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ORIGINAL ARTICLE

Assessing risk of and adaptation to sea-level rise in the European Union: an application of DIVA

Jochen Hinkel · Robert J. Nicholls · Athanasios T. Vafeidis · Richard S.J. Tol · Thaleia Avagianou

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Abstract This paper applies the DIVA model to assess the risk of and adaptation to sea-level rise for the European Union in the 21st century under the A2 and B1 scenarios of the Intergovernmental Panel on Climate Change. For each scenario, impacts are estimated without and with adaptation in the form of increasing dike heights and nourishing beaches. Before 2050, the level of impacts is primarily determined by socio-economic development. In 2100 and assuming no adaptation, 780×10^3 people/year are estimated to be affected by coastal flooding under A2 and 200×10^3 people/year under B1. The total monetary damage caused by flooding, salinity intrusion, land erosion and migration is projected to be about US$ 17×10^9 under both scenarios in 2100; damage costs relative to GDP are highest for

J. Hinkel (✉)
Potsdam Institute for Climate Impact Research (PIK), Potsdam, Germany
e-mail: hinkel@pik-potsdam.de

J. Hinkel
European Climate Forum (ECF), Potsdam, Germany

R. J. Nicholls
School of Civil and Environmental Engineering and Tyndall Centre for Climate Change Research, University of Southampton, Southampton SO17 1BJ, UK

A. T. Vafeidis
Institute of Geography, Christian-Albrechts University Kiel, "Coastal Risks and Sea-Level Rise" Research Group, The Future Ocean Excellence Cluster, Ludewig-Meyn-Str. 14, 24098 Kiel, Germany

R. S. Tol
Economic and Social Research Institute, Dublin, Ireland

R. S. Tol
Institute for Environmental Studies, Vrije Universiteit, Amsterdam, The Netherlands

R. S. Tol
Department of Spatial Economics, Vrije Universiteit, Amsterdam, The Netherlands

T. Avagianou
Department of Geography, University of the Aegean, University Hill, Mytilene 81100 Lesvos, Greece

the Netherlands (0.3% of GDP under A2). Adaptation reduces the number of people flooded by factors of 110 to 288 and total damage costs by factors of 7 to 9. In 2100 adaptation costs are projected to be US$ 3.5×10^9 under A2 and 2.6×10^9 under B1; adaptation costs relative to GDP are highest for Estonia (0.16% under A2) and Ireland (0.05% under A2). These results suggest that adaptation measures to sea-level rise are beneficial and affordable, and will be widely applied throughout the European Union.

Keywords Adaptation · DIVA model · Europe · Flood risk · Sea-level rise

1 Introduction

Sea-level rise will raise mean and extreme sea levels threatening the world's coastal zones with a range of impacts. The Fourth Assessment Report (AR4) of the Intergovernmental Panel on Climate Change (IPCC) estimates that global average sea level rose about 17 cm during the 20th century and projects that within the 21st century it will continue to rise by an additional 18 cm to 59 cm (IPCC 2007a). However, as stated in the IPCC Synthesis Report (IPCC 2007b), no reasonable upper bound of sea-level rise can be determined as we are unsure how rapidly the major ice sheets (Greenland and Antarctica) could collapse in a warming world. Several post-AR4 papers support the view that a 1 m+rise in sea level over the next century cannot be discounted at present (e.g., Grinsted et al. 2009; Vermeer and Rahmstorf 2009).

The impacts of sea-level rise on the coastal areas of Europe are expected to be overwhelmingly negative based on earlier studies and reviews, such as Rotmans et al. (1994), Nicholls (2000), de la Vega-Leinert et al. (2000), Nicholls and Klein (2005), Rochelle-Newall et al. (2005) and Nicholls and de la Vega-Leinert (2008). The major impacts are expected to be increased flooding and permanent inundation of low-lying coastal areas, increased erosion of beaches and cliffs, and degradation of coastal ecosystems. Locally, salinisation effects may be important. Coastal morphology and human utilisation will condition the nature of these impacts and their implications: in general, coastal lowlands with microtidal conditions are most susceptible.

These existing studies are limited due to the broad treatment of impacts, or being based on inconsistent data. The European-funded project DINAS-COAST (Dynamic and Interactive Assessment of National, Regional and Global Vulnerability of Coastal Zones to Sea-Level Rise; http://www.pik-potsdam.de/dinas-coast/) addressed some of these limitations by developing a new global coastal database, a set of consistent climatic and socio-economic scenarios and an integrated simulation model called DIVA (http://www.diva-model.net; DINAS-COAST Consortium 2006). The model consists of a number of modules that represent coastal subsystems developed by experts from various engineering, natural and social science disciplines (Hinkel 2005; Hinkel and Klein 2009).

In the project PESETA (Projection of economic impacts of climate change in sectors of the European Union based on bottom-up analysis), Richards and Nicholls (2009) used the DIVA model (version 1.5.5) to show that the costs of adaptation are much less than the expected damages due to sea-level rise. These results were highlighted in the European Commission's Green and White Papers on Adaptation (European Commission 2007, 2009). The Mediterranean and the Baltic appears more vulnerable than the Atlantic coasts of Europe. However, in global terms, Europe appears to have a relatively low vulnerability to sea-level rise (Hoozemans et al. 1993; Nicholls et al. 1999; Nicholls 2004). The database used in the PESETA project was the original one developed in the DINAS-COAST project and based on the GLOBE (Global Land One-km Base Elevation Project) global elevation data (Hastings et al. 1999).

In the meantime, better, higher resolution elevation data has become available from the shuttle radar topography mission (SRTM). This paper applies DIVA (version 3.1.1) together with improved data on elevation and area parameters to assess the risk of and adaptation to sea-level rise for the coastal countries of the European Union (EU27). We exclude British, French, Danish and Dutch overseas territories and autonomous regions. Impacts are simulated for the SRES A2 and B1 scenarios, first without and then with adaptation. Impacts are discussed at EU27 and national levels in terms of expected number of people subject to annual flooding, people forced to migrate due to land lost, economic costs of—both bio-physical and social—damages and costs of adaptation.

The impacts of sea-level rise on coasts are strongly influenced by socio-economic development (Nicholls et al. 2007). Europe's coast changed dramatically through the 20th Century due to a growing population, economy and new sectors such as the Mediterranean tourist industry. These changes will continue through the 21st Century, although in an uncertain manner (Alcamo et al. 2007). Europe has an aging population and in some Eastern regions population is falling. If this trend continues, coastal populations will fall (e.g. Kont et al. 2008). On the other hand, immigration (or an increase in fertility) may offset this trend. The B1 and A2 scenarios considered here reflect these trends. In both cases, Europe's (and the world's) GDP/capita rises, but much more under the B1 scenario. In contrast, under the A2 scenario, Europe's population continues to rise, while under the B1 scenario, population declines slightly over the 21st century. Rising wealth leads to greater damage potential, even under stable population, as this increases the assets along the coast, while increasing population also increases the exposure to coastal hazards.

The rest of the paper is organized as follows. Section 2 presents the data, the DIVA model and the scenarios used in the analysis. Section 3 presents the potential impacts attained without considering adaptation and Section 4 those with considering adaptation. Section 5 discusses the results and concludes.

2 Methodology

2.1 Data

We use the data from the coastal database that was developed by the above mentioned DINAS-COAST project. This database was developed specifically to address the needs of coastal impact and vulnerability analysis at global and regional scales and also fits the specific requirements of the modelling tool. The database employs six different geographic features and references all data to 12,148 linear coastline segments of variable length (averaging 70 km), which represent homogeneous units in terms of their impacts and vulnerability to sea-level rise (Vafeidis et al. 2008). The segmentation of the coastline was performed on the basis of a series of physical, ecological, administrative and socio-economic criteria and is described in detail by McFadden et al. (2007). The DIVA database contains information on approximately 80 physical and socio-economic parameters of the world's coast. Examples of such parameters include data on elevation, geomorphic and landform types, coastal population and land use (see Vafeidis et al. 2006).

For the present application, an updated version of the DIVA database for the study area (i.e. the EU27) was used. This version is based on the original database, but includes updates on elevation and area parameters as well as other minor data corrections.

Specifically, the new data on elevation and areal extents were calculated for the EU27 countries using data from the more detailed SRTM digital elevation model (Rabus et al. 2003; http://srtm.usgs.gov/). Due to their higher resolution (90 m instead of 1 km) SRTM data are better suited to regional-scale analysis and are expected to lead to improved estimates of the impacts of sea-level rise. It should however be noted that the SRTM dataset only includes land surfaces that lay between 60° north latitude and 54° south latitude. Consequently, no data updates are available for most parts of Fennoscandia, although the relatively low human population in this area means that in aggregate terms, our European estimates are still greatly improved. Details on the methods used for calculating the elevation and area parameters in DIVA can be found in Vafeidis et al. (2006).

It is important to note that sea-level rise impacts computed at global and continental scales can only be indicative due to the limited vertical accuracy of the available digital elevation models (Rabus et al. 2003). The data employed in the present study are the best currently available, and the relative accuracy of the elevation dataset is in general much higher than the absolute accuracy (Lichter et al. 2010). However, the SRTM represents a surface model, and hence ground elevation may be overestimated in some areas such as forested areas, with the high vegetation canopy, and also in urban areas where the tops of buildings may be recorded. All these errors are biased to underestimate areas at risk of flooding. Nevertheless, even though we cannot use these data to define the exact areas that will be flooded we can obtain a reasonable estimate of the extent of the flooded area for a given rise in sea level, which is what we need.

2.2 The DIVA model

The DIVA model is an integrated model of coastal systems that assesses biophysical and socio-economic impacts of sea-level rise and socio-economic development. One important innovation introduced by DIVA is the explicit incorporation of a range of adaptation options; impacts do not only depend on the selected climatic and socio-economic scenarios but also on the selected adaptation strategy.

DIVA is driven by climatic and socio-economic scenarios. The climatic scenarios consist of the variables temperature change and sea-level rise. The socio-economic scenarios consist of the variables land-use class, coastal population growth and GDP growth. The land-use classes are the 19 land-use classes of the IMAGE 2.2 model (IMAGE Team 2002), although the important distinction is between agricultural and non-agricultural land use.

DIVA first downscales to relative sea-level rise (RSLR) by combining the sea-level rise scenarios due to global warming with the vertical land movement. The latter is a combination of glacial-isostatic adjustment according to the geo-physical model of Peltier (2000) and an assumed uniform 2 mm/year subsidence in deltas. Human-induced subsidence (due to ground fluid abstraction or drainage) is not considered due to the lack of consistent data or scenarios. Based on the relative sea-level rise, four types of bio-physical impacts are assessed: (1) dry land loss due to coastal erosion, (2) flooding and (3) salinity intrusion in deltas and estuaries.

Both direct and indirect coastal erosion are assessed. The direct effect of sea-level rise on coastal erosion is estimated using the Bruun Rule (Zhang et al. 2004; Nicholls 2002). Sea-level rise also affects coastal erosion indirectly as tidal basins become sediment sinks under rising sea level, trapping sediments from the nearby open coast into tidal basins. This indirect erosion is calculated using a simplified version of the ASMITA model (Aggregated Scale Morphological Interaction between a Tidal basin and the Adjacent coast; Stive et al.

1998; Van Goor et al. 2003). About 200 tidal basins around the world are considered, 40 of which lie within the EU27 coastal countries.

DIVA includes beach/shore nourishment, i.e. the replacement of eroded sand (or sand that is expected to be eroded), as an adaptation option. 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). Shore nourishment is substantially cheaper than beach nourishment, but the benefits are not felt immediately. The way these options are applied is discussed further below.

The flooding of the coastal zone caused by sea-level rise and associated storm surges is assessed for both sea and river floods. Large parts of the coastal zone are already threatened by flooding due to extreme sea levels produced during storms. These extreme events produced by a combination of storm surges and astronomical tides will be raised by mean sea level: the return period of extreme sea levels is reduced by higher mean sea levels. The magnitude of this effect depends on the slope of the exceedance curve. Sea-level rise also raises water levels in the coastal parts of rivers (via the backwater effect), increasing the probability of extreme water levels. DIVA considers both these flooding mechanisms. Due to the difficulties of predicting changes in storm surge characteristics (e.g., von Storch and Woth 2008), the present storm surge characteristics are simply displaced upwards with the rising sea level following 20th Century observations (e.g., Zhang et al. 2000; Woodworth and Blackman 2004; Haigh et al. 2010). Taking into account the effects of dikes, flood areas for return periods from 1-in-1 to 1-in-1000 years are computed.

The adaptation option considered is dikes, drawing on the experience of Deltares, including its application in the global analysis of Hoozemans et al (1993). Since there is no empirical data on actual dike heights available at a global level, initial dike heights were estimated for the base year of 1995 using the demand for safety function as explained below. Based on these dikes, land elevations and relative sea level, the frequency of flooding is estimated over time. This is further converted into flooded people and economic flood damages based on population density and GDP (see below). For a detailed presentation of the flooding model see Tol (2006) and Tol et al. (2010).

River flooding is evaluated in a similar fashion along 115 major rivers, the following 30 of which lie within the study area of this paper: Adour, Axios, Charente, Dalalven, Daugava, Douro, Ebro, Elbe, Evros, Garonne, Guadalquivir, Guadiana, Jucar, Kemijoki, Loire, Minho, Mondego, Nemunas, Oder, Po, Rhine/Meuse, Rhone, Schelde, Segura, Seine, Tagus, Thames, Tiber, Vistula, and Weser.

For the same rivers, DIVA also assesses the impacts of salinity intrusion into the river deltas or estuaries. Based on Schijf and Schnfeld (1953), the relative sea-level rise and the storm surge characteristics, the length of salt water intrusion into the river and the land area affected by salinity are calculated (Maaten 2006). No adaptation options are considered for surface salinisation. DIVA does not take account of salinity intrusion into coastal aquifers as this is a complex process which demands too much data to realistically model it at broad scales.

DIVA also estimates the social and economic consequences of the physical impacts described above. Social consequences are expressed in terms of three indicators. The *coastal floodplain population* gives the number of people that live below the 1000 year storm surge level. The indicator *people actually flooded* gives the expected number of people subject to annual flooding. The indicator *forced migration* gives the number of people that have to migrate from the dry land permanently lost due to erosion. For the calculation of these population numbers, the gridded population of the world has been used (CIESIN and CIAT 2004).

The economic consequences are expressed in terms of damage costs and adaptation costs. The cost of dry land loss is estimated based on the land-use scenarios and the assumption that only agricultural land is lost. Agricultural land has the lowest value and it is assumed that if land used for other purposes (e.g., industry or housing) is lost then those usages would move and displace agricultural land. The value of agricultural land is a function of income density. The cost of salinity intrusion into river deltas is calculated in terms of the agricultural land affected and the assumption that saline agricultural land has half the value of pristine land. The cost of floods is calculated as the expected value of damage caused by sea and river floods based on a damage function logistic in flood depth. The costs of migration are calculated on the basis of loss of GDP per capita. For a detailed account of the valuation of impacts see Tol (2006).

Adaptation costs are estimated for the two adaptation options considered: dike building and beach nourishment. Dike costs are taken from the global vulnerability assessment carried out by Hoozemans et al. (1993). The costs of beach nourishment were derived by expert consultation. Different cost classes are applied, depending on how far the sand for nourishment needs to be transported as this is a significant determinant of such costs.

DIVA computes impacts both without and with adaptation. Without adaptation, DIVA only computes potential impacts in a traditional impact analysis manner. In this case dike heights are maintained, but not raised, so flood risk rises with time as relative sea level rises. Beaches and shores are not nourished. With adaptation, dikes are raised based on a demand function for safety (Tol and Yohe 2007), which is increasing in per capita income and population density, but decreasing in the costs of dike building (Tol 2006).

With adaptation, beaches and shores are nourished according to a cost-benefit analysis that balances costs and benefits (in terms of avoided damages) of adaptation. Shore nourishment has a lower cost than beach nourishment, but is not widely practised at present and has the disadvantage of not immediately maintaining the beach. Beach nourishment is therefore chosen as the better adaptation option, but only if the tourism revenue is sufficient to justify the extra costs. The number of tourists and their spending follows the HTM, an econometric model of tourism flows (Hamilton et al. 2005a,b). In HTM, tourism numbers increase with population and income. Climate change pushes tourists towards the poles and up the mountains. However, while Mediterranean countries would see their *market share* fall as a result of climate change, the tourism market grows fast enough to have an increase in absolute tourism numbers.

It is important to note that the purpose of the adaptation strategy is not to compute an optimal adaptation policy but to model how coastal managers could respond to sea-level rise. The complementary adaptation strategies serve the same purpose as the climate and socio-economic scenarios, i.e. to explore possible futures. DIVA's different adaptation strategies show how different assumptions made about the behaviour of coastal planners translate into differences in impacts and adaptation costs.

2.3 Scenarios

We ran DIVA with two sets of scenarios based on the IPCC SRES A2 and B1 storylines (Nakicenovic and Swart 2000). The A2 storyline assumes a socio-economically heterogeneous world and a continuously increasing global population. Global emissions increase throughout the century. The B1 storyline assumes a socio-economically converging world; global population and emissions peak in 2050 and decline thereafter. Per capita economic growth is slower under A2 than B1. A2 can be considered a business as usual scenario, and B1 is sometimes seen as a (costless) mitigation scenario with stabilization during the twenty-second century at a concentration of about 550 ppm CO2 (Swart et al. 2002), although formally none of the SRES scenarios represent mitigation.

The socio-economic component of the scenarios was derived from regional realizations of the SRES storylines produced with the IMAGE2.2 model (IMAGE Team 2002) by applying regional growth rates of GDP and population (Tol 2006). Figure 1 shows the resulting evolutions of GDP and population for the EU27 coastal countries. Similarly to the global figures, population numbers are higher under A2. Differences, however, only become significant after 2030, when population decreases under B1while it continues to increase under A2. GDP grows much faster under B1.

The climatic component of the scenarios was derived with the climate model of intermediate complexity CLIMBER-2 of the Potsdam Institute for Climate Impact Research (Petoukhov et al. 2000). A climate sensitivity of 3°Celsius and globally uniform sea-level rise were assumed. Figure 2 shows the resulting global mean sea-level rise under the two SRES scenarios. Due to the slow response of the ocean to global warming, differences between the two scenarios in terms of global mean sea-level rise only become significant after the middle of the 21st century.

It is important to note that RSLR is much lower for Fennoscandia than for the rest of Europe, because the former still experiences a glacial isostatic uplift of several millimeters per year. Under the A2 scenario, RSLR—compared to the level of 1995—reaches about 20 cm in 2100 for Sweden and Finland compared to about 50 cm for most other European countries.

Each scenario set is run without and with adaptation in the form of heightening the dikes and nourishing the beaches as described above. The following four simulations are available:

1. A2 sea-level rise and socio-economic development without adaptation (A2+NO)
2. A2 sea-level rise and socio-economic development with adaptation (A2+AD)
3. B1 sea-level rise and socio-economic development without adaptation (B1+NO)
4. B1 sea-level rise and socio-economic development with adaptation (B1+AD)

The impacts of these four simulations are discussed in terms of the following variables:

- Average relative sea level rise: the sum of the relative sea-level rise of each coast-line segment weighted by the length of the segments.

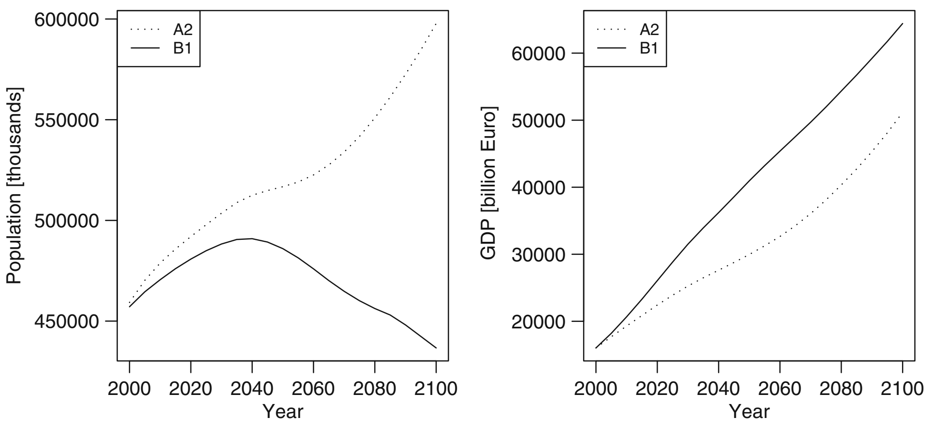

Fig. 1 Population and GDP of the EU 27 coastal countries under the A2 and B1 scenarios

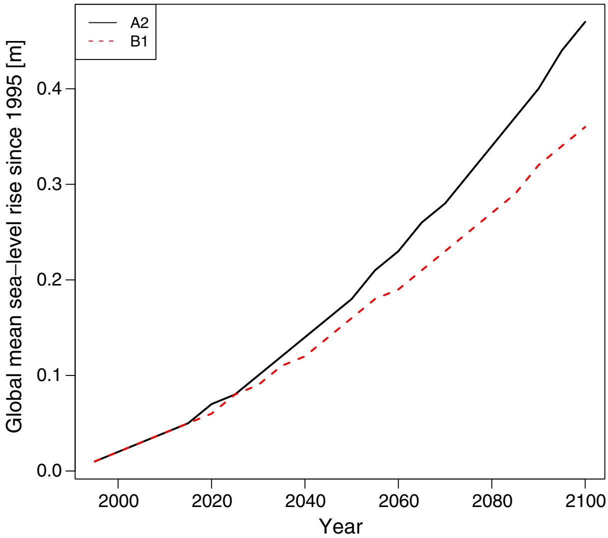

Fig. 2 Global mean sea-level rise under the A2 and B1 scenarios

- People flooded: expected number of people subject to annual flooding.
- Migration: the number of people forced to migrate due to land loss by erosion.
- Damage cost: the annual cost of economic damage caused by the sum of coastal flooding, dry land loss, wetland loss, salinity intrusion and migration.
- Adaptation cost: the annual cost of adaptation due to raising dikes and nourishment of beaches.
- Total cost: the sum of damage and adaptation costs. In the case of the no adaptation simulations, total cost equals damage cost.

3 Potential impacts without adaptation

Table 1 gives an overview of the impacts at the aggregate level of the EU27 coastal countries under the two simulations without adaptation (i.e., A2+NO and B1+NO). The number of people affected annually by coastal flooding grows significantly, in particular during the second half of the century, reaching 780×10^{3} in 2100 under A2, which is about 0.13% of the projected EU27 population and 70 times higher than in 2000. Under B1+NO, 200×10^{3} people will experience annual flooding, which is about 0.05% of the projected

Table 1 People flooded, land lost, damage, adaptation and total cost at the level of EU 27 for the simulations without adaptation (A2+NO and B1+NO)

	People flooded [thousand/year]		Land loss [km²/year]		Damage cost [million €/year]		Adaptation cost [million €/year]		Total cost [million €/year]	
2010	15.0	14.8	3.4	3.4	3,136	3,329	0	0	3,136	3,329
2030	21.3	20.1	6.7	5.6	4,767	5,662	0	0	4,767	5,662
2050	35.0	28.9	9.9	7.8	6,450	8,192	0	0	6,450	8,192
2100	776.2	204.5	16.4	12.2	16,933	17,496	0	0	16,933	17,496

EU27 population and 20 times higher than in 2000. Differences between the two simulations are in all cases minor until 2050, reflecting that there are only minor differences in sea-level rise and socio-economic development between the A2 and B1 scenarios up to this time. This also illustrates the inevitability of some impacts of sea-level rise over the coming century irrespective of the mitigation policy.

In absolute terms, the Netherlands, United Kingdom and France appear to be most affected with more than 100×10^3 people flooded annually in each country under A2+NO in 2100, followed by Spain, Latvia, Poland and Italy with around 50×10^3 people affected in each country (Fig. 3). Under the B1+NO simulation, the numbers are generally only about a third of those under A2+NO in 2100. The countries most affected are France, the Netherlands, Poland and the United Kingdom with about 30×10^3 each. In terms relative to national population the countries estimated to be most affected are Latvia with 1.34% and the Netherlands with 0.61% of their populations experiencing coastal flooding under A2+NO in 2100. For all other countries the fraction lies below 0.3% of the countries' populations.

Damage costs increase roughly by a factor of 5 during the century under both scenarios (Table 1). Under A2+NO, damage costs are estimated to be € 3.1×10^9 per year in 2010 and € 16.9×10^9 per year in 2100. Damages are actually slightly higher under B1 compared to A2, because the higher sea-level rise under A2 is compensated by the smaller GDP growth under A2, which in turn reduces damage costs. In other words, the exposure grows faster under B1, so there is more to be damaged in the coastal zone. Total damage costs amount to roughly 0.04% of GDP of the EU27 coastal countries in 2100 under both scenarios.

The major contributor to the damage costs are sea floods, salinity intrusion and, in particular towards the end of the century, migration resulting from land lost due to coastal erosion (Table 2). The contributions of the various types of impacts to the total damage cost are roughly similar under both scenarios.

On the level of individual countries, damage costs are by far highest in the Netherlands (€ 5.4×10^9 per year under A2 in 2100) followed by Germany, France and the UK with costs between € 2×10^9 and € 3×10^9 per year under A2 in 2100 (Fig. 4). As it was the case for the EU27 as a whole, damage costs are slightly higher under B1 compared to A2 in 2100, which reflects that the lower sea-level rise under B1 is compensated by the faster growth of GDP. Damage costs relative to national GDP are highest in the Netherlands (0.3% in 2100 under A2). For all other countries relative damage costs do not exceed 0.1% of GDP under both scenarios.

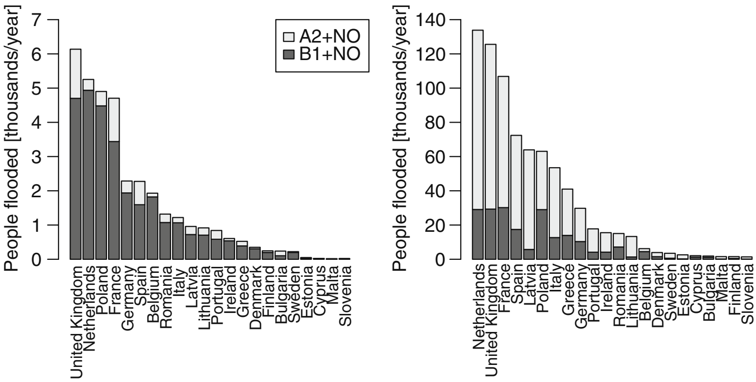

Fig. 3 Countries most affected in terms of people flooded under the A2 and B1 scenarios without adaptation in 2050 (*left*) and 2100 (*right*)

Table 2 Contribution of the different impacts to the total damage cost at the level of EU 27 for the simulations without adaptation (A2+NO and B1+NO)

	Salinity intrusion [million €/year]		Land loss [million €/year]		Sea floods [million €/year]		River floods [million €/year]		Migration [million €/year]		Total damage cost [million €/year]	
Time	A2	B1	A2	B1	A2	B1	A2	B1	A2	B1	A2	B1
2010	842	872	1	2	2,182	2,335	18	20	92	99	3,136	3,329
2030	1,005	1,122	4	4	3,501	4,274	36	44	218	223	4,767	5,662
2050	1,147	1,326	7	7	4,861	6,398	63	79	371	386	6,450	8,192
2100	2,010	1,844	16	10	13,637	14,483	283	274	986	884	16,933	17,496

Figure 4 also shows the contributions of the different impacts to the overall damage cost on the level of individual countries under both scenarios in 2050 and in 2100. In most countries, sea floods contribute more than 70% to the overall damages. In Germany, Poland, France, the Netherlands and Italy, salinity intrusion contributes between 7 and 36% to the total damage cost under A2 in 2100, owing to the large deltas and estuaries of these countries. Note that we only consider salinity intrusion along rivers (Section 2). The most affected rivers are the Seine, the Rhine/Meuse, the Garonne, the Elbe and the Oder. Sea-level rise increases the length that salt water intrudes into these rivers by 20 to 30% between 2000 and 2100 under A2.

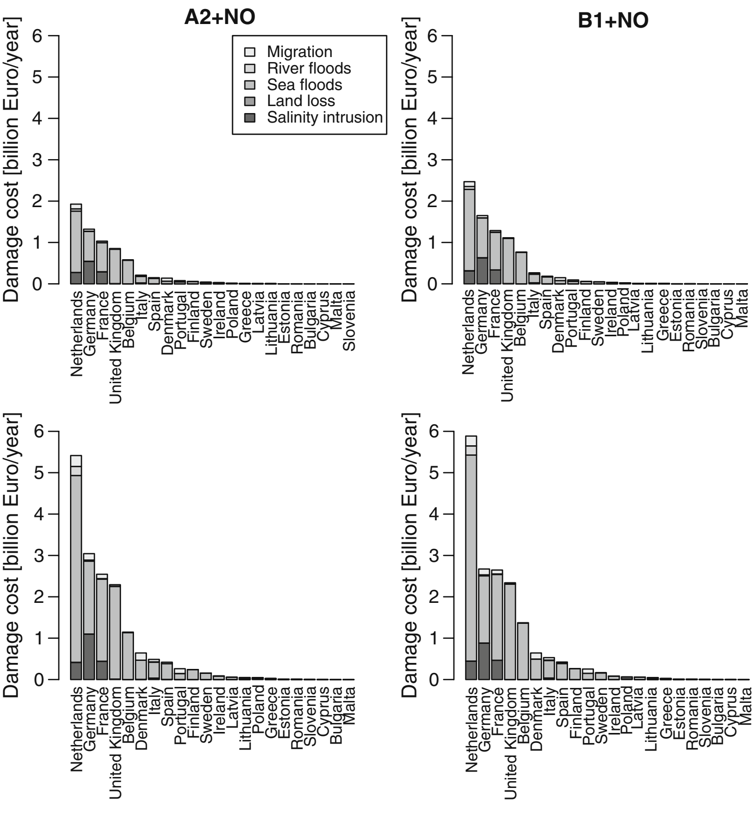

Fig. 4 Damage cost under the A2 and B1 scenarios without adaptation in 2050 (*top*) and 2100 (*bottom*)

4 Adaptation costs and residual damages

Given the magnitude of the potential impacts presented above it is very unrealistic to assume that no adaptation takes place as this would mean that people continue to dwell and accumulate assets in the coastal zone even when experiencing high damages. For assessing coastal impacts, it is thus more meaningful to assume adaptation to be the "business as usual scenario" rather than no adaptation. What kind of adaptation model to use for "realistically" assessing impact is, however, still subject to ongoing research. Here we consider adaptation in the form of two protection options: dike building and beach (or shore) nourishment as described in Section 2. In coastal management, a wider range of options is available, including accommodating for rising sea-levels and retreating from the coast (Klein et al. 2001). The implementation of these further options is, however, embedded in smaller scale socio-institutional management and planning processes, which are difficult to predict.

Table 3 summarizes the impacts at the level of the EU27 for the two simulations that include adaptation (A2+AD and B1+AD). Compared to the previous simulations without adaptation, adaptation reduces damages significantly. Under A2, adaptation reduces the number of people flooded by a factor of 7 in 2050 and by a factor of 288 in 2100. Under B1 the number is reduced by a factor of 12 in 2050 and by a factor of 111 in 2100. The number of people flooded per year actually decreases over the century under the simulations with adaptation even though sea level is rising, because dikes are raised to a higher protection level as GDP increases (expressing people's decreasing tolerance of risk with rising wealth). The countries most affected in 2100 under A2 with adaptation are the Netherlands with 0.7×10^3 people flooded per year and the UK and France each having 0.6×10^3 people experiencing annual flooding. In most countries, it is cost effective to fully nourish sandy beaches and land loss due to coastal erosion is negligible.

Under both scenarios, damage costs hardly increase during the century because dikes are raised in response to a greater demand for flood safety due to increasing wealth (Table 3). In 2100 damage costs are roughly a factor of 8 to 9 lower under the simulations that include adaptation compared to those presented above that do not. At the same time, annual adaptation costs increase approximately linearly during the century, with differences between the two scenarios only becoming significant after 2050 (Table 3). In 2100, € 3.5×10^9 per year is required under A2 and € 2.6×10^9 per year under B1 for building dikes and nourishing beaches in the EU25 coastal countries. The sum of damage and adaptation cost under the simulations with adaptation, however, are significantly lower than damage costs under the simulations without, which is in accordance with the PESETA simulations (Richards and Nicholls 2009).

Table 3 People flooded, land lost, damage, adaptation and total cost at the level of EU 27 for the simulations with adaptation (A2+AD and B1+AD)

	People flooded [thousands]		Land loss [km²/year]		Damage cost [million €/year]		Adaptation cost [million €/year]		Total cost [million €/year]	
Time	A2	B1	A2	B1	A2	B1	A2	B1	A2	B1
2010	7.3	7.0	0	0	1,790	1,858	1,141	1,377	2,931	3,235
2030	6.4	3.9	0	0	1,936	1,632	1,677	1,591	3,613	3,223
2050	5.3	2.5	0	0	1,954	1,531	2,277	1,925	4,231	3,456
2100	3.4	1.8	0	0	2,291	1,917	3,536	2,621	5,827	4,538

When assuming adaptation, salinity intrusion contributes about 90% to the total damage costs at the level of the EU27 in 2100 (Table 4). Adaptation effectively reduces costs of sea and river floods as well as of land loss and migration due to erosion. Since no engineering options against salinity intrusion are considered here, the costs of this impact dominates the total damage costs. Note that it is assumed that farmers adapt by switching to salt-tolerant crops. If not, the value of land would drop to essentially zero.

On a country level, Germany has the highest adaptation cost in 2100 (€ 619×10^6 per year under A2), followed by the UK, Denmark, France and the Netherlands (Fig. 5). On average, sea dike building and beach/shore nourishment contribute roughly equally to the total adaptation costs of the EU27, with sea dike building having the greater contribution at the beginning of the century and beach/shore nourishment at the end. The shift is caused by the rise in tourism, as a result of population growth, economic growth, and climate change. A larger number of tourists means that beaches become more valuable, and thus worth protecting by nourishment. At the country level, there is a group of countries consisting of Lithuania, Portugal, Germany, the Netherlands, Estonia, Romania, France, Denmark, Spain, Italy and Belgium with a high and over the century increasing contribution of nourishment (Fig. 5). These are the countries with long sandy beaches and thus popular with tourists. For the other countries, the share of nourishment on the total adaptation cost is below 20% under both scenarios.

Figure 5 also shows the distribution of total cost, that is the sum of damage and adaptation cost on the level of the EU27 countries. Total costs are generally higher under A2 compared to B1, because the higher sea-level rise under A2 leads to higher salinity intrusion and sea flood damages as well as to higher beach/shore nourishment costs. Total costs relative to national GDP are much smaller compared to the simulations without adaptation. Under A2 and in 2100 total relative costs are highest for Estonia (0.16%). For all other countries relative total costs do not exceed 0.06% of GDP under both scenarios.

5 Discussion and conclusions

We applied the DIVA model, an integrated model of coastal natural and social systems, to assess the risk of and adaptation to sea-level rise for Europe's coastal zone. Impacts of sea-level rise, socio-economic development, and coastal adaptation were estimated in terms of the number of people affected by annual flooding, the number of people forced to migrate due to coastal erosion, monetary damage costs and adaptation cost. The assessment is based on the IPCC SRES A2 and B1 scenarios. For each scenario, impacts were estimated first

Table 4 Contribution of the different impacts to the total damage cost at the level of EU 27 for the simulations with adaptation (A2+AD and B1+AD)

	Salinity intrusion [million €/year]		Land loss [million €/year]		Sea floods [million €/year]		River floods [million €/year]		Migration [million €/year]		Total damage cost [million €/year]	
Time	A2	B1	A2	B1	A2	B1	A2	B1	A2	B1	A2	B1
2010	842	872	0	0	937	974	6	5	4	4	1,790	1,858
2030	1,005	1,122	0	0	921	510	3	0	5	3	1,936	1,632
2050	1,147	1,326	0	0	805	199	1	0	3	6	1,954	1,531
2100	2,010	1,844	0	0	283	76	0	0	0	0	2,291	1,917

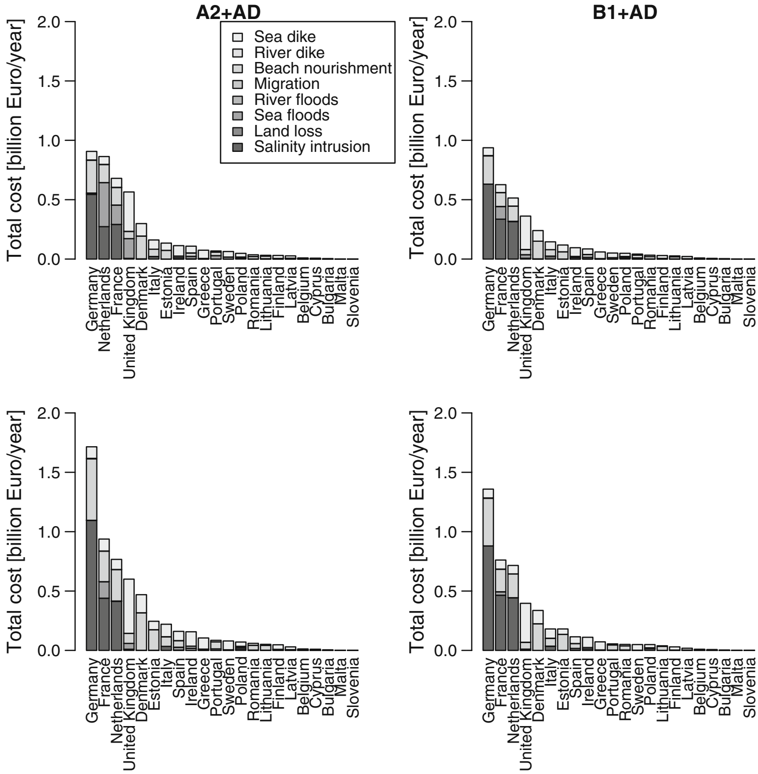

Fig. 5 Total cost (i.e., damage cost + adaptation cost) under the A2 and B1 scenarios with adaptation in 2050 (*top*) and 2100 (*bottom*)

without adaptation and then assuming adaptation in the form of increasing dike heights and nourishing beaches.

While over the 21st Century, sea-level rise constitutes a risk for Europe, in the first half of this century, coastal impacts are predominantly driven by socio-economic development. Due to the delayed response of the ocean to global mean temperature rise, differences in sea-level rise are minor between the SRES scenarios up to 2050. Hence, differences in impacts between A2 and B1 reflect more the differences in population and GDP growth between the two scenarios. This also means that coastal impacts are not sensitive to mitigation during the first half of the century.

In the second half of the century, the consequences of sea-level rise become significant; assumptions on socio-economic development do, however, continue to have a strong influence on the magnitude of impacts. Without assuming adaptation, both, the higher sea-level rise as well as the higher coastal population growth of A2 relative to B1 result in significantly higher numbers of people affected by flooding under the former scenario (780×10^3 per year under A2 in 2100 compared to 200×10^3 per year under B1). In terms of economic damage, there is, however, little difference between the two scenarios, because the lower sea-level rise under B1 is compensated by faster economic growth and more coastal assets to be damaged. In 2100, damages are estimated to amount to roughly € 17×10^9 per year under both scenarios without adaptation.

Under both scenarios the greatest part of the total monetary damage is estimated to be caused by sea floods and increasingly so during the century. While the gradual effects of sea-level rise such as coastal erosion and, for some regions, salinity intrusion contribute to the overall damages, the major monetary damage is due to extreme events produced by a combination of storm surges and astronomical tides, and amplified through the gradual rise in mean sea level.

Adaptation reduces the impacts substantially. In 2100 and under A2, damage costs are reduced roughly by a factor of 7, the number of people flooded by a factor of 228 and land loss due to coastal erosion ceases. Growing GDP and associated land values makes building dikes and nourishing beaches cost-effective. The number of people affected by flooding does in fact fall during the century as a growing GDP leads to risk aversion which is expressed as higher protection levels within DIVA. In absolute terms, the costs for adaptation are substantial. In 2030, roughly € 1.6×10^9 per year will be needed for adaptation under both scenarios, and in 2100 it will be € 3.5×10^9 per year under A2 and € 2.6×10^9 per year under B1. Building dikes and nourishing beaches contribute roughly equally to these costs. Relative to GDP, annual adaptation costs constitute 0.005 % of GDP under B1 and 0.009% under A2 in 2100. Hence, adaptation delivers substantial benefits, and it looks affordable in relation to the size of the economy under both of the scenarios considered here.

These results suggest that adaptation will be widespread, which is in line with previous studies (Richards and Nicholls 2009; European Commission 2007). There is, however, high uncertainty in what kind and level of coastal adaptation to expect, and recent experience suggests that many European countries are only just beginning to recognise the problems that sea-level rise might bring (Tol et al. 2008). DIVA only considers a very limited range of adaptation options. In coastal management a much wider range of options would be considered (e.g., Klein et al. 2001), and this may lower damage and adaptation costs compared to those estimated by DIVA. For example, DIVA does not consider the building of salt water intrusion barriers to prevent salt water travelling up rivers basins and damaging agricultural land, a process that leads to high damages in some countries, such as the UK, Germany and France. These damages can be reduced by salt water intrusion barriers, which are often combined with flood defence structures (e.g., the Dutch delta works after the 1953 storm surge). The integration of adaptation within coastal management also needs to be considered to make sure that the adaptation measures are consistent with wider objectives for coastal development (e.g., Klein et al. 1999).

It is likely that this assessment underestimates impacts due to a number of processes that are not considered in the current version of DIVA. DIVA does not consider changes in storm frequency and intensity, which may occur under climate change in Europe (e.g., Lowe et al. 2009). These changes could increase coastal flooding, coastal erosion and associated damage and adaptation costs. However, reliable projections cannot currently be made with confidence (von Storch and Woth 2008). Furthermore, the assessment is based on national estimates of GDP and population growth. In most instances, coastal GDP and population are, however, growing faster than national averages due to rapid coastal development and urbanization that is found in most of the world's coastal zone. Last, the sea-level rise scenarios applied excluded the potentially significant but uncertain contribution of ice discharge from the Greenland and Antarctic Ice Sheets, which could in the worst case lead to sea-level rise of 1 m or more by the end of the century (Lowe et al. 2009).

Despite employing the best available global datasets, model results in some areas may be affected by data-related uncertainties. Such uncertainties constitute an inherent characteristic of global datasets due to the considerable spatial variation in the accuracy of the data as a result of various factors such as data collection practices and techniques, local conditions, accessibility and others. Of particular importance to DIVA for estimating damage and costs is the accuracy of the elevation and population data. The accuracy of elevation data depends on numerous parameters (e.g. terrain elevation, aspect, resolution) and constitutes a potential source of error. Accuracy issues for the SRTM data that have been used in this paper are explained in detail by Rodriguez et al. (2005). A particularly important outcome of their study on the spatial distribution of accuracy of the SRTM elevation data is that the values of the data in coastal regions are of much higher accuracy compared to other regions of the world. While further analysis of the quality of the SRTM data is required, including assessing any bias due to surface as opposed to ground elevations, the updated database used here leads to improved estimates of coastal impacts, adaptation costs and vulnerability.

Given these limitations and uncertainties, further research should continue to improve the accuracy of regional and global datasets in particular for elevation and population density. A wider range of sea-level rise as well as socio-economic scenarios should be applied to explore the full range of possible impacts. Future work should also aim at considering further adaptation options and at exploring the trade-offs and synergies between these options as well as the timing of different adaptation strategies.

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