLR+AD
IMAGE 'business as usual' scenario (IBAU)	4	64	IBAU+NO	IBAU+AD
IMAGE mitigation scenario (I450)	2	42	I450+NO	I450+AD
Rahmstorf (2007) 'business-as-usual' scenario (RBAU)	4	126	RBAU+NO	RBAU+AD
Rahmstorf (2007) mitigation scenario (R450)	2	104	R450+NO	R450+AD

adaptation strategy (AD), flood risk is reduced through the construction of new and the increase in height of existing flood defences, and beach erosion is reduced through nourishment. Note that no adaptation measures are considered for salt water intrusion.

The adaptation options considered in response to flooding are dikes, drawing on the experience of Delft Hydraulics (now Deltares), including its application in the global analysis of Hoozemans et al. (1993). In the no adaptation strategy, it is assumed that no flood defences are currently in place at Africa's coast. This assumption was made because there are no empirical data on actual dike heights available for Africa, and only a few places in Africa have substantial protection measures in place, in particular the Nile delta in Egypt adjacent to Alexandria.

In the *adaptation* strategy, it is assumed that dikes are raised based on a demand function for safety, which is increasing in per capita income and population density, but decreasing in the costs of dike building. This function was derived econometrically based on empirical data of actual protection levels in Europe (Tol 2006). This function was also applied to estimate initial dikes heights for the base year of 1995, as no empirical data on actual dike heights were available. For a detailed presentation of the flooding model, see Tol (2006) and Tol et al. (in preparation).

Dike costs are estimated in terms of costs of dike building/upgrading and dike maintenance (including operation costs). Operational costs reflect the costs of drainage landward of the dike, such as drain clearance and pumping costs: without drainage, this land would often become waterlogged or flooded due to rainfall and rising water tables, combined with the lack of natural drainage. Most of the data that was found on dike maintenance and operation cost came from the Netherlands (IPCC CZMS 1990; Verhagen 1998; Kok et al. 2008). A range of estimates of maintenance and operational values were identified, with river dikes being consistently lower in cost, reflecting the lack of wave loadings. Maintenance costs as high as 2% were identified in some cases (UNCTAD 1985; Smedema et al. 2004). Taking a conservative view, this study assumes maintenance cost of 1% for sea-dikes and 0.5% for river-dikes following Nicholls et al. (2010b).

In response to beach erosion, nourishment (placing of additional sand onto existing beach areas) is considered. Volumetric demand and different cost classes are applied to determine the cost. The cost classes range between US$ 3 to US$ 12 per cubic meter sand depending on how far the sand for nourishment needs to be transported, as well as on the presence of tourism, because if beaches are not used for tourism cheaper shore (i.e. underwater) nourishment can be applied (Hinkel et al., in preparation). In the no adaptation strategy, beaches are not nourished. In the adaptation strategy, beaches are nourished following a cost-benefit approach.

We analyse five sea-level scenarios (Table 2). The first two scenarios were developed in the context of the project ADAM (Adaptation and Mitigation; www.adamproject.eu; van Vuuren et al. 2009) with the IMAGE model (version 2.4). The first scenario is a 'business-as-usual' scenario (termed IBAU hereafter) that does not include any policy efforts towards mitigation of climate change and leads to a 4°C increase of global mean temperature in 2100 compared to pre-industrial levels. The second scenario is a stringent mitigation scenario (termed I450 hereafter) that corresponds to the ambition to limit global mean temperature increase to no more than 2°C compared to pre-industrial levels. This scenario aims at stabilising greenhouse gas concentrations in the atmosphere at around 450 ppm CO_2eq, after an initial overshoot to about 510 ppm CO_2eq. In order to achieve the 2°C target, emissions would have to peak around 2020 and subsequently decline to zero (or lower) by the end of the century (Meinshausen et al. 2009).

For the climate change and sea-level rise components of the scenarios, the IMAGE model includes the MAGICC model to compute uniform global mean sea-level change, in combination with a pattern scaling method to obtain grid level changes for temperature. The global mean sea-level projections attained are in a similar range than the estimates given in the Fourth Assessment Report (Meehl et al. 2007). The no-mitigation scenario leads to about 64 cm of

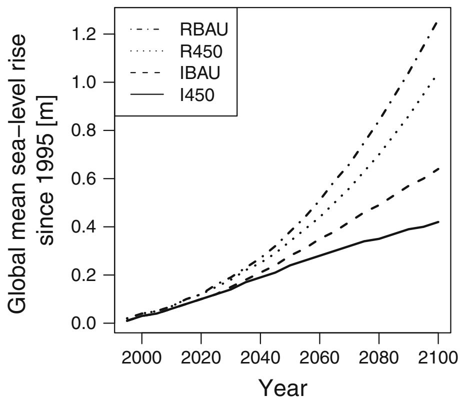


Fig. 1 Global mean sea-level rise under the Rahmstorf and IMAGE scenarios used in this paper

global mean sea-level rise and the mitigation scenario to 42 cm in 2100 compared to 1995 levels (Fig. 1).

To explore a wider range of uncertainty for sea-level rise, we use a third scenario (called RBAU hereafter) based on Rahmstorf (2007) who predicted a higher rate of sea-level rise than Meehl et al. (2007) based on empirical relationships between past temperatures and sea-level rise. From this third scenario, we derive a fourth 'high sea-level rise mitigation' scenario (called R450 hereafter) by assuming that stabilising emissions at 450 ppm CO_2eq through mitigation would lower sea-level rise by the same absolute amount than mitigation lowers sea-level rise in the 'conservative' estimates produced with the IMAGE/MAGICC model (i.e. the 22 cm difference between IBAU and I450 in 2100). This assumption can not be defended physically due to a lack of physical models that are able to predict the effects of global warming (and hence mitigation) on ice sheet discharge which is responsible for the higher-end sea-level rise projections (Rahmstorf 2007). Analytically, this assumption is useful, because it allows to compare the sensitivity of impacts under higher sea-level rise conditions with the ones under lower conditions.

Finally, for analytical reasons, we also include a scenario that assumes no rise in global mean sea-level (called NOSLR). Under this scenario, local sea level will still change due to uplift/subsidence as described in the last Section.

All scenarios assume the same socio-economic development in terms of population and GDP growth (Fig. 2). This socio-economic development pathway was projected with the IMAGE model, assuming autonomous technological progress and the worldwide diffusion of goods and services result in a convergence between world regions. It also reflects that estimates of population growth for twenty-first century have generally been revised downwards since the development of the SRES scenarios (van Vuuren et al. 2007). Changes are assumed to be uniform within countries, and hence, net coastward migration is not considered here. The choice to have only one socio-economic scenario is motivated by the goal of this paper to explore the effects of mitigation and adaptation on sea-level rise impacts. Fixing the socio-economic scenario helps to keep the results analytically tractable and to investigate the uncertainty surrounding the rate and magnitude of sea-level rise and the effects of adaptation.

Each of the five scenarios is run together with the no adaptation strategy (symbolised as +NO) and with the adaptation strategy that raises dikes and nourishes beaches as described above (symbolised as +NO). Table 2 summarises the ten simulations thus attained.

Results

This section presents a summary of the physical impacts, damage and adaptation costs of the impacts of sea-level rise on Africa for the four sea-level rise scenarios from 2000 to 2100. The top 15 countries are ranked for each parameter.

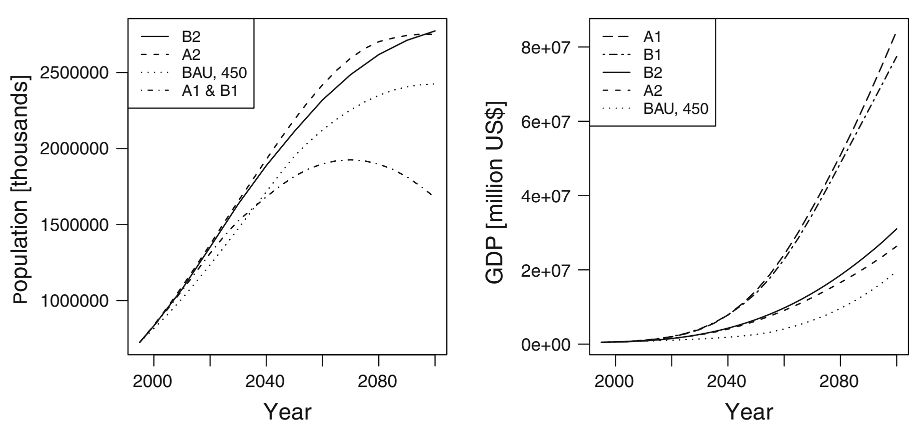


Fig. 2 Comparison of Africa's population (*left*) and GDP growth (*right*) between the SRES scenario families and the IMAGE scenario used in this paper

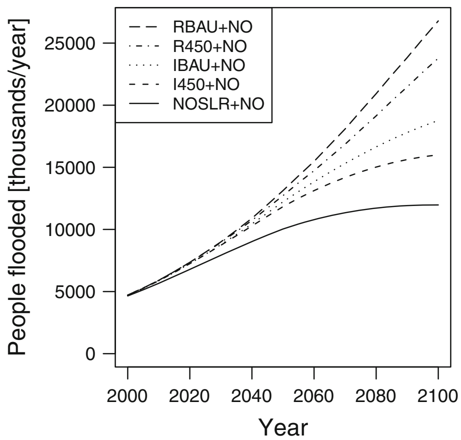


Fig. 3 Number of people flooded per year from 2000 to 2100 for Africa as a whole under the simulations without adaptation

People flooded

People flooded consider the expected number of people subject to annual flooding taking into account coastal topography, population and defences, as well as sea level.

Assuming that there are no protection measures currently in place, the number of people flooded assessed with DIVA is just below 5 million people per year (0.6% of Africa's population) in the base year of 2000 (Fig. 3). As described in the last section, this number does not take into account protection measures that are currently in place in the Nile delta in Egypt adjacent to Alexandria (and possibly in some other flood-prone areas in Africa) due to the difficulty of obtaining data on these. Assuming uniform protection levels of 1-in-10 years and 1-in-100 years in Egypt and no protection for the rest of Africa in 2000 lowers the number of people flooded for the whole of Africa to 3.4–3.8 million people per year, respectively.

Assuming no adaptation, the number of people flooded increases throughout the century under all scenarios considered (Fig. 3). Under the no sea-level rise scenario, the number increases to about 12 million people per year in 2100, due to population increase and local sea-level rise caused by subsidence. Under the conservative IBAU scenario, about 19 million people will experience flooding at least once a year in 2100, and under the high sea-level rise RBAU scenario, it will be 27 million people if no adaptation measures are taken. Under both scenarios, mitigation reduces the impacts by about 3 million people per year.

On a country level and assuming no adaptation, Egypt, Mozambique and Nigeria are the countries most affected in 2100 under the RBAU scenario with over 8, 5 and 3 million people flooded per year, respectively (Fig. 4). In relative terms Guinea-Bissau, Mozambique and Gambia are the countries most affected with above 10% of their populations expected to be flooded annually under the RBAU scenario in 2100. The rank order of the most affected countries does not change significantly with the different sea-level rise scenarios. The contribution of population increase to the total impacts is most significant for countries with densely populated deltas such as Guinea-Bissau and Mozambique, as shown by the scenario that only considers socio-economic development but no global mean sea-level rise (NOSLR).

Assuming adaptation in terms of building and upgrading dikes reduces the number of people flooded in 2100 by factors above 100 compared to the no adaptation simulations. Under IBAU about 0.07 million, people will be flooded annually for Africa as a whole in 2100, and under RBAU, it will be about 0.20 million. Under the RBAU scenario, most of these people are again located in Mozambique, Nigeria and Egypt (Fig. 5). Mozambique is also the most affected country in relative terms followed by

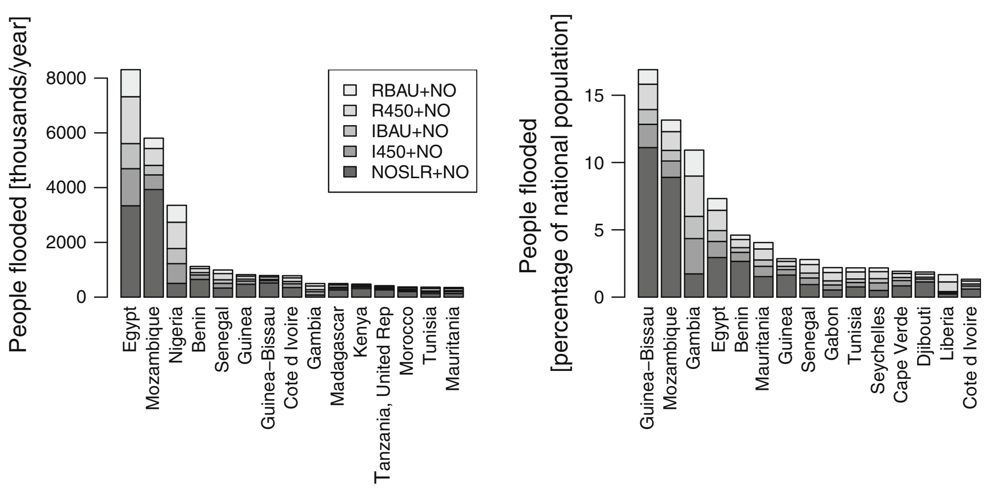


Fig. 4 Absolute (*left*) and relative (*right*) numbers of people flooded per year for the 15 highest ranking African coastal countries in 2100 under the simulations without adaptation. Countries are ranked as to their values under the Rahmstorf BAU scenario

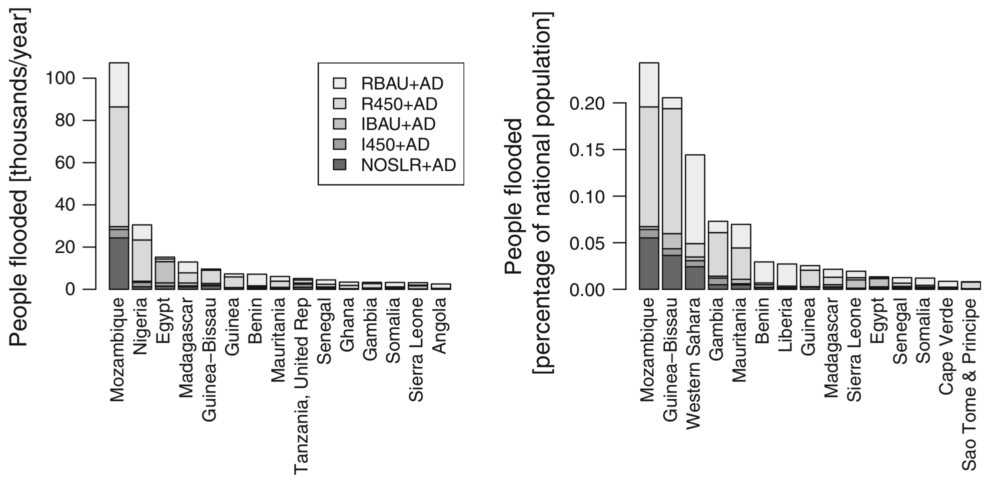
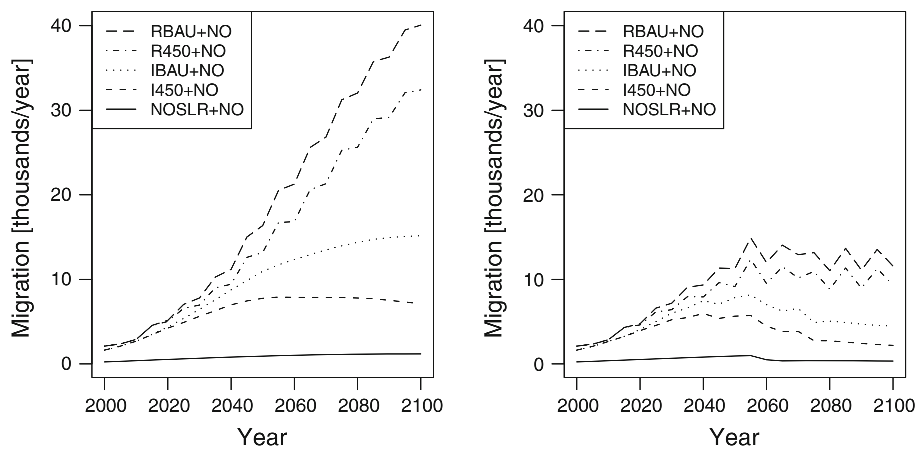


Fig. 5 Absolute (*left*) and relative (*right*) numbers of people flooded per year for the 15 highest ranking African coastal countries in 2100 under the simulations with adaptation. Countries are ranked as to their values under the Rahmstorf BAU scenario

Fig. 6 Number of people forced to migrate due to coastal erosion per year from 2000 to 2100 for Africa as a whole under the simulations without adaptation (*left*) and with adaptation (*right*)



Guinea-Bissau. The relatively high numbers of people flooded in these countries despite the protection efforts being made reflects their low coastal GDP densities which means that less money is spent on building dikes, resulting in lower protection levels and more frequent floods.

Forced migration (due to erosion)

Under forced migration, we consider the number of people forced to migrate due to land loss by erosion. We do not consider migration due to more frequent flooding to avoid double counting with flood impacts above.

Generally, the number of people forced to migrate is more sensitive to changes in sea-level rise (Fig. 6) than the number of people flooded discussed above. Under the conservative no-mitigation scenario (IBAU), about 15 thousand people are expected to migrate every year in 2100 due to the lost of land. Under the high-end no-mitigation scenario (RBAU), 40 thousand people per year are expected to migrate. In both cases, mitigation reduces these numbers by about 8 thousand per year. Adaptation reduces these numbers by about 75%.

On a country level (Fig. 7) and in absolute terms, Nigeria, Mozambique, Egypt and Cote d' Ivoire are the countries most affected with 4–11 thousand people forced to migrate per year in 2100. Under the NOSLR scenario, migration is negligible for most countries except those that have higher rates of local sea-level rise due to subsiding deltas such as Egypt and Nigeria. The ranking of countries does not differ significantly between the conservative and high sea-level rise scenarios. Adaptation in terms of nourishment reduces migration by about 75%. The effect of mitigation is roughly in the same range for both the high and low sea-level rise scenarios.

Damage cost

Damage costs are the annual expected cost of economic damage caused by coastal flooding, dry land loss, salinity

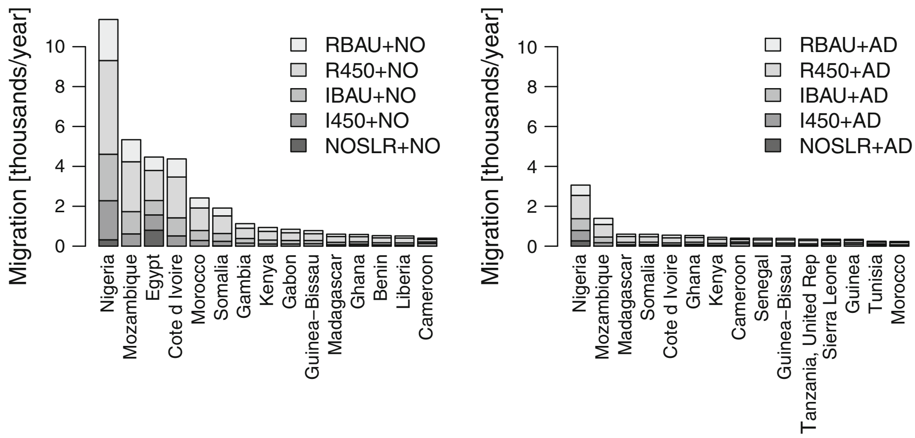


Fig. 7 Number of people forced to migrate due to coastal erosion per year for the 15 highest ranking African coastal countries in 2100 under the simulations without adaptation (*left*) and with adaptation (*right*). Countries are ranked as to their values under the Rahmstorf BAU scenario

intrusion and forced migration. Costs are represented in undiscounted 1995 US$.

Assuming no adaptation and no global mean sea-level rise (NOSLR+NO), damage costs in Africa as a whole increase significantly with time, reaching approximately US$ 3.4 billion per year in 2100 (Fig. 8). This mainly reflects the cost of sea-floods that occur without climate change due to present-day climate variability (i.e. extreme water levels) and increasing wealth. The same uncertainty exists for these costs as for people flooded as these damage costs assume no defences.

Still assuming no adaptation but adding global mean-sea-level rise, damage costs increase to US$ 5.8 billion per year for the unmitigated conservative sea-level rise scenario (IBAU) and US$ 8.9 billion per year for the unmitigated high sea-level scenario (RBAU). Under the last two scenarios, mitigation is roughly equally effective in reducing damages in 2100 by about US$ 1 billion compared to the no-mitigation cases. Under all scenarios, sea floods make up the greatest part of the damage cost followed by salinity intrusion and migration costs. Over the century, the shares of salinity intrusion and migration costs increase.

Adaptation significantly reduces the damage costs (Fig. 8). Under all scenarios, damage costs in 2100 are only roughly half of those under the simulations without adaptation. With adaptation, salinity intrusion contributes with the largest part to the damage costs with growing shares of sea flood cost and migration cost towards the end of the century under the higher-end sea-level rise scenarios. This suggests that Africa faces significant challenges to keep up with higher-end rises in sea-level because the upgrading of dikes and the nourishment of beaches made possible through the increasing wealth is jeopardised by the fast rises in sea-level expected under the high-end scenarios towards the end of the century. The costs of salinity intrusion continue to grow since adaptation measures are not considered here.

Without adaptation, Egypt is by far the country most affected in absolute terms with damage costs of above US$ 5 billion per year in 2100 under the high-end no mitigation scenario (RBAU), which constitutes about one half of the

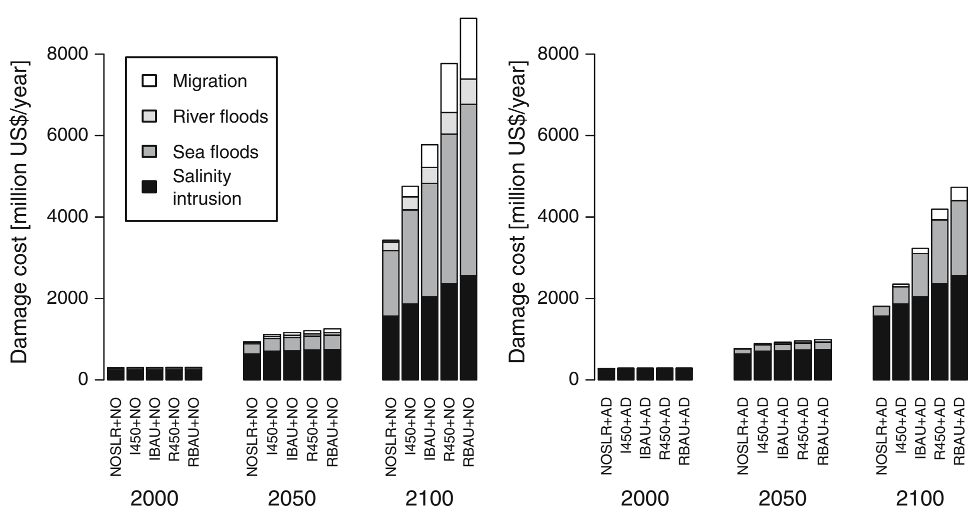
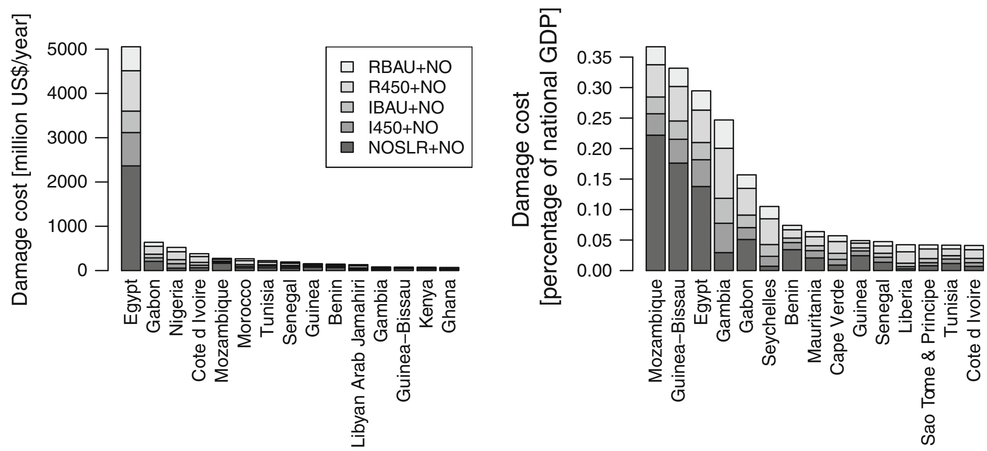


Fig. 8 Annual damage cost in 2000, 2050 and 2100 for Africa as a whole under the simulations without adaptation (*left*) and with adaptation (*right*)

Fig. 9 Absolute (*left*) and relative (*right*) annual damage cost for the 15 highest ranking African coastal countries in 2100 under the simulations without adaptation. Countries are ranked as to their values under the Rahmstorf BAU scenario



damage cost of Africa as a whole (Fig. 9). In relative terms, Mozambique, Guinea-Bissau and Egypt stand out with an estimated damage costs of over 0.25% of national GDP in 2100 under the same scenario.

The group of most affected countries does not change significantly when assuming adaptation (Fig. 10). Again, Egypt stands out as the most affected country in absolute terms with damage costs above US$ 3 billion per year. In relative terms, this time Mozambique is most affected closely followed by Guinea-Bissau and Egypt with damages amounting to over 0.15% of national GDPs in 2100 under the RBAU scenario.

The African countries differ greatly in their sensitivity to changes in sea-level rise under the simulations with adaptation (Fig. 10). Mozambique, Egypt, Guinea-Bissau and Gabon already experience high damage costs under the NOSLR scenario and are thus not sensitive to relative small changes in lower-end sea-level rise. Other countries, such as Gambia, Senegal, Benin and Cap Verde, experience relatively little damage under the NOSLR scenario, but show a high sensitivity to small rises in sea-level rise.

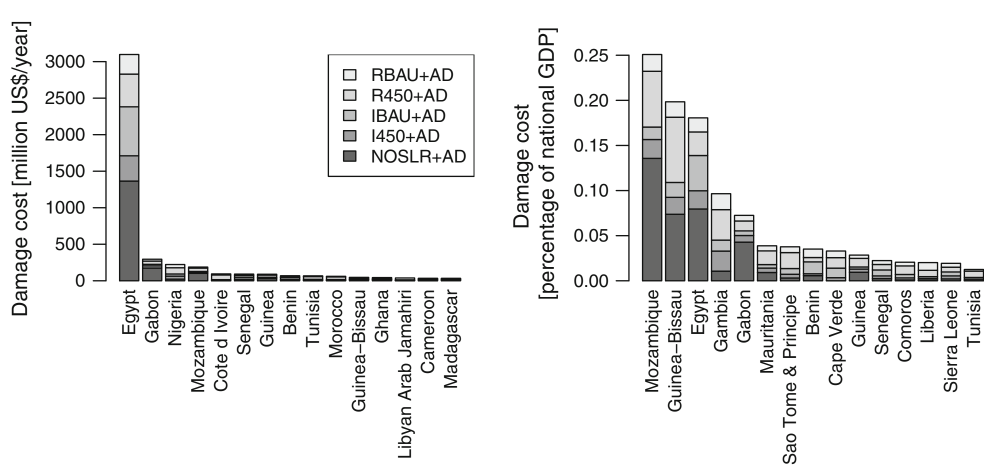
The differential sensitivities of the countries to adaptation are predominantly a result of the proportion between salinity intrusion cost and the total damage cost. The total damage costs of Egypt and Gabon, for example, are not very sensitive to the adaptation strategy simulated here because a significant proportion of the damage costs is caused by salinity intrusion (Fig. 11) against which no adaptation measures are considered here but would potentially be available. Other countries, which do not have large coastal river/estuarine systems with salinity intrusion damages, are much more sensitive to changes in sea-level rise, because the largest proportion of the costs would be caused by sea floods.

Adaptation deficit

In many parts of the world, activities are not adapted to the current climate variability, which has been called adaptation deficit (Parry et al. 2009), and this needs to be considered before considering adaptation to future climate change. Using DIVA, the adaptation deficit could be considered the capital cost of building and upgrading dikes adapted to the current coastal extreme water level variability.

Assuming that no dikes would be present anywhere in Africa, the capital cost of building dikes is estimated by

Fig. 10 Absolute (*left*) and relative (*right*) annual damage cost for the 15 highest ranking African coastal countries in 2100 under the simulations with adaptation. Countries are ranked as to their values under the Rahmstorf BAU scenario



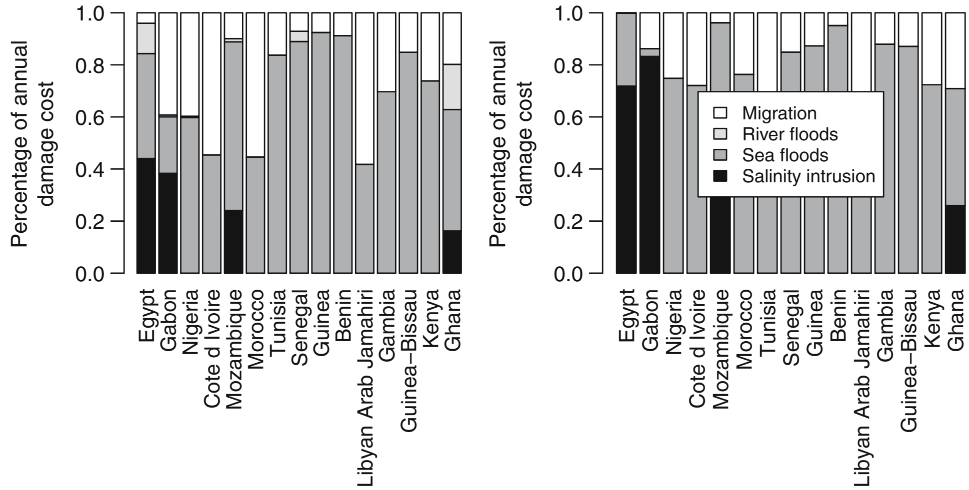


Fig. 11 The relative contribution of the different types of impacts to the annual damage cost in 2100 without adaptation (*left*) and with adaptation (*right*) under the Rahmstorf BAU scenario for the 15 highest ranked African coastal countries

DIVA to about US$ 300 billion. The share of Egypt, which is—as mentioned before—probably the only African country that currently has dikes in place, is only about 3 US$ billion, which means that the US$ 300 billion is probably a reasonable estimate of Africa's current adaptation deficit with respect to coastal flooding. Usually, these costs would be distributed over time. Assuming a planning and implementation horizon for coastal defences of 50 years (Nicholls et al. 2010a) would mean that, in simple terms, US$ 6 billion per year would need to be spent over 50 years to address the adaptation deficit. It is also important to note that these dikes need to be maintained and as the stock of dikes grows, maintenance costs will also become significant. The annual cost of maintaining the full stock of these dikes would be about US$ 3 billion per year.

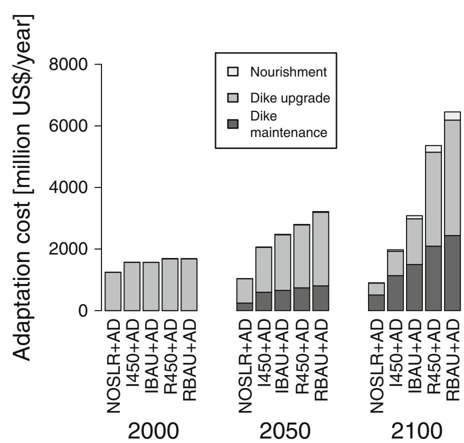


Fig. 12 Annual adaptation cost in 2000, 2050 and 2100 for Africa as a whole under the simulations with adaptation

Adaptation costs

Adaptation costs are the annual cost of adapting to future relative sea-level rise and socio-economic development due to upgrading dikes, maintaining the upgraded parts of the dikes and nourishing beaches. These costs are calculated assuming that Africa's coast is adapted to current climate variability, which means that the adaptation costs reported below do not include the capital and maintenance costs of the dikes build to overcome the adaptation deficit as reported above.

Dike upgrade costs make up the largest share of adaptation cost throughout the century (Fig. 12). They decrease during the century under the lower scenarios (IBAU and I450) while they increase under the higher-end scenarios (RBAU and R450). Dike maintenance costs increase with the growing dike capital stock during the century under all scenarios reaching about US$ 2 billion per year under the highest sea-level rise scenario in 2100. The figure also shows that the relatively small changes in sea-level rise attained through mitigation make a significant difference in terms of the investment in coastal adaptation that Africa requires.

The countries facing the highest absolute adaptation costs in 2100 are Somalia, South Africa, Mozambique and Madagascar (Fig. 13). Adaptation costs increase significantly for higher sea-level rises: Adaptation costs under the Rahmstorf scenarios are generally two to three times higher than those under the IMAGE scenarios. The group of countries most affected in relative terms differs considerably from the group most affected in absolute terms. In particular, Western Sahara, Guinea-Bissau, Mozambique, Somalia and Equatorial Guinea face significant relative costs with 0.3% of their national GDP that needs to be invested in maintaining and upgrading dikes as well as

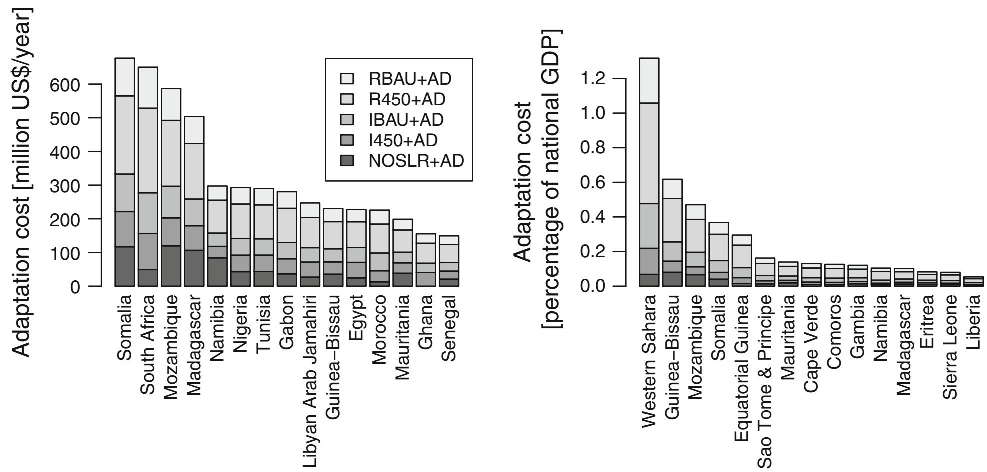


Fig. 13 Absolute (*left*) and relative (*right*) annual adaptation cost for the 15 highest ranking African coastal countries in 2100 under the simulations with adaptation. Countries are ranked as to their values under the Rahmstorf BAU scenario

nourishing beaches throughout the century under the RBAU scenario.

Discussion

The results show that the costs that Africa would need to spend for adapting to future sea-level rise and socio-economic development is in the same order of magnitude as the current adaptation deficit. The adaptation deficit in Africa (or elsewhere) has so far not been assessed in any detail (Parry et al. 2009) and owing to a lack of empirical data on existing defences this study could only give the rough estimate of US$ 300 billion capital costs with about US$ 3 billion per year for maintenance. This large deficit makes adaptation to sea-level rise following the strategy applied in this paper less likely.

Even when assuming that there would not be a current adaptation deficit in Africa, no unambiguous argument can be made in favour of protecting Africa's coasts by upgrading dikes and nourishing beaches. Table 3 summarises and compares the relevant damage and adaptation costs for the lowest (I450) and highest (RBAU) sea-level scenarios considers here. For analytical reasons, we have also included a hypothetical simulation that assumes that Africa would be adapted to the current climate but does not upgrade its dikes throughout the century (i.e. initial dikes, no adaptation; NI). Assuming this and adopting a pure monetary perspective, then adaptation would only be effective towards the end of the century and for the higher-end sea-level rise scenarios, because only in this case are the annual costs of adaptation smaller than the damage cost avoided through adaptation. When also taking into account the social impacts, however, a strong argument in favour of adaptation can be made as adaptation reduces the number of people flooded by two orders of magnitude towards the end of the century. Adaptation measures should be focused in areas where there is the greatest need, such as densely populated cities or industrialised areas as here the benefit to cost ratio would be greatest.

It needs to be kept in mind that any estimate of adaptation costs and adaptation deficits requires a normative choice to be made on what it means to be adapted to a given climate. Defining this for coastal flooding is particularly difficult because the benefits of adaptation measures are distributed over long periods of time. In DIVA, we assumed a demand function for safety that follows the 'Western' world's view on what protection level is desirable given a surge regime, a coastal population density and associated wealth (Tol 2006). Assuming a lower demand for safety would lower the adaptation deficit and the costs of adaptation. Note that a cost-benefit analysis would not avoid the need for a normative choice, because costs and benefits would need to be balanced inter-temporally, which in turn requires the normative choice of a discount rate.

Future work needs to explore feasible and desirable adaptation strategies in more detail and also from an adaptation decision-making perspective. The strategies explored here are stylised from an impact assessment perspective, based on only two options and hence give only an indicative estimate. From an adaptation decision-making perspective, impacts need to be embedded into a decision analytical framework such as cost-benefit analysis, cost-effectiveness or real option analysis. Further potentially lower cost options and strategies need to be considered. For instance, with appropriate land use planning, there is a significant potential to minimise future growth in the risks due to sea-level rise in a number of expanding coastal cities such as Mombasa and Dar es Salaam (Kebede et al. 2011; Kebede and Nicholls 2011).

Adaptation would also be more costly than assessed here because there is need for other investment such as port upgrade and measures to counter salt water intrusion if

Table 3 A comparison of the costs and benefits of the adaptation strategies considered in this paper

	Adaptation strategy	2000		2050		2100	
		I450	RBAU	I450	RBAU	I450	RBAU
Damage cost	No initial dikes, no adaptation (NO)	3.1	3.1	1.1	1.3	4.8	8.9
	Initial dikes, no adaptation (NI)	0.3	0.3	1.0	1.3	4.5	8.6
	Initial dikes, adaptation (AD)	0.3	0.3	0.9	1.0	2.4	4.8
Damage cost avoided through adaptation (AD minus NI)		0.0	0.0	0.1	0.3	2.1	3.8
Adaptation cost		1.6	1.7	2.1	3.2	2.0	6.5

possible. The analysis of coastal port cities by Nicholls et al. (2008) highlighted concerns about flood exposure and its management in African port cities. Hence, the adaptation cost estimated here is clearly a minimum cost. Further impediments to adaptation exist due to the low adaptive capacity in Africa, and even if sufficient funds for adaptation suddenly appeared, the weakness in institutional capacities would impede the implementation of adaptation. Hence, coastal adaptation and development need to be closely linked, and this is likely to be true across all climate change issues in Africa.

The results also give some indication on the effectiveness of climate change mitigation. Table 4 shows by how much mitigation reduces impacts for the low-end IMAGE (I450 compared to IBAU) and high-end Rahmstorf (R450 compared to R450) scenarios. Mitigation is more effective in reducing damages and costs under the former compared to the latter. This is not surprising, since this paper made the assumption that mitigation reduces global sea-level rise under the Rahmstorf scenarios by the same absolute amount (and hence smaller relative amount) as it does under the IMAGE scenarios.

Considering the rankings of countries in absolute terms, several countries consistently appear in the top rankings for people-based impacts, including Egypt, Mozambique and Nigeria. For economic damages, Egypt stands out with between US$ 2 and 5 billion of yearly damage costs in 2100 under the sea-level rise scenarios considered here. In absolute terms, the highest adaptation costs occur in Somalia, South Africa, Mozambique and Madagascar. The adaptation costs for Egypt are relatively small compared to the high potential damages the country is facing, which suggests that protection is, already from a pure monetary perspective, a meaningful strategy. In terms relative to national GDP, Western Sahara, Guinea-Bissau and Mozambique are most affected countries.

Comparison with the country studies mentioned in the literature review is difficult. Results for some parameters are of the same order of magnitude with previous study estimates (for example residual damage for Nigeria; see French et al. 1995), while others show significant differences (e.g. for land loss in Senegal, DIVA underestimates it compared with Dennis et al. 1995). However, this is likely to be due to the difference in the methods used and defining the coastal zone. Furthermore, in DIVA adaptation, costs are estimated based on an empirical relationship between observed protection levels and GDP and population densities. Other studies may have used different methods to calculate levels of protection or different baselines, which may explain the difference in costs. More assessment at the country level is required to enhance our understanding at this important scale of action. Such assessments should also include a wider range of adaptation options and strategies including the spectrum of protect, accommodate and retreat options as well as portfolios of these.

This study has assumed a globally uniform rate of sea-level rise to estimate impacts. In reality, sea-level rise will not be globally uniform as it is dependent on temperature variations, mixing, patterns of thermal expansion and gravitational effects (Mitrovica et al. 2001; Meehl et al. 2007). For instance, the Mediterranean has experienced a lower rate of sea-level rise in comparison to the global average over the second half of the twentieth Century (Tsimplis and Baker 2000). Hence, whilst impacts on Mediterranean countries may be severe, the impacts will take longer to emerge if the rate of sea-level rise continues to be slower through the twenty-first century.

Table 4 Relative reduction of impacts and adaptation costs through mitigation in 2100

	IBAU/I450		RBAU/R450	
	+NO	+AD	+NO	+AD
Global mean sea-level	34%	34%	17%	17%
People flooded	15%	29%	11%	25%
Damage cost	18%	27%	13%	11%
Adaptation cost		36%		17%

Even without climate-induced sea-level rise, there are costs for the whole of Africa's coast—in common with the rest of the world—due to natural and locally induced subsidence and increases in population and GDP. Local man-induced subsidence due to drainage and ground fluid withdrawal of susceptible soils/sediments may increase rates of relative sea-level rise, especially in the deltaic areas (Becker et al. 2002; Ericson et al. 2006; Garcia et al. 2007; Syvitski et al. 2009). These issues have been apparent in south, south-east and east Asia through the twentieth century (Nicholls 1995, 2010a), but are less apparent in Africa to date. Africa appears less susceptible to this threat due to the lack of extensive Holocene deposits in the coastal zone, apart from a few populated deltas such as the Nile. Nonetheless, the effects of human-induced subsidence should be investigated systematically as has the potential to exacerbate the problems and costs of responding to sea-level rise in susceptible areas.

Other aspects of climate change not been considered in this study could have important effects on Africa's coasts such as the possibility of more intense tropical storms hitting the coast of East Africa, in particular in Mozambique, Tanzania and Madagascar (Nicholls 2006). Additionally, higher temperatures and lower precipitation would tend to reduce river levels affecting river discharge and water availability that has unforeseen impacts for agriculture, fisheries and industry. Changes and intensification to farming practices also means that wetlands are at risk as they are converted to agriculture and industrial use, reducing a natural form of coastal defence. For example, in the Zambezi River delta that discharges into the ocean in Mozambique, Coleman et al. (2008) calculated a 25-km^2 annual loss of the delta plain due to agriculture and reclamation between 1986 and 2000. These losses are far more significant than wetland loss caused by other causes, such as sea-level rise, and if they continue, only limited coastal wetlands may survive to be impacted by sea-level rise. Schuijt (2002) found that African wetlands are threatened by human activities, reclamation, development and the over-use of resources by local populations.

These results are only a beginning, and further work is required to better understand the implications of sea-level rise for Africa in a broad sense. The DIVA results can be improved by increasing the spatial resolution of the underlying data and adding more information in particular on different socio-economic pathways and adaptation options and strategies. To get more local detail, more national and sub-national assessments are required, which also considering appropriate adaptations in a local context. Lastly, the linkages between adaptation and development need more exploration, and the current adaptation deficit needs to better assessed and its implications analysed.

Conclusion

This paper has provided a quantitative assessment of the potential sea-level rise impacts on Africa at continental and national scales including the benefits of mitigation and applying adaptation measures in form of building dikes to protect against coastal flooding and nourishing beaches to protect against coastal erosion. We considered two no-mitigation sea-level rise scenarios, the first one being a conservative estimate produced with the IMAGE model, leading to 64 cm rise in 2100 compared to the level of 1995. The second one is a high estimate based on Rahmstorf (2007), leading to 126 cm rise in 2100. Both scenarios were accompanied with a mitigation scenario in which stringent mitigation stabilises emissions at the level of 450 CO2eq and restricts sea-level rise to 42 cm and 104 cm, respectively.

The results show that sea-level rise poses a significant risk to Africa. With a large and growing population in the coastal zone and a low ability to adapt because of low national wealth and adaptive capacity, most countries around the continent appear to be highly vulnerable. Without adaptation, physical, human and financial impacts will be significant. On a continental scale, under the sea-level rise scenarios considered here, 16–27 million people are expected to be flooded per year, and damage costs will reach between US$ 5 and US$ 9 billion per year in 2100, if no adaptation takes place. If adaptation measures (in terms of beach nourishment and dike construction) are employed, the number of people flooded can be reduced by two orders of magnitude and the economic damages cut by half in 2100. This would, however, require significant financial efforts. First, a capital investment in dikes of about US$ 300 billion would be needed in order to adapt to the current surge regime with US$ 3 billion per year for maintenance. Second, annual investments (capital and maintenance) in the range of US$ 2 to US$ 3 billion per year in 2050 and US$ 2 to US$ 6 billion per year in 2100 are needed in order to adapt to future changes in sea-level and socio-economic development.

These results suggest that protecting large parts of Africa by building dikes is not rational from a pure monetary perspective but may still be desirable when taking into account the avoided social impacts. In any case, applying coastal adaptation measures poses a significant financial challenge to Africa and may therefore not happen unless there is financial support to meet this challenge. Delivering such adaptation may even be more costly and difficult than the headline cost suggests because the adaptation costs accounted for here are incomplete and a lack of adaptive and institutional capacity.

Considering the national results, the countries that stand out as being most vulnerable both in terms of people-based impacts as well as in terms of economic costs include Egypt, Mozambique, Nigeria and Gabon. In terms of high adaptation costs relative to national GDP, a different group of predominately less wealthier countries and small island states stand out, including Western Sahara, Guinea-Bissau, Mozambique, Somalia, Equatorial Guinea, Sao-Tome & Principe, Mauritania, Gambia and Sierra Leone.

The issue of sea-level rise and Africa requires further attention, including improving these analyses and more studies that look at impacts and adaptation in more detail and considering a greater variety of adaptation options and strategies. In particular, the development agenda in coastal areas needs to carefully consider both the adaptation deficit and future sea-level rise. With up-to-date and consistent information across all African countries, this study fills the knowledge gap concerning the limited previous national and continental scale studies available and provides a basis for carrying out more detailed analysis. Adaptation will be essential to today's and future climate and identification of the appropriate mixture of protection, accommodation and retreat strategies should be one priority.

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