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Economic impacts of climate change in Europe: sea-level rise

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Abstract This paper uses two models to examine the direct and indirect costs of sea-level rise for Europe for a range of sea-level rise scenarios for the 2020s and 2080s: (1) the DIVA model to estimate the physical impacts of sea-level rise and the direct economic cost, including adaptation, and (2) the GTAP-EF model to assess the indirect economic implications. Without adaptation, impacts are quite significant with a large land loss and increase in the incidence of coastal flooding. By the end of the century Malta has the largest relative land loss at 12% of its total surface area, followed by Greece at 3.5% land loss. Economic losses are however larger in Poland and Germany ($483 and $391 million, respectively). Coastal protection is very effective in reducing these impacts and optimally undertaken leads to protection levels that are higher than 85% in the majority of European states. While the direct economic impact of sea-level rise is always negative, the final impact on countries' economic performances estimated with the GTAP-EF model may be positive or negative. This is because factor substitution, international trade, and changes in investment patterns interact with possible positive implications. The policy insights are (1) while sea-level rise has negative and huge direct economic effects, overall effects on GDP

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are quite small (max −0.046% in Poland); (2) the impact of sea-level rise is not confined to the coastal zone and sea-level rise indirectly affects landlocked countries as well (Austria for instance loses −0.003% of its GDP); and (3) adaptation is crucial to keep the negative impacts of sea-level rise at an acceptable level.

1 Introduction

Sea-level rise is often ranked among the most serious of the impacts of climate change, affecting even rich countries such as those in Europe. Sea-level rise increases the destructive power of storms and floods, accelerates erosion, and threatens freshwater supplies on the coast — each of which has a direct impact on the economy. Sea-level rise would also threaten coastal wetlands, which are important areas for nature conservation, recreation, and fisheries, and widely designated under the EU Habitats Directive. And while Europe's coastal lowlands may well be protected by raised dikes and other measures, the same may not be true elsewhere potentially inducing fluxes of migrants produced by sea-level rise. This paper assesses the impacts of sea-level rise on Europe, using two state-of-the-art models to estimate the physical impacts and the economic implications, respectively.

This is not the first such exercise, as shown by the literature review in Section 2. However, this is the first detailed economic impact assessment for the countries of the European Union (EU) integrating both bottom-up and top-down methodologies. The EU coastline characteristics are captured by the DIVA model which couples high (sub-national) geographical resolution with the physical quantification of all the major direct impacts of sea-level rise (erosion, increased flood risk and inundation, coastal wetland loss and change, surface salinisation). The higher order costs of these impacts are then assessed with GTAP-EF, a computable general equilibrium model for the EU with country detail which shows implications for GDP, investment, international trade flows and ultimately welfare.[1]

One of the crucial features of sea-level rise is that its impacts vary along the coast, with coastal geomorphic type, climate, and ecology, socio-economic and land use characteristics, and coastal management policies. This implies that aggregate estimates of the impact of sea-level rise (as was hitherto the standard in the economic literature) hide important regional differences. This paper sheds light on these issues.

The work has been conducted as part of the PESETA (Projection of Economic impacts of climate change in Sectors of the European Union based on boTtom-up Analysis) EC-funded project whose objective is the multi-sectoral assessment of the impacts of climate change in Europe for the medium- and long-term. Its analyses propose an integration of high-resolution physical data with economic assessments conducted at the country level. In addition to coastal areas, PESETA investigates impacts on agriculture, tourism, human health, and river floods.

The paper proceeds as follows. Section 2 reviews the literature. Section 3 presents the physical and biological impacts of sea-level rise, as well as the direct economic costs. Section 4 estimates the economy-wide implication. Section 5 concludes.

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[1] GTAP-EF is based on the GTAP model (Hertel 1996), in the version modified by Burniaux and Truong (2002) and subsequently extended by ourselves to account for land loss and adaptation costs (see further). It is calibrated on GTAP 6 database (Dimaranan 2006).

2 State-of-the-art and contribution to the literature

Sea-level rise which is associated to a set of impacts on natural and social economic systems is one of the most studied consequences of climate change. The costs of sea-level rise and of protection against it are equally prominent in the estimates of the costs of climate change.

In the early 1990s the IPCC had already proposed methodologies and estimates of the cost of sea-level rise and of the benefit of coastal protection (IPCC CZMS 1990, 1991, 1992). This issue was subsequently investigated in a large body of literature. The majority of studies are based on engineering research and inventories of the threatened area and subsequently people and activities at risk, to which an economic value is attached. This figure is the base to which the cost of coastal protection can be compared for a cost-benefit analysis (Nicholls et al. 2007). Studies in this vein include investigations at the global level with macro regional and country detail (see e.g. Hoozemans et al. 1993; Fankhauser and Tol 1996; Tol 2002, 2007), at the macro-regional level (see e.g. Fankhauser (1994); Yohe et al. (1996); Yohe and Schlesinger (1998) for the USA; Nicholls and Klein (2005); CEC (2007) for Europe), at the country level (see e.g. Dennis et al. (1995) for Senegal, Volonte and Nicholls (1995) for Uruguay, Volonte and Arismendi (1995) for Venezuela, Morisugi et al. (1995) for Japan, Zeider (1997) for Poland) and at the site level (see e.g. Gambarelli and Goria (2004) for the Fondi plane in Italy, Breil et al. (2005) for the city of Venice, Smith and Lazo (2001) for the Estonian cities of Tallin and Pärnu, and the Zhujian Delta in China; Saizar (1997) for Montevideo).

This vast literature concentrates on the direct costs of sea-level rise and of possible adaptation options. The main result of these studies is that the cost of sea-level rise (albeit in some cases a small fraction of GDP) can be high in absolute terms. As an example, US$ 0.06 billion is the estimated annuitised cost of 50 cm. of sea-level rise over a century for the USA (Yohe et al. 1996) and US$ 3.4 billion for Japan (Morisugi et al. 1995). An annual cost ranging from Euros 4.4 to 42.5 billion is the evaluation proposed for Europe by CEC (2007) for a sea level increase of 22 and 96 cm., respectively. The Netherlands, Germany and Poland are expected to suffer a cumulated undiscounted capital loss of US$ 186, 410 and 22 billions for 1 meter of sea-level rise according to Nicholls and Klein (2005). Against this background, coastal protection seems to be not only effective, but also efficient in most cases. This is for instance confirmed for Europe as a whole (CEC 2007; see also Nicholls and Klein 2005), and for the Netherlands (Delta Commission 2008), Germany (Sterr 2008), Poland (Zeider 1997; Pruszaka and Zawadzkab 2008), for Japan (Morisugi et al. 1995) and for the more developed areas of Senegal (Dennis et al. 1995). Based on the threatened values and the cost of protection, Tol (2007), showed, that high levels of coastal protection (>70% of the threatened coast) would be optimal for the majority of the world's regions. However, for some countries or sites the efficient level of coastal protection is likely to be low or even zero, pointing out the importance of carefully evaluating benefits and costs of different options for sea-level rise adaptation. This could be for instance the case for Dar es Salaam and of the entire populated coastline of Tanzania (Smith and Lazo 2001), and most of Uruguay (Volonte and Nicholls 1995) and Venezuela (Volonte and Arismendi 1995).

The above studies are all based on a direct costing approach: they basically evaluate costs multiplying a quantity loss (land or capital) or "displaced" (people), by the unitary "price" of the item lost or of the displacement. By contrast, few papers have attempted to assess the "higher-order" impacts of sea-level rise and coastal protection. The issue here is to consider explicitly the goods' and factors' substitution mechanisms triggered by changes in relative prices responding to an initial land and property loss, or to investment in coastal protection, and their final effects on welfare or GDP.

Deke et al. (2001) do this using a recursive dynamic computable general equilibrium (CGE) model to estimate economy-wide implications of sea-level rise at a global scale, but they restrict the study to the costs of coastal protection, ignoring land loss and its wider economic consequences. The costs of coastal protection are subtracted from investment and, as they use a Solow-Swan growth engine to drive their recursive dynamics, this essentially reduces the capital stock, and hence economic output. However, the stimulus to the construction sector from investing in dikes and seawalls is neglected.

Darwin and Tol (2001) use a static global CGE model. They consider both the cost of sea-level rise in a no protection scenario and that of "optimal" coastal protection modelled as an instantaneous loss of productive capital. Like Deke et al. (2001), Darwin and Tol (2001) ignore the induced demand of coastal protection, and thus probably overstate the impact of sea-level rise. "Their" direct protection cost is composed of the cost of protection proper, and of fixed capital and land lost.

According to Deke et al. (2001) the direct protection costs against the 13 cm. of sea-level rise forecasted for 2030, are a tiny percentage of GDP, ranging from 0.001% in Latin America to 0.035% in India. However, coastal protection investment reduces "productive" capital stock and the input substitution processes triggered by capital scarcity imply a welfare loss ranging from 0.3% of India to 0.006% of Western Europe with respect to the no protection case. The study also highlights the different results produced when countries are ranked according to direct costs or welfare losses. This is because of the redistribution of regional as well as international allocation effects of a slightly lower path of investment.

In the no protection case, Darwin and Tol (2001) estimate the annuitised total cost for 50 cm. of sea-level rise in 2100 of nearly US$ 66 billions. The highest losses among OECD countries are the nearly US$ 7 billions of Europe. Note that Asian economies as a whole appear more threatened with an annuitised loss of US$ 42 billions. With an optimal protection policy direct annuitised costs are US$ 4.4 billions for the world as a whole. In developed regions they are fairly small, ranging from almost nothing to 0.009% of total 1990 investment. In developing countries they reach the highest level in the China-South Korea-Taiwan-Hong Kong region where they amount to 0.1% of 1990 expenditure. Welfare effects in the protection case highlight a total loss of US$ 4.9 billions, approximately 13% higher than world direct cost. The additional losses are not equally distributed: in general, international trade tends to redistribute losses from regions with relatively high damage to regions with relatively low damages.

In the view of the importance of considering both direct and higher order cost of sea-level rise, the present research focuses on the EU using two models: (1) a direct cost estimation of sea-level rise, based on a bottom-up approach (the DIVA model); and (2) a general equilibrium assessment of those costs, based on a top-down approach.

The DIVA (Dynamic and Interactive Vulnerability Assessment) model (DINAS-COAST Consortium 2006) is an integrated impact-adaptation model, allowing the interaction between a series of biophysical and socio-economic modules to assess impacts of sea-level rise. The DIVA model provides a more comprehensive perspective on the impacts of sea-level rise, with results available from sub-national to global scales units (McFadden et al. 2007; Vafeidis et al. 2008).

A major weakness of earlier studies is that they only examine a subset of the physical consequences of sea-level rise, whereas DIVA allows all the major direct impacts of sea-level rise to be quantitatively evaluated in physical terms (Table 1). These include (i) increased erosion, (ii) increased inundation probability and submergence, (iii) coastal

Table 1 Sea-level impacts and adaptations considered within the DIVA model in this study

Sea-level rise effects	Physical impact	Costed impact	Adaptation
Erosion	Land loss	Land loss costs	Beach nourishment
	Forced migration	Forced migration cost	
Inundation	Land loss	Land loss costs	Dike upgrade
	Increased flood incidence	Expected annual flood damages	
	Forced migration	Forced migration cost	
Wetlands	Wetland loss	Not costed	Not considered
	Wetland change		
Salinisation	Agricultural damage	Salinisation costs	Not considered

wetland loss and change, and (iv) salinisation of selected coastal rivers. These result in physical changes and corresponding monetary costs such as land loss costs, (forced) migration costs, sea flood costs, and (surface) salinisation costs. Adaptation is an explicit part of the DIVA model and the consequences of several stylised homogenous adaptation options can be explored together with their costs, including options from no protection to total protection. In this analysis no adaptation and adaptation options are compared. For beach erosion, nourishment is the adaptation used based on a cost-benefit approach which considers land and tourism values. For flooding, defence 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 demand function is posited as the solution to a cost-benefit analysis (Tol 2006). Hence, adaptation in this analysis is represents protection (or “hold the line”) options.

The top-down assessment uses the GTAP-EF model, which is a CGE model representing the major EU economies at a country level, and the rest of the world as an aggregate region (see Bosello et al. 2007). In contrast to Deke et al. (2001), the present study does not restrict its analysis to the cost of coastal protection, but explicitly examines land losses and their wider economic consequences. In addition, while Deke et al. (2001) subtract the costs of coastal protection from investment, in this CGE assessment, coastal protection is explicitly modelled as an additional investment, thus including its multiplicative effect. This is also a novel feature with respect to Darwin and Tol (2001) who ignored the induced demand of coastal protection, which may overstate the impact of sea-level rise. Coastal protection investment is not “free” and is “funded” by a decreased consumption.

3 Estimate of the physical and direct economic impacts

3.1 Climate scenarios

Direct physical and then economic impacts of climate-change induced sea level rise have been estimated via the DIVA model. The EU countries considered by the investigation are reported in Table 2.

For consistency across the PESETA project, the DIVA model has been used to assess the sea-level rise implications of ECHAM4 and HADCM3 GCM results for low, medium and high scenarios of sea-level rise (Gordon et al. 2000; Roeckner et al. 1996). The global sea-level rise figures used within this analysis are shown in Table 3. The outputs of the ECHAM4 and HADCM3 GCMs are also compared to the low and high IPCC Third

Table 2 Regional disaggregation of EU within the DIVA model

Regions			
Belgium	Greece	Poland	Spain
Bulgaria	Ireland	Malta	
Croatia	Italy	Portugal	
Estonia	Latvia	Romania	
Finland	Lithuania	Slovenia	
Germany	Netherlands	Sweden	
France (Juan de Nova Island, Wallis & Futuna, Glorioso Island, Territory near Wallis & Futuna, French Southern Territories, St Pierre & Miquelon, St Johns)	Denmark (Greenland, Faeroes)	United Kingdom (Gibraltar, Isle of Man, Guernsey, Jersey, Polynesia, Cayman Islands, Pitcairn Islands, Turks & Caicos, Virgin Islands, Anguilla, St Kitts & Nevis, Falkland Islands, South Georgia, Saint Helena, British Indian Ocean Territory)	

The areas in brackets and italics were excluded from the analysis as they are outside Europe and/or not part of the EU

Assessment Report (TAR) sea-level rise scenarios which encompass a wide range of uncertainty in sea-level rise projections, but explicitly excluding uncertainties due to ice sheet instability and melting in Antarctica (Church et al. 2001).

Figure 1 displays modelled predictions of sea-level rise from 1990 to 2100, for each GCM and SRES storyline.

For both climate models, sea-level rise is lower for the B2 than A2 storyline, reflecting the lower greenhouse gas emissions. The HADCM3 model consistently predicts lower sea-level rise than the ECHAM4 model, with increasing divergence over time. This reflects the increasing uncertainty in the sea-level rise projections as the timescale gets longer.

In DIVA, these global estimates of sea-level rise are downscaled to relative sea-level rise using estimates of land uplift and subsidence. Hence, even without climate change, slow relative sea-level change (both rise and fall) occurs due to these geological processes.

3.2 Physical impacts

Results of the coastal systems physical impact assessment are available for individual European countries, for all parameters and each scenario.

Table 3 Global sea-level rise for low, medium and high climate sensitivities, at 2100, for the A2 and B2 SRES storylines and associated greenhouse gas emissions

Global Climate Model	ECHAM4		HADCM3		IPCC TAR
Socio-Economic Scenario	A2	B2	A2	B2	A2/B2
Sea-Level Rise Scenario					
Low (cm)	29.2	22.6	25.3	19.4	9
Medium (cm)	43.8	36.7	40.8	34.1	
High (cm)	58.5	50.8	56.4	48.8	88

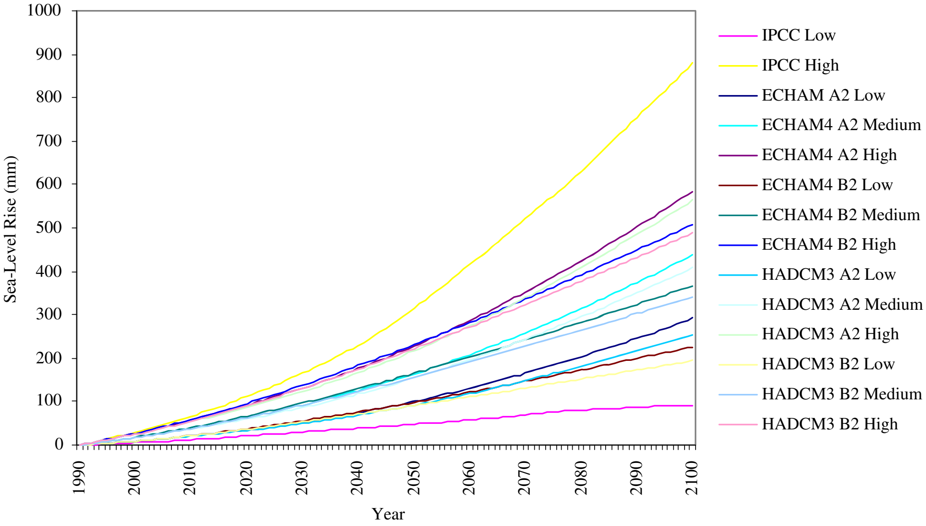

Fig. 1 Sea-level rise for each of the emission scenarios and the climate models used in the PESETA analysis

Here we just report the aggregated values for the EU concerning:

- land loss due to erosion and submergence (areas below a flood return period of 1 in 1 year);
- intertidal habitat loss (comprising saltmarsh and unvegetated tidal flats);
- expected number of people flooded each year.

Note that there are some impacts without climate-induced sea-level rise due to uplift and subsidence, and hence some areas experience relative sea-level rise, and flooding occurs under present climate. The impacts are generally higher for the A2 storyline for all models. This is due to both the higher rates of sea-level rise (Table 3, Fig. 1) and the larger increase in population within this storyline. It is also clear that adaptation significantly reduces the impacts, where relevant..

Without adaptation, land loss due to both submergence and erosion increase over time and with the rate of sea-level rise (Fig. 2). These losses are substantially reduced with adaptation with annual land loss due to submergence potentially being reduced by two or three orders of magnitude (2080s, high sea-level rise, both A2 and B2). Annual land loss due to erosion is notably less than submergence, but is still observed to decrease with adaptation. Wetland losses also increase with higher rates of sea-level rise and over time (Fig. 3).

The number of people actually flooded also increases over time and with increasing sea level if no adaptation is undertaken. It is large in absolute terms (Fig. 4): for instance under the A2 (ECHAM4) scenarios the expected number of people flooded range from 2.2×10^5 to 1.4×10^6 people per year in the 2080s assuming no adaptation. However, when adaptation is considered, the numbers of people flooded are significantly reduced and are relatively constant across the sea-level scenarios and over time. This reflects that average protection levels increase over time under both the A2 and B2 storylines, and the main consequence of higher sea-level rise is more investment if higher defences. Under the A2 scenario with adaptation, the number of people actually flooded remains relatively stable over time as increased protection is offset by increasing coastal population (i.e. exposure). Under a B2 scenario including adaptation, the number of people flooded falls from the 2020s the 2080s as the exposed population is similar, having peaked in the 2050s and subsequently fallen (Arnell et al. 2004).

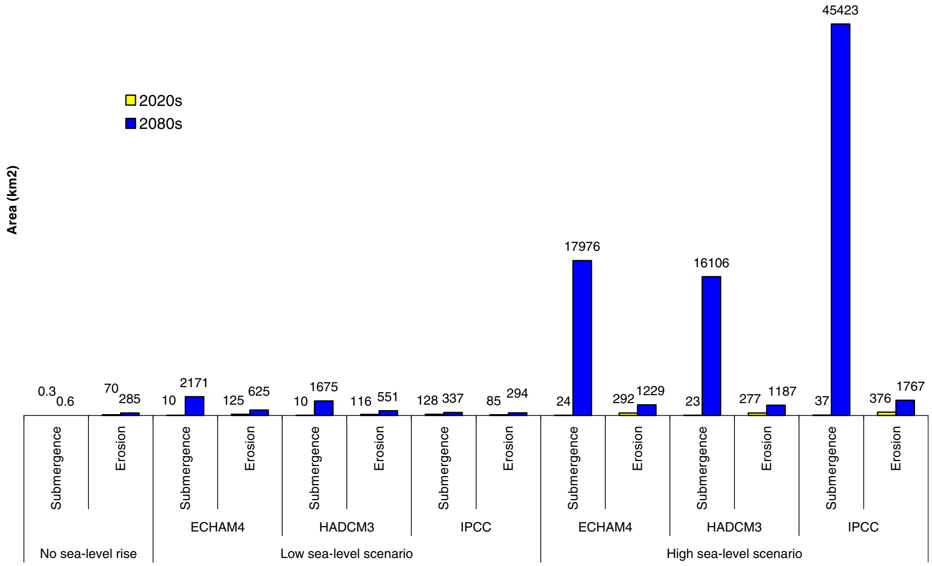

Fig. 2 Comparison of DIVA estimates of annual land loss in the EU under the A2 storyline without adaptation

3.3 Direct economic costs

Direct economic costs are based on a number of parameters, including population and GDP/capita and they have been divided into three main categories:

- adaptation costs (the sum of costs due to dike upgrade and beach nourishment);

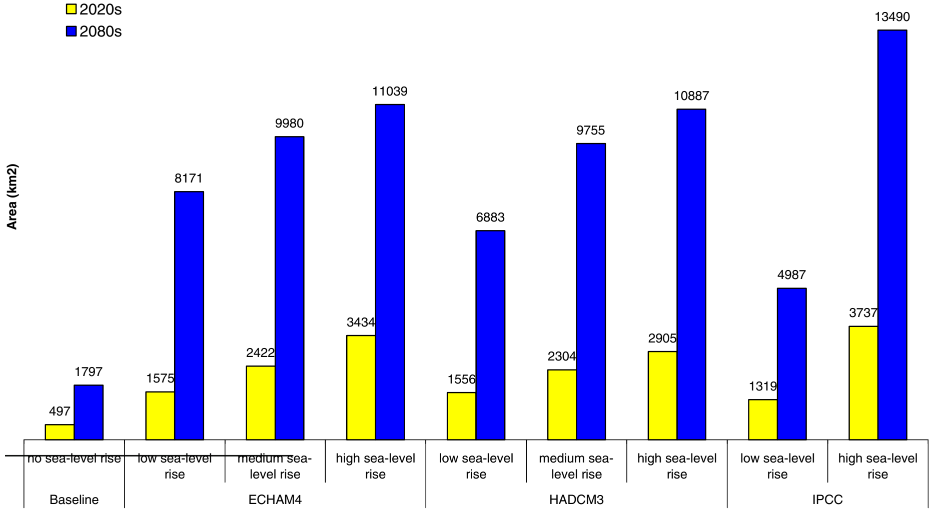

Fig. 3 Comparison of DIVA estimates of total intertidal loss (since 1995) in the EU under the A2 storyline

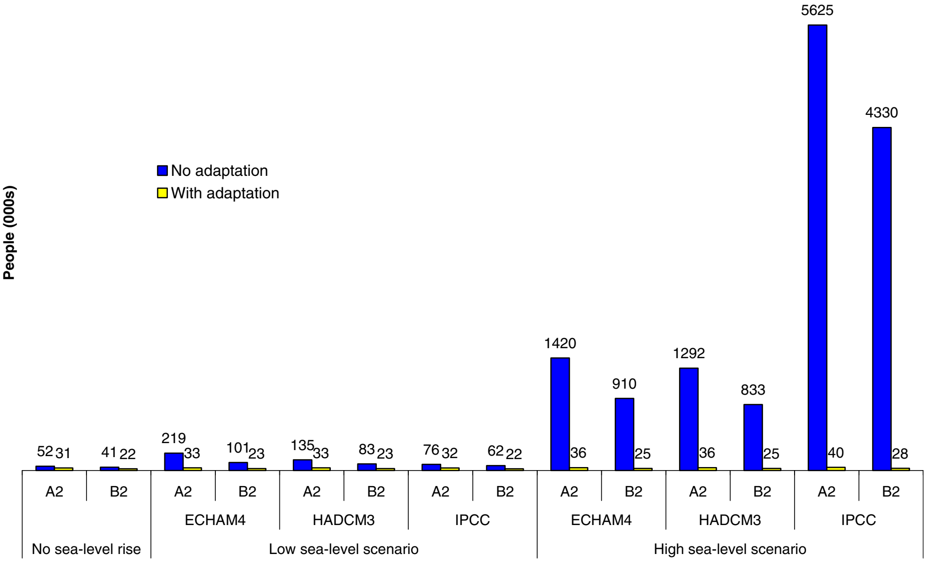

Fig. 4 Comparison of DIVA estimates of the expected number of people flooded per year in the EU with and without adaptation by 2080s

- total residual damage costs (the sum of costs of expected annual flood damage, land loss, forced migration, and salinisation) (land loss and forced migration are due to the combined effect of submergence and erosion); and
- net benefit of adaptation (the damages avoided by adaptation minus the adaptation costs).

Note that there are some damages without climate-induced sea-level rise due to uplift and subsidence, and hence some areas experience relative sea-level rise, and flooding and salinisation occurs under present climate. There are also some adaptation costs without global sea-level rise due to a combination of responding to relative sea-level rise due uplift/subsidence, and dike upgrade due to increasing risk aversion with rising living standards. The costs of habitat change and loss or possible adaptation costs for coastal habitats are not considered here.

Flooding and migration dominate the damage costs without adaptation. For the 2080s and A2 socio-economics, the IPCC low scenario has over 90% of damage costs due to flooding, while with the IPCC high scenario migration is over 50% of damage cost, and over 40% due to flooding. Absolute damage costs fall dramatically due to adaptation: in the above cases, fort the IPCC low scenario, flood damage is reduced by 99%, while for the IPCC high scenario, flood damage is reduced by more than 90%, and migration costs by more than 99%. There is no adaptation to salinity intrusion within DIVA, so these costs are constant with or without adaptation measures. As already noted, salinity intrusion costs are significant assuming no climate-induced sea-level rise: they increase with greater rise and are slightly larger under the A2 storyline, as would be expected (Fig. 5).

The incremental adaptation costs of sea-level rise under each scenario have been calculated by subtracting the cost of adaptation under the scenario without any climate change (as some protection activities are undertaken anyway), from the costs of adaptation under each sea-level rise scenario. These costs (Table 4) increase over time from the 2020s to the 2080s, with increasing sea-level rise, and range from negligible in the 2020s under the lowest sea-level rise scenario, to about € 2.3 billion/year by the 2080s under the highest scenario.

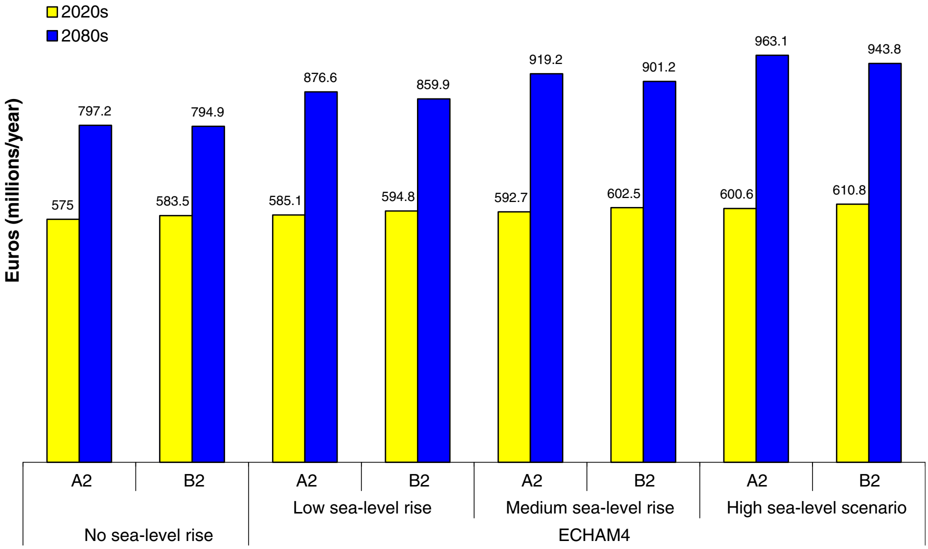

Fig. 5 Annual costs of damages due to salinity intrusion estimated by DIVA for the EU under the ECHAM4 scenario (millions €/year; 1995 values)

Total residual damage costs increase over time from the baseline in 1995 to the 2080s (Fig. 6). Damage costs for the high rate of sea-level rise for the 2080s are substantially higher than for a low rate of sea-level rise and both are substantially reduced if adaptation is undertaken. Costs of people migrating due to land loss through submergence and erosion are also substantially increased under a high rate of sea-level rise, assuming no adaptation, and increase over time. When adaptation is included, this displacement of people becomes a minor impact, showing the important benefit of adaptation to coastal populations under rising sea levels. It is important to note that the high sea-level rise costs without adaptation shown in Fig. 6 are exaggerated by IPCC sea-level values used which translate into high costs as a result of sea flooding.

Finally, although adaptation costs increase over time, this analysis suggests that the net benefits of adaptation are substantial even in the 2020s (Fig. 7).

Table 4 Annual adaptation costs of sea-level rise in the EU (millions €/year) (1995 values)

Sea-Level Rise Scenario	A2		B2	
	2020s	2080s	2020s	2080s
IPCC Low	41.4	−8.9	41.5	−11.8
IPCC High	803.8	2319.5	806.8	2349.7
ECHAM4 Low	175.4	635.4	237.3	361.3
ECHAM4 Medium	356.2	1012.3	391.8	706.8
ECHAM4 High	563.5	1428.7	607.8	1051.2
HADCM3 Low	144.8	518.2	206.5	245.7
HADCM3 Medium	322.3	905.6	387	629.4
HADCM3 High	526.7	1381.5	597.8	1005.2

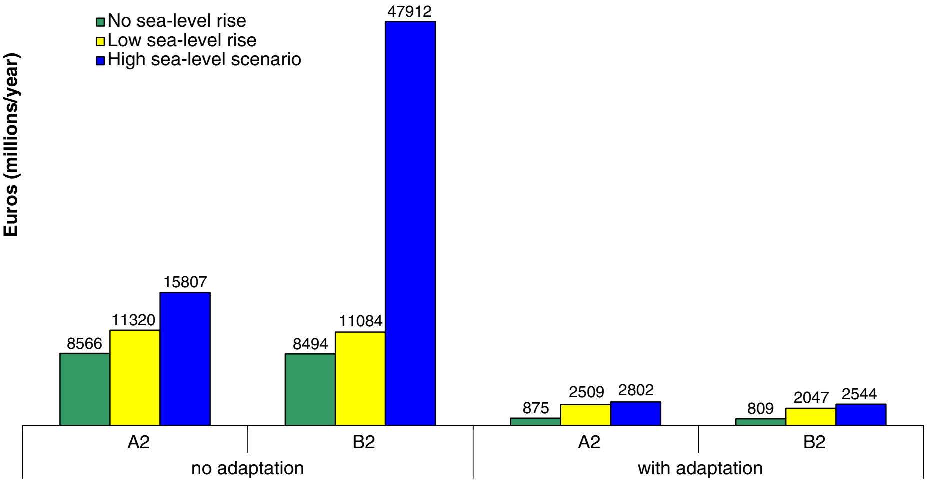

Fig. 6 Averaged annual total residual costs estimated by DIVA for the EU for the 2080s for no sea-level rise and the IPCC TAR low and high scenarios (millions €/year; 1995 values)

4 Estimates of the economy-wide impacts

The direct economic impacts are measured by gauging physical quantities in monetary units. This, however, only gives a first order approximation of the economic effects associated with the loss of a productive resource.

For example, when coastal land is lost because of sea-level rise, the market rent of the remaining land will increase, thereby increasing the income of land owners. Economic activities, which directly or indirectly use that land, will be characterised by higher production costs. This entails changes in relative competitiveness of industries and regions, changes in the terms of trade and in the whole structure of the economy. Eventually, economic effects of sea-level rise will also be felt in regions and sectors not directly affected by the resource loss.

To assess these system-wide effects, we use a computable general equilibrium (CGE) model of the world economy, along the methodology described in Bosello et al. (2007). The CGE model uses land losses and adaptation costs computed by the DIVA model as input data, and considers four sectors and 26 regions (25 European States and the Rest of the World), as specified in Table 5.

It is worth emphasising that albeit the analysis is focussed on the EU, economic interactions of the EU with the “rest of the world” need to be (and are) taken into account as sea-level rise dynamics in the ROW region are simulated. International exchanges of goods and services (i.e. the possibility to re-locate resources spatially) are indeed one of the crucial determinants of the final economic impact. This means that physical impacts of sea-level rise need to be assessed at the world level. To do so, the DIVA model is again particularly appropriated as it provides by default this information. The simulation exercises are then based on comparative static analyses, where a set of alternative equilibrium states are compared: two baselines “without sea-level rise”, where the model is re-calibrated at the years 2025 and 2085, and several counterfactual scenarios, considering various hypotheses of sea-level rise, economic growth[2] and adaptation. The 16 counterfactual scenarios are summarised in Table 6.

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[2] The economic growth scenarios refer to the IPCC SRES scenarios A2 and B2 (Nakicenovic and Swart 2000)

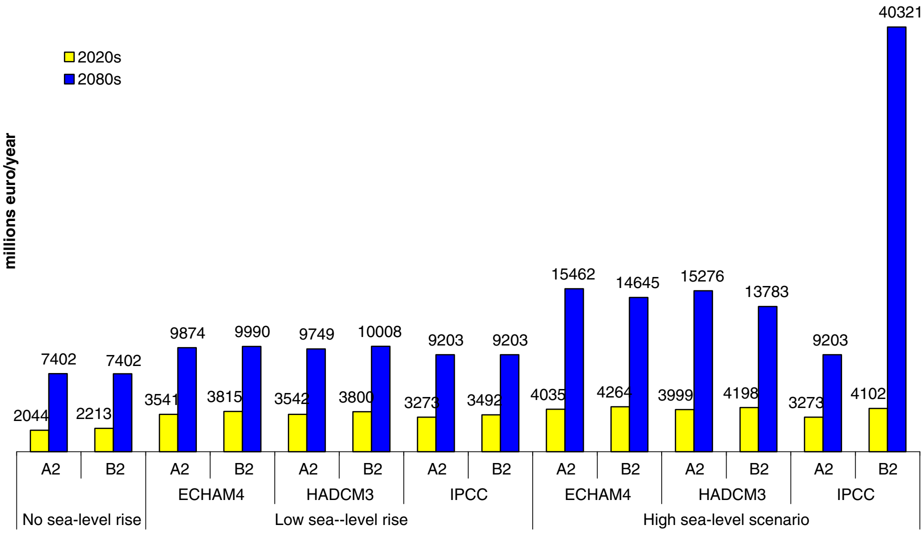

Fig. 7 Net annual benefit of adaptation for the EU as assessed by DIVA for the range of sea-level rise scenarios (millions €/year; 1995 values)

In the "no-adaptation" scenarios, it is assumed that no defensive expenditure takes place, so that all the threatened land is lost in terms of productive potential. As said, square kilometres of land lost per country/regions are directly derived from the DIVA model runs. These are implemented within the model by exogenously reducing the endowment of the primary factor "land" in all countries, in variable proportions. It is worth stressing that land in the CGE model is used as an input only by the agricultural sectors. In other words the simulations estimates the macroeconomic effect induced by the loss of productive land to agriculture and neglects potential effects on infrastructure, physical capital or on labour productivity caused for instance by forced displacement.

In the "adaptation" scenarios, on the contrary, we assumed that a lower amount of land is lost because of sea-level rise. This corresponds exactly to areas that according to the DIVA

Table 5 Industrial and regional disaggregation of the CGE model

Sectors			
Agriculture & Food			
Heavy industries and Energy sectors			
Light Industry			
Services			
Regions			
Austria	France	Lithuania	Slovenia
Belgium	Germany	Luxembourg	Spain
Cyprus	Greece	Malta	Sweden
Czech Republic	Hungary	Netherlands	United Kingdom
Denmark	Ireland	Poland	ROW (Rest of the World)
Estonia	Italy	Portugal	
Finland	Latvia	Slovakia	

Table 6 Alternative simulation scenarios

SLR No Adaptation			SLR Optimal Adaptation		
A2	High SLR	2025	A2	High SLR	2025
		2085			2085
	Low SLR	2025		Low SLR	2025
		2085			2085
B2	High SLR	2025	B2	High SLR	2025
		2085			2085
	Low SLR	2025		Low SLR	2025
		2085			2085

model cost/benefit exercise are not worth protecting.[3] The protection of remaining zones requires some specific investment in coastal defences the levels and costs of which are again provided by the DIVA model. Protective interventions, in practice, take the form of dike building and upgrade, and beach nourishment. In the model, this is translated into an exogenous increase of regional investment expenditure, matching the cost of coastal protection. This investment crowds out consumption though.

To illustrate the typical output of our simulation exercises, Tables 7 and 8 show estimated variations in some macroeconomic variables for the two scenarios “2085 A2 High Sea-level Rise”, with and without adaptation.

With the exception of Malta, which is estimated to lose 12% of its total land area, the fraction of land lost is quite small in all other EU countries ranging from 0.002% in Finland to the 3.5% in Greece; note that there are also a number of landlocked countries, which do not lose any land. The highest losses affect those countries characterised by a higher proportion of coastal zones over their total land or by more vulnerable coastal zones.

Albeit small, land loss is a negative shock on a primary production factor, accordingly the price of the scarcer land input increases (from 3% in the Czech Republic to 61% in Malta), the prices of land intensive goods increase (from 0.3% in Austria to 4.6% in Malta) and the final impact on GDP is generally negative (ranging from 0.0003% in The Netherlands to 0.08% in Malta).

It is interesting to note that in the landlocked EU countries the value of land increases anyway. This effect is not due to a direct loss of productive land, but to land scarcity at the EU level which, increasing agricultural prices EU wide, increasing rents. Although land is not mobile internationally, international trade of agricultural products (and more generally of other goods and services) allows a partial equalisation of factor prices across countries.

Moreover, the GDP result is not always negative. In 7 cases, prevalently in older EU countries, slight GDP gains are experienced (ranging from 0.009% for Sweden to 0.005% for Cyprus). Here the initial negative impact on land is contrasted by two different mechanisms: (a) international capital flows, and (b) international trade flows. These are discussed in more detail below.

International capital flows are driven by the relative price of capital in each country. The higher the capital return, the higher the share of international investments flowing into a country, with positive implications in terms of regional GDP variations, since investment is one component of GDP.

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[3] This also explains why under the adaptation scenarios some countries like Belgium, Estonia or Denmark experience positive and non negligible land losses.

Table 7 A2 Scenario, High Sea-level Rise 2085. Main Macroeconomic Indicators (no adaptation)

	Land losses			GDP (*)	Investment (*)	Terms of trade (*)	Per Capita Utility (*)
	% of country total	Value (Million $)	Value as% of GDP				
Austria	0	0	0	−0.0036	0.194	−0.001	−0.005
Belgium	−0.023	0.17	0.000017	−0.0042	0.155	−0.011	−0.012
Denmark	−1.241	26.74	0.004674	0.0022	0.234	0.059	0.026
Finland	−0.002	0.05	0.000012	−0.0004	0.295	0.041	0.016
France	−0.331	111.44	0.002411	0.0045	0.271	0.068	0.024
Germany	−0.936	391.60	0.005705	0.0028	0.282	0.054	0.021
UK	−1.173	77.23	0.001435	−0.0039	0.259	0.016	0.000
Greece	−3.542	203.04	0.032805	−0.0299	0.125	0.090	−0.008
Ireland	−2.706	104.51	0.027093	−0.0139	0.138	0.036	0.015
Italy	−0.605	60.05	0.001732	0.0026	0.275	0.060	0.019
Luxembourg	0	0	0	−0.0033	0.113	−0.025	−0.017
Netherlands	−0.639	24.69	0.001566	−0.0003	0.224	0.085	0.030
Portugal	−0.677	30.80	0.005619	−0.0065	0.130	−0.028	−0.020
Spain	−0.186	13.52	0.000569	−0.0094	0.234	0.082	0.013
Sweden	−0.099	2.25	0.000308	0.0009	0.292	0.037	0.016
Cyprus	−2.182	1.50	0.002532	0.0056	0.141	−0.054	−0.023
Czech Rep	0	0	0	−0.0008	0.043	−0.013	−0.012
Estonia	−1.636	11.76	0.038573	−0.0448	−0.301	−0.047	−0.097
Hungary	0	0	0	−0.0017	0.084	0.047	0.035
Latvia	−0.770	4.64	0.008035	−0.0078	0.007	−0.025	−0.038
Lithuania	−0.096	2.34	0.002174	−0.0061	0.034	0.009	−0.005
Malta	−12.806	12.73	0.062321	−0.0827	−0.169	−0.025	−0.104
Poland	−1.014	483.21	0.032823	−0.0464	−0.331	−0.112	−0.087
Slovakia	0	0	0	−0.0056	0.151	0.008	−0.001
Slovenia	−0.027	0.16	0.000228	0.0015	0.105	−0.020	−0.013
ROW	−1.411	61 669.89	0.028866	−0.0317	−0.069	−0.011	−0.036
World prices of food and agriculture			1.16				
World prices of energy commodities			−0.03				

(*) Values expressed as % changes wrt A2 2085 baseline

Interestingly in the western EU investment inflows are generally higher than in the New Member countries among which Malta, Poland and Estonia experience capital outflows. Two countervailing effects are at play. GDP losses induced by the negative shock lower the value of national resources, including capital. At the same time economies can substitute land with capital, capital supply is fixed in the short run, and this translates into higher capital returns. This second effect seems to prevail in the western EU, while the first effect prevails in the new member countries.. This stresses also the importance of primary factor substitution possibilities within economic systems: the higher flexibility of the more developed economies help them to more easily smooth the initial negative shock, or even turn it into an economic gain. Finally, the EU as a whole is a net attractor of foreign capital from the ROW aggregate in which the fall in the relative price of capital services is particularly strong.

Table 8 A2 Scenario, High Sea-level Rise, 2085. Main Macroeconomic Indicators (with adaptation)

	Land losses (% of country total)	Coastal Protection Expenditure as% of GDP	Investment (induced by coastal protection)	Private Consumption	GDP	Terms of trade	Per Capita Utility
Austria	0	0	0	−2.105	−0.218	−0.670	−0.513
Belgium	−0.022	0.0008	0.297	−2.789	−0.041	−0.842	−0.491
Denmark	−0.729	0.0844	39.083	−3.793	0.825	4.145	2.613
Finland	−0.001	0.0133	6.142	−5.157	−0.540	−0.523	−0.642
France	−0.007	0.0100	4.974	−2.699	−0.104	−0.268	−0.120
Germany	−0.046	0.0090	4.082	−2.670	−0.143	−0.294	−0.186
UK	−0.005	0.0126	6.679	−0.744	0.008	0.595	0.207
Greece	−0.056	0.0241	8.774	−0.181	0.086	1.571	0.654
Ireland	−0.011	0.0481	19.803	−10.702	−0.432	0.469	0.204
Italy	−0.019	0.0061	2.794	−2.228	−0.112	−0.618	−0.237
Luxembourg	0	0	0	−1.804	−0.070	−0.518	−0.337
Netherlands	−0.301	0.0305	11.378	−2.467	0.186	1.310	0.831
Portugal	−0.021	0.0262	9.356	−1.769	0.119	1.117	0.577
Spain	−0.001	0.0082	2.946	−3.089	−0.071	−0.975	−0.289
Sweden	−0.0001	0.0148	7.351	−4.615	−0.247	−0.382	−0.308
Cyprus	0	0.0262	10.733	0.775	0.101	3.090	1.472
Czech Rep	0	0	0	−3.573	−0.130	−0.344	−0.324
Estonia	−0.217	0.2133	83.751	−3.629	0.596	2.784	3.789
Hungary	0	0	0	−3.776	−0.299	−0.692	−0.730
Latvia	−0.005	0.0500	16.777	−0.072	0.079	1.962	1.432
Lithuania	−0.035	0.0097	4.784	−0.101	0.011	0.598	0.391
Malta	0	0.0063	2.552	2.708	0.258	0.815	0.891
Poland	−0.002	0.0036	1.994	−0.966	−0.013	−0.090	−0.013
Slovakia	0	0	0	−3.317	−0.045	−0.261	−0.192
Slovenia	0	0.0008	0.288	−3.602	−0.024	−0.437	−0.215
ROW	−0.159	0.0167	7.788	−2.634	0.004	0.001	0.081
World prices of food and agriculture			0.41				
World prices of energy commodities			0.24				

All values expressed as % changes wr A2 2085 baseline except coastal protection expenditure in% of GDP

International trade flows influence the terms of trade. In particular, two main effects are at work here: higher world prices for agricultural commodities benefit net-exporters of agricultural goods, whereas lower prices for oil, gas, coal, oil products, electricity, and energy-intensive industries, driven by the overall decrease in aggregated demand, benefit the net importers of raw materials and energy products. EU countries are expected to benefit from this situation compared to the ROW, and indeed terms of trade generally improve. However, within the EU, gains are again predominant in the EU15 while among new member countries only in Hungary, Lithuania and Slovakia do the terms of trade ameliorate.

Interesting insights can be obtained also by the comparison of the direct cost of land loss with the final GDP effects. In 15 cases, GDP losses are higher than direct costs (including the 5 countries where no land is lost, but the GDP change is negative). In the 10 remaining cases the opposite happens. This encompasses the 7 countries experiencing GDP gains and a further 3 cases. Moreover, there is no direct relationship between the environmental impact and the economic impact as the initial rank of winners and losers eventually changes. This highlights the importance of considering these indirect effects via a general equilibrium analysis, as substitution effects and international trade work as impact buffers or multipliers.

In the optimal adaptation scenario, there is a smaller negative economic shock — since the stock of land resources is optimally preserved — which coexists with a change in the structure of final demand, because investment increases and household consumption decreases.

In absolute terms, optimal coastal defence can be extremely costly. For example, the UK spends a total of US$ 44.5 billion (undiscounted) over the period 2001 to 2085, which is the highest expenditure in the EU. However, on an annual basis, and compared to national GDP, these costs are quite small. On a relative basis, the highest value is represented by the 0.2% of GDP in Estonia. Coastal protection, in its turn, fosters investment in all the countries with a vulnerable coast. Investment thus increases from a minimum of the 0.28% in Slovenia to a maximum of the 83% in Estonia. To meet this extra demand for investment, all regions increase their savings, reducing at the same time the share of income devoted to private consumption. This pattern is especially strong in Ireland (−10%) and Finland (−5%). The impact on country GDP is mixed. There are 11 countries that gain (from the 0.008% of UK to the 0.8% of Denmark), while all other regions lose slightly (from the −0.01% of Poland to the −0.54% of Finland).

These outcomes depend on the interplay between the initial land loss, the additional investment demand and the decrease and re-composition of private consumption demand. The countries that attract relatively higher additional investment, benefit in terms of trade improvements and usually experience a smaller contraction of private consumption. The role of consumption in sustaining GDP is quite important. Emblematic is the case of Ireland where high investment and terms of trade gains are not able to compensate for the crowding out of private consumption, with negative implications for GDP.

As a concluding remark: by inspecting the general equilibrium impacts of coastal protection, one could conclude that for 12 EU countries no protection would be better than protection. This result however should be interpreted with caution considering that: (1) the model is static, thus the expansive role of investment fostered by coastal defence is only partly captured; (2) GDP impacts neglect completely property losses as GDP only measures the flows of goods and services produced by a country and not the change in its factor endowments; and (3) the study only models losses incurred by the agricultural sector disregarding effects on infrastructure and population.

5 Concluding remarks and policy implications

In this paper, we use the DIVA model to estimate the physical impacts of sea-level rise and the direct economic cost. We use the GTAP-EF model to assess the wider economic implications. Land losses due to submergence are much larger than land losses due to erosion. Coastal protection is very effective in preventing forced migration, even under a high sea-level rise scenario. Adaptation also reduces the residual impacts of sea-level rise by an order of magnitude. While the direct economic impact of sea-level rise is zero or negative, the total economic impact may be positive or negative. This is firstly because of international trade, which also means that landlocked countries such as Austria are affected indirectly by sea-level rise. Countries that have relatively small direct impacts of sea-level rise gain in competitiveness, and this may more than offset the initial negative effects. Investment is the other crucial higher-order impact of sea-level rise. While forced investment in coastal protection is bad for the overall economy, it also provides a stimulus for the construction sector. As coastal protection is localised, this effect would in fact stimulate local and regional economies — and in the case of Europe, it would stimulate the economies of some smaller countries.

The results come with a number of caveats. We used two models only, one for each stage of the impact assessment, and other modellers should test the robustness of our findings. Indeed an extensive set of sensitivity analyses is a logical next step. The results are as complete as the models that we used and thus omit some of the effects of sea-level rise, particularly the interactions between possible changes in storms and sea-level rise, and between tourism and sea-level rise. More adaptation options could also be considered. We omitted the economic impacts of the loss of coastal wetlands, and ignored migration in the world outside of Europe. All of these issues are referred to future research.

The policy implications are threefold. First, sea-level rise has negative economic effects but, given the above caveats, these effects are not particularly dramatic. Second, the impact of sea-level rise is not confined to the coastal zone and sea-level rise indeed affects landlocked countries as well. Third, adaptation is crucial to keep the negative impacts of sea-level rise at an acceptable level. This may well imply that some European countries will need to adopt a coastal zone management policy that is more integrated and more forward-looking than is currently the case. Similar conclusions have been found based on national scale assessments (Tol et al. 2008).

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