Environ Resource Econ (2016) 65:813–839
DOI 10.1007/s10640-015-9927-8

Physical and Economic Consequences of Sea-Level Rise: A Coupled GIS and CGE Analysis Under Uncertainties

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Accepted: 8 June 2015 / Published online: 24 July 2015

Abstract This paper develops a modelling framework that links GEMINI-E3, a multi-regional, multi-sectoral computable general equilibrium model with a cost-benefit analysis approach at local level using geographical information system tools to assess the physical and economic consequences of sea-level rise (SLR) in the twenty first century. A set of future scenarios is developed spanning the uncertainties related to global warming, the parameters of semi-empirical SLR estimates, and coastal developments (cropland, urban areas and population). The importance of incorporating uncertainties regarding coastal development is highlighted. The simulation results suggest that the potential development of future coastal areas is a greater source of uncertainty than the parameters of SLR itself in terms of the economic consequences of SLR. At global level, the economic impact of SLR could be significant when loss of productive land along with loss of capital and forced displacement of populations are considered. Furthermore, highly urbanised and densely populated coastal areas of South East Asia, Australia and New Zealand are likely to suffer significantly if no protective measures are taken. Hence, it is suggested that coastal areas needs to be protected to ameliorate the overall welfare cost across various regions.

Keywords Climate change · Sea-level rise · GIS · Computable general equilibrium model · Coastal impacts · Uncertainty · Adaptation

JEL Classification C68 · D58 · Q54

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1 Introduction

Sea-level rise (SLR) could have significant physical impacts on coastal zones and islands, with potentially high economic consequences (Bosello et al. 2007; Nicholls and Cazenave 2010; Ackerman and Stanton 2011; Hallegatte et al. 2013). The Fifth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC 2013) predicts that global sea level is likely to rise by between around 25 cm and 1 m by 2100 in response to increased ocean warming and loss of mass from glaciers and ice sheets. Uncertainties in SLR arise not only from uncertainties in emissions but also from physical climate parameters. Projected regional changes of sea level can be up to 100 % larger than global averages but in most regions are expected to be similar to global mean values. This global rise of sea level will contribute to increased coastal inundation and erosion, ecosystem loss, saltwater intrusion in surface and groundwater resources and damage of infrastructures across different regions.

With nearly two-fifths of the world population living in coastal zones, flooding from SLR and storm surges has the potential to prompt large-scale migration of human populations, together with political instability, and could cause devastating loss of homes, businesses, infrastructures, and coastal shallow-water ecosystems (Ackerman and Stanton 2011). According to a foresight report by the UK government office for science, these problems may be further exacerbated in the coming decades by net migration that in many cases is towards environmentally vulnerable regions rather than away from them (Foresight 2011; Black et al. 2013). The overall impacts of SLR include the direct implications of SLR for coastal populations and regions as well as consequent indirect effects in terms of potential disruption in the economic activities in other inland regions. Nevertheless, societies have options to protect, accommodate and retreat from possible SLR impacts (Fankhauser 1995). There is much less understanding of retreat and accommodation costs compared to protection cost for which there exists a long history of coastal management and engineering experience (Nicholls et al. 2010). Furthermore, there will be a multitude of protection options including sea and river dikes, beach/shore improvements, port upgrades and land use planning. The trade-off is between the costs of protection on the one hand, and the value of the land at threat on the other hand, but it should also take into account that protection walls lead to a reduction in the damage from storm surges, while on the other hand they accelerate the loss of valuable wetlands by inhibiting them from migrating inland (Fankhauser 1995).

It is evident that SLR could be a significant problem if it is ignored, and hence it needs to be considered within the policy process on climate change in terms of mitigation and adaptation (Nicholls 2002). Without proper mitigation and adaptation strategies, the economic consequences of SLR could be immense depending on local socio-economic and geographical conditions. It is evidently not feasible to study all vulnerable coastlines in the required detail, and a global assessment of SLR damage will therefore necessarily have to be based on a top-down approximation (Fankhauser 1995). There are only a few studies that look at the general equilibrium effects of SLR (Darwin and Tol 2001; Deke et al. 2001; Bosello et al. 2007, 2012). Darwin and Tol (2001) have suggested that the results from such models could be significantly more realistic than simpler approaches considering only direct economic impacts and ignoring the effects of variations in prices and international trade. A recent study by Bosello et al. (2012) addresses adaptation costs and indirect economic effects of land loss due to SLR at a European level. In addition to land area loss, it is also necessary to take into account the vulnerability of population and assets while estimating the economic cost of SLR (Hallegatte et al. 2013).

Bosello and De Cian (2013) reviewed the different modelling approaches in the study of the impacts of sea-level rise and stressed the need for improving the communication between bottom-up and top-down methodologies. In this study, we address the physical and economic consequences of SLR for different regions across the world by combining a computable general equilibrium (CGE) model and cost-benefit analysis with a geographical information system (GIS) tool considering different levels of uncertainties. The importance of such linkages between spatial and macroeconomic data is emphasized in the paper by Nordhaus (2006). There are so far only a few studies (Chen et al. 2000; Ludeña et al. 2009; Farinosi et al. 2012; Carrera et al. 2014) that have attempted such a link. We note that, in addition to the loss of productive land for the agricultural sector, potential effects on physical capital and the labour force caused by forced displacement are also considered in this paper. The next section describes the methodological framework, models and methods used in this paper. Section 3 explains the uncertainties regarding the impacts of SLR. Section 4 presents simulation results and analysis. Finally, some conclusions and recommendations are discussed in Sect. 5.

2 Methodological Framework

The methodological framework used to analyze the potential physical and economic consequences of SLR is shown in Fig. 1. The temperature profile required to calculate SLR is provided by the climate model Planet-simulator—efficient numerical terrestrial scheme (PLASIM-ENTS) (Sect. 2.2.1) and a semi-empirical relationship developed by Rahmstorf et al. (2012) is used to calculate SLR. Then, physical impacts of SLR specifically on agricultural land area loss, capital loss, and people affected are estimated using GIS tools at each coastal segment.[1] These impacts are then incorporated in the CGE model GEMINI-E3 to conduct economic analysis without protection cost. In the case of economic analysis, first, a cost and benefit model is developed to evaluate the protection cost incurred by cropland area loss, urban area loss and number of people affected and then this information is implemented in GEMINI-E3. Models and methods used for the analysis are described in the following sections.

2.1 General Equilibrium Model: GEMINI-E3

GEMINI-E3[2] (General Equilibrium Model of International-National Interactions between Economy, Energy and Environment) is a multi-country, multi-sector, recursive dynamic CGE model comparable to the other CGE models (EPPA and ENV-Linkage) built and implemented by other modelling teams and institutions, and sharing the same long experience in the design of this class of economic models (Bernard and Vielle 2008). The standard model is based on the assumption of total flexibility in all markets, both macroeconomic markets such as the capital and the exchange markets (with the associated prices being the real rate of interest and the real exchange rate, which are then endogenous), and microeconomics or sector markets (goods, factors of production). The model assumes that capital and labour are immobile across regions. Although labour endowment used in scenarios takes into consideration migration assumptions that are derived from UN projection data (United Nations and Social Affairs,

[1] Coastal segments are independent from each other and vary in length, hence the larger the length of coastal segment, the greater the cost of protection.

[2] All information about the model can be found at http://gemini-e3.epfl.ch, including its complete description.

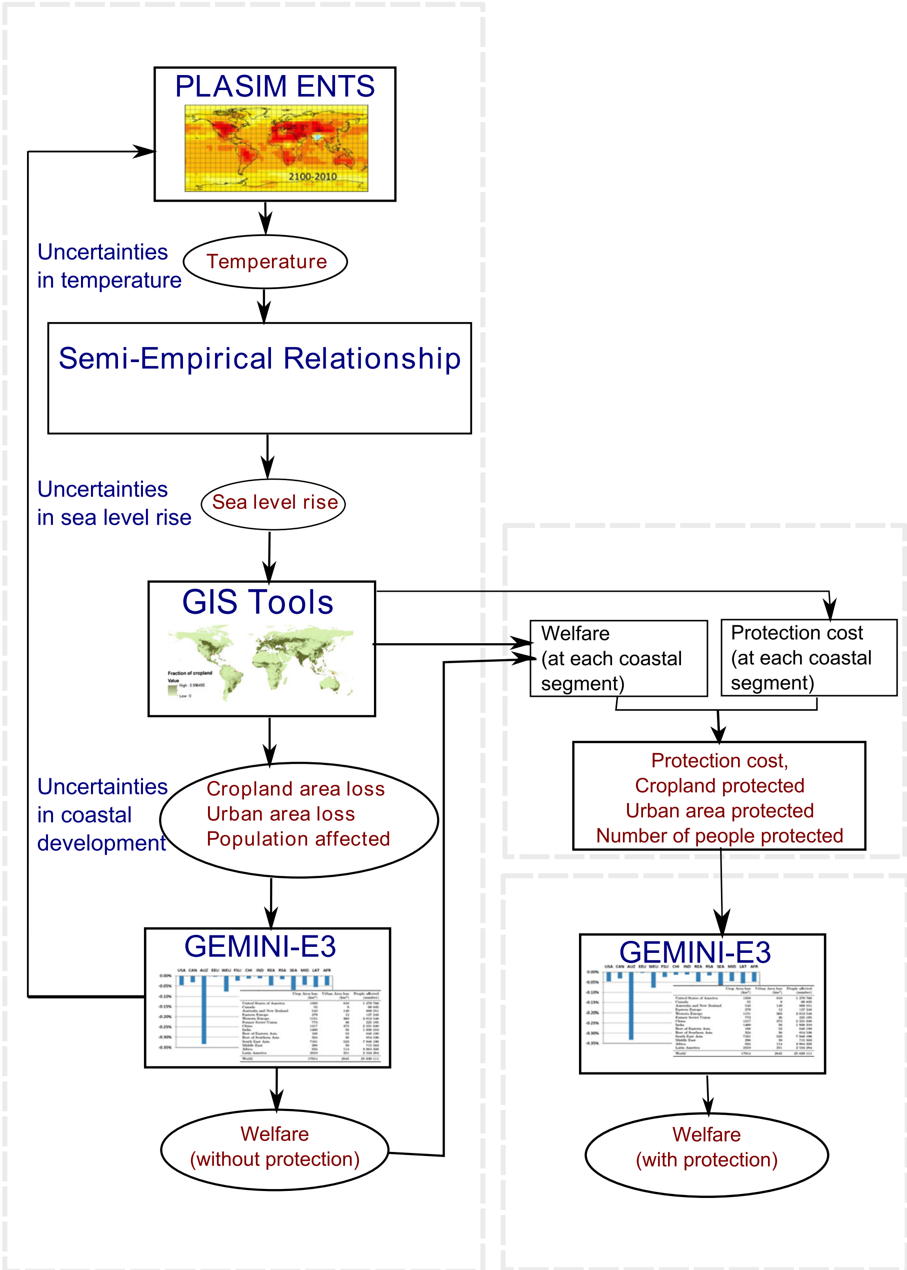

Fig. 1 Methodological framework

2011), we nevertheless assume that SLR will not affect migration across the 14 regions described by GEMINI-E3.

The GEMINI-E3 model used in this paper is built on the GTAP-8 database (Narayanan et al. 2012). This database incorporates a consistent representation of energy markets in

Table 1 Dimensions of the GEMINI-E3 model

Regions	Energy sectors/goods
Africa (AFR)	01 Coal
Australia and New Zealand (AUS)[a]	02 Crude oil
Canada (CAN)	03 Natural gas
China (CHI)	04 Refined petroleum
Eastern European Countries (EEU)	05 Electricity
Former Soviet Union (FSU)	Non-energy sectors/goods
India (IND)	06 Forestry
Latin America (LAT)	07 Mineral products
Middle East (MID)	08 Chemical, rubber, plastic
Rest of Eastern Asia (REA)	09 Metal and metal products
Rest of Southern Asia (RSA)	10 Paper products, publishing
South East Asia (SEA)	11 Land transport
United States of America (USA)	12 Sea transport
Western European Countries (WEU)	13 Air transport
	14 Consuming goods
Primary factors	15 Machinery and equipment goods
Labour	16 Services
Capital	17 Dwellings
Energy resource (sectors 01-03)	18 Construction
Land (sectors 06, 20-24)	19 Water
	20 Paddy rice
	21 Wheat
	22 Cereals
	23 Oilseeds
	24 Rest of agriculture sectors

[a] The region Australia and New Zealand also includes Oceanic countries

physical units, social accounting matrices for each individual country/region, and the whole set of bilateral trade flows. Carbon emissions are computed on the basis of fossil fuel energy consumption in physical units. For the modelling of non-CO_2 greenhouse gas emissions (Methane: CH_4, nitrous oxide: N_2O and fluorinated gases), we employ region and sector-specific marginal abatement cost curves and projection of emissions provided by the US-EPA (U.S. Environmental Protection Agency 2011, 2012). The sectoral and regional classifications used in this paper are presented in Table 1.

Reference scenarios in GEMINI-E3 are built on the basis of (1) projections (or assumptions) on population and economic growth in the various countries/regions, (2) energy prices in the world markets, particularly the oil price and (3) national (energy) policies. We have used the UN median variant to project population (United Nations and Social Affairs United Nations and Social Affairs 2011). Data from the International Energy Outlook (Energy Information Administration 2013) and TIAM-WORLD (TIMES Integrated Assessment Model) (Labriet et al. 2013) are used to project GDP growth and energy prices. We build a reference baseline for the period 2007-2100 with yearly time-steps. In terms of emissions, our reference baseline (or Business As Usual, BAU) is closely related to representative concentration pathways (RCP) 6.0 (Vuuren et al. 2011) up to 2080. After this year, carbon emissions continue to grow in our model, where no climate constraint is imposed, contrary to RCP 6.0.[3]

Incorporating SLR impacts in GEMINI-E3 In this paper, (1) loss of cropland area, (2) capital loss, (3) number of people affected and (4) investments in protection measures are simulated in GEMINI-E3 to investigate the impacts of SLR on national/regional economies. This is implemented through reducing the land endowment, capital stock and labour supply, which is exogenous in the model. The costs of migration and those of building housing, infrastructure and dikes are financed by government by direct taxation on households in the GEMINI-E3 model. This is usually the case as coastal adaptation measures are led by the government and much of the cost is financed by the government (Nicholls et al. 2010). Other economic impacts including costs related to uplift and subsidence, investment in beach/shore improvements, port upgrades and dike maintenance are not considered in this paper. Also, note that we do not consider the non-market value of coastal land. The ecosystem services provided by coastal land are diverse; they range from recreation activities to biodiversity conservation including ecological production of goods and services. Barbier et al. (2011) point out that improving the assessment of the valuation of these ecosystem services should be a top priority of their management. By omitting these values, we certainly underestimate the cost of lost land.

Modelling Agricultural Land Area Loss In GEMINI-E3, factor inputs for manufacturing and service sectors are materials, energy, labour and capital. In addition to these factor inputs, land is also used as a factor of production of agricultural products. Loss of cropland can thus be easily incorporated in the model by exogenously reducing land endowment of various economies in accordance with SLR impacts.

Modelling Capital Loss Similarly, capital loss is implemented exogenously through a decrease in capital endowment. As loss in capital is difficult to estimate we assume that capital loss is proportional to the loss in urban area (thus a 10 % decrease in urban areas results in a 10 % decrease in capital) that can be estimated with relative ease using GIS tools.

Modelling Number of People Affected The revenue required by the government for resettlement of coastal inhabitants and related costs, and the decrease in labour supply related to the number of people affected are also considered in this paper. In the literature (e.g. Tol 2002a, b; Nicholls et al. 2011a), a commonly used approximation asserts that the cost of the permanent displacement of a person including the related cost of rebuilding houses and infrastructure is three times the GDP per capita of the affected country. The same assumption is used here and we further assume that the government finances these displacement costs through an increase of direct taxation on households. In the case of labour supply, one year of labour is lost for the number of people affected in the labour force by sea-level rise.

2.2 Estimating Sea-Level Rise

2.2.1 Climate Model: PLASIM-ENTS Emulator

To estimate SLR, we first use the emulator of the climate model PLASIM-ENTS (Holden et al. 2014) to compute the warming profile related to the GEMINI-E3 baseline scenario. PLASIM-ENTS is the Planet Simulator (Fraedrich et al. 2005) coupled to the ENTS vegetation and

[3] Note that the BAU concentration profile is computed by the climate module of GEMINI-E3 whose carbon cycle model differs from the one used for RCPs. Thus, even if BAU and RCP emissions are close, the BAU concentration profile differs from the RCP6.

land surface model (Williamson et al. 2006), here run at T21 resolution (approximately 5°). PLASIM-ENTS has a 3D dynamic atmosphere, flux-corrected slab ocean, flux-corrected slab sea ice and dynamic coupled vegetation. The validations of both PLASIM-ENTS and its emulator PLASIM-ENTSem are described in detail in Holden et al. (2014). We note that the slab sea ice was held fixed in the simulations used to build the version of the emulator used here, which predates the configuration described in Holden et al. (2014). The emulator performs generally very well in capturing the spatial variability and magnitude of warming simulated by more complex models, but the neglect of the sea-ice feedback in this configuration results in understated DJF (December-January-February) warming in the Arctic, and this leads to conservative projections of globally averaged warming. Under GEMINI-E3 BAU forcing, this neglect of sea-ice feedbacks understates globally averaged warming by 0.2 °C in 2050 and by 0.5 °C in 2100.

PLASIM-ENTSem is built from an ensemble of simulations of PLASIM-ENTS corresponding to 188 separate input parameter sets, varying 22 key atmospheric, vegetation, sea-ice and ocean parameters. These parameterisations were selected to widely sample from reasonable input parameter space but are each constrained to produce a reasonable modern climate state. See Holden et al. (2014) for a detailed description of the ensemble design approach and philosophy. When we apply the emulator, we calculate the emulated warming that is associated with each of the 188 parameterisations. The spread of warming across this 188-member ensemble was shown in Holden et al. (2014) to be comparable to the range of warming of the CMIP5 (Coupled Model Intercomparison Project Phase 5) ensemble of high-complexity model simulations. The emulated ensemble therefore allows us to provide meaningful uncertainty estimates for the warming associated with the GEMINI-E3 baseline scenario. We incorporate this into our uncertainty analysis of the SLR projections.

2.2.2 Semi-empirical Relationship for SLR

In the research conducted by Rahmstorf (2007), the projection of global SLR in 2100 is 0.5 to 1.4 metres compared to 1990. A variety of different approaches (physically based and semi-empirical) and assumptions (thermal expansion, glacier melting and polar ice sheet mass) results in a wide range of global SLR estimates. The range of future climate-induced SLR remains highly uncertain with continued concern that large increases during the twenty-first century cannot be ruled out (Nicholls et al. 2011b). Rahmstorf (2007) argued that given the complexity involved in modelling the physically based projections of SLR, the semi-empirical models can provide a pragmatic alternative to estimate SLR. However, one must be aware of the assumptions made in such an approach where the observed relationship between temperature and SLR of the past is assumed to be continued in the future, which may not be the case. Nordhaus (2010) found that the RICE model projection of SLR is in the middle of the range of alternative estimates from semi-empirical methods developed by Rahmstorf (2007). In Rahmstorf et al. (2012) the authors calibrate and compare about 30 semi-empirical links between global temperature and global sea level, $S(t)$, each one based on different equations, assumptions and data sets for temperature and sea level with different statistical techniques. They conclude that the most relevant semi-empirical relationship is given by

$$\frac{\mathrm{d}S}{\mathrm{d}t} = a(T(t) - T_0) + b\frac{\mathrm{d}T}{\mathrm{d}t} \tag{1}$$

with $a = 5.6$ mm/year/°C, $b = -66$ mm/°C and $T_0 = -0.43$ °C. T is the global mean temperature (computed by PLASIM-ENTS emulators in our analysis) and T_0 is the previous equilibrium temperature value. This model version includes adjustments both for the reservoir storage and the most recent estimate of groundwater pumping, and appears to give the best fit over the calibration period used in Rahmstorf et al. (2012). We use this relationship in this paper.

2.3 Estimating Physical Impacts Using GIS Analysis

In this section, we derive a GIS approach to estimate agricultural land area loss, urban area loss and number of people affected. We first use the model GTOPO30[4] which is a global digital elevation model with a horizontal grid spacing of 30 arc seconds (approximately 1 km) developed by the U.S. Geological Survey by combining a number of source datasets with varying horizontal resolution and vertical elevation accuracy. The estimated vertical elevation in GTOPO30 is given to the nearest metre above mean sea level with all lowland coastal cells being assigned an elevation of at least 1 m. To determine the impact of SLR, grid cells located at an altitude of 1 metre are extracted using ArcGis. This information is then used to calculate cropland area loss, urban area loss and number of people affected due to 1 metre of SLR in all coastal regions. This is the best available source of information at the global scale; however, higher accuracy in the vertical elevation data would give more accurate measurements of the physical impact of sea-level rise. The global coastal region is divided into 27,992 coastal segments using the GIS tool. We use then simple linear interpolation techniques to estimate crop land area loss, urban area loss and number of people affected for SLR <1 m.

Loss in agricultural land area is calculated using a land-use database developed within the Representative Concentration Pathways (RCP) project.[5] These harmonized data (Hurtt et al. 2011) represent fractional land-use patterns and underlying land-use transitions annually for the past (1500–2005) and the RCPs (2005–2100) at $0.5° \times 0.5°$ resolution. The database includes transitions between cropland, pasture, primary and secondary (recovering) land, including the effects of wood harvest and shifting cultivation, as well as land-use changes and transitions from/to urban land. We estimate the land area loss for agriculture sectors with the cropland area loss in the scenario RCP 6.0 which is very close to GEMINI-E3 BAU. Similarly, the database for urban area is taken from the land-use RCP database.

The number of people affected by SLR is calculated using a gridded population dataset. We use the Global Rural-Urban Mapping Project, version 1 (GRUMPv1) (Center for International Earth Science Information Network et al. 2004). This database consists of human population estimates for the years 1990, 1995, and 2000 by 30 arc-second (approximately 1 km) grid cell. After the year 2000, we use the median-fertility variant of the UN population projection data (United Nations and Social Affairs 2011) for each country (or region) for each year until 2100. Population growth rates are defined and used at the country level such that each grid cell uses an appropriate country-level value. This assumption makes it possible to project the population density at local level but cannot capture the movement of people from one location to other within the country.

2.4 Estimating Damage and Protection Costs: A Combined GIS/CGE Approach

To estimate adaptation cost related to a given scenario of SLR and future coastal developments, first, the costs of potential damages of SLR and the costs of possible adaptation measures have to be estimated. Then, these two sets of costs can be used at the local scale

[4] For more details refer to http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/gtopo30.

[5] For more details refer to http://www.iiasa.ac.at/web-apps/tnt/RcpDb/dsd?Action=htmlpage&page=welcome.

(coastal segments) to decide whether adaptation is required or not. In this study, the only adaptation option considered is the construction of dikes, which, if constructed, are assumed to perfectly protect all the land below the threshold altitude behind the relevant coastal segment. The cost of damage depends on the cropland area, urban area and number of people affected in each coastal segment. In order to estimate the adaptation cost (i.e. cost of building dikes) at each coastal segment, first we need to estimate the physical impacts of SLR on coastal cropland, urban area and population also at each coastal segment. This is achieved by using ArcGIS analytical tools as described in the previous section. Then, the following steps are taken at each decade:

- Firstly, the share of cropland, urban area, number of people affected and coastal length of each segment is determined using analytical tools within ArcGIS.
- Secondly, the share of cropland area, urban area and number of people affected are multiplied by the respective welfare cost[6] that is calculated from GEMINI-E3 separately. The total damage cost at each coastal segments is the sum of damage cost for all the three cases. The damage cost can be represented as $D_s = SC_s.WC_i + SU_s.WU_i + SP_s.WP_i$, where WC_i, WU_i and WP_i are the welfare costs due to cropland area loss, urban area loss and number of people affected in the region 'i' respectively; SC_s, SU_s and SP_s are the share of cropland area loss, urban area loss and number of people affected in each segment, 's' (with $s \in i$), respectively.
- Thirdly, the protection cost is determined by multiplying the coastal length of each segment by the cost of building dikes per unit length of coastline. The cost of building dikes is taken from the Global Vulnerability Assessment (GVA) report (Hydraulics 1993) where it is estimated to equal 11.5 million 2007 US$ per km. In reality, however, there are large variations in the costs of dike building depending on local economic factors, design choices and types of measures in rural or urban environment. Jonkman et al. (2013), explores three cases (The Netherlands, New Orleans and Vietnam) but detailed information on variations in protection cost at global scale are lacking. Therefore, to address the effects of possible variations of protection cost, a basic sensitivity analysis is carried out here by dividing and multiplying the protection cost from the GVA report by two.
- Finally, the decision to protect is taken at the start of each decade depending on whether the protection cost at the beginning of the decade is lower or higher than the total damage cost for that decade. For example, if the protection cost in the year 2010 is less than total damage cost from the year 2011 to 2020 then it is decided to protect at each segment of coastal region in the year 2010, otherwise it is not protected.

It is to be noted that the cost-benefit approach taken in this paper is a theoretical exercise. The approach we have used takes into account high-resolution spatial physical data (cropland, urban areas, number of people) but does not take into account the details of local environmental, socio-economic and political factors. Policy recommendations derived using such an approach need to be viewed with caution. In the model, the cost of coastal protection is financed by the government through revenue collected from increases in direct taxation on households. It is a way to introduce in a recursive dynamic CGE model a proactive investment to limit the weaknesses of CGE relative to inter-temporal feedback as pointed out by Wing and Lanzi (2014).

[6] Like other general equilibrium models, GEMINI-E3 assesses the welfare cost of scenarios through the measurement of the households surplus. We give the welfare change in absolute value (i.e. US $) but also in relative term by dividing it by the household consumption. To compare our results with those of other published studies that use other economic indicators, it should be noted that in these scenarios the welfare change divided by household consumption is close to the percentage change of household consumption, the relative prices being not significantly affected by the sea-level rise.

3 Uncertainties Concerning Impacts of Sea-Level Rise

The physical and economic impacts of SLR depend on two main factors that are highly uncertain, (1) the amplitude of SLR itself which depends on uncertain climatic factors including ocean thermal expansion and glacial melting, driven principally by global warming, and (2) the future development of coastal areas. In this section, we propose to address these uncertainties by developing a set of representative scenarios of the possible evolution of these factors. Nonetheless, there are also other uncertainties related to sea-level rise coming from soil erosion, subsidence and storm surges that are not considered in this study.

3.1 Temperature: PLASIM-ENTS Emulators

The primary driver for global SLR is global warming. In order to generate contrasted SLR scenarios for our sensitivity analysis, we consider three possible profiles of warming for the GEMINI-E3 BAU scenario that are computed by the PLASIM-ENTS emulator. Recall that for a given concentration profile over the period 2000-2100, the PLASIM-ENTS emulator provides indicators of global warming resulting from forward integration starting from 188 plausible modern climate states, each state differing in the setting of 22 key atmospheric, vegetation, sea-ice and ocean parameters (Holden et al. 2014). The main indicator corresponds to the average warming computed in these 188 states. The PLASIM-ENTS emulator also produces data on warming uncertainty summarised through the percentiles of the distribution. In Fig. 2, we display the average temperature increase as well as the 10 and 90 % percentiles relative to the BAU concentration profile. Thus, for our sensitivity analysis, we selected:

- Minimum (Mn): a low warming scenario corresponding to the 10 % percentile;
- Maximum (Mx): a high warming scenario corresponding to the 90 % percentile;
- Average (Av): the average warming scenario.

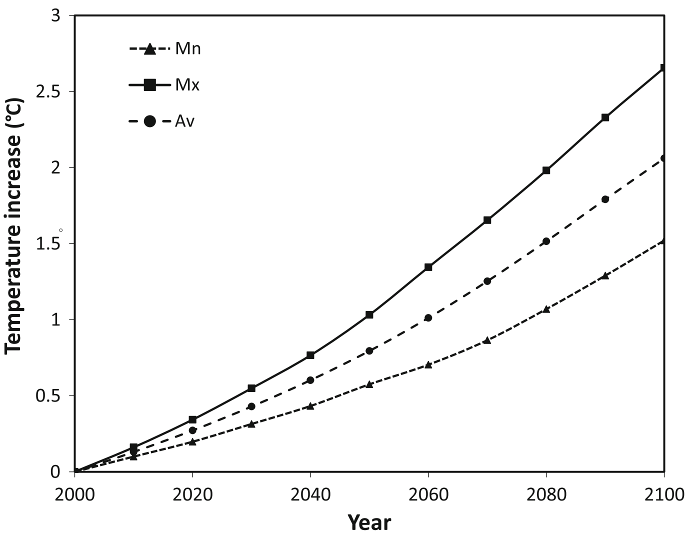

Fig. 2 Global temperature increase in degree Celsius (base year 2000)

Table 2 Uncertain parameters of sea-level rise

	Minimum (Mn)	Average (Av)	Maximum (Mx)
a (mm/year/°C)	4.8	5.6	6.3
b (mm/°C)	−98	−66	−34
T_0 (°C)	−0.53	−0.43	−0.33

As we will use the area between percentiles 10 and 90 % containing 80 % of the 188 plausible climate states, our study will allow us to quantify economic impacts of SLR with a 80 % confidence interval (with respect to temperature increase uncertainty).

3.2 Sea-Level Rise: Parameters of Semi-empirical Relationship

A second source of uncertainty affecting our model-projected SLR is the SLR prediction model itself. In this paper, we use the semi-empirical relationship (Eq. 1) developed by Rahmstorf et al. (2012) to convert global temperatures into SLR estimates. We therefore have to capture the uncertainties in this particular model for SLR. In their study, the authors determine the parameters of the semi-empirical link between global temperature and global sea-level in a wide variety of ways, using different equations, different data sets for temperature and sea level as well as different statistical techniques. In Rahmstorf et al. (2012), the authors also report calibration errors, σ, for these parameters making it possible to define three contrasted models corresponding to minimum (Mn), average (Av) and maximum (Mx) values of parameters a, b and T_0 (see Table 2). For each parameter, we compute extreme values corresponding to the bounds of its 95 % confidence interval (i.e. average value $\pm 2\sigma$). Note that correlations between the three parameters may exist but Rahmstorf et al. (2012) do not attempt to quantify them. However, ignoring parameter correlations and taking worst cases for each parameter independently leads to relatively minor variability in SLR estimates of <20 cm, which we consider acceptable in a sensitivity analysis. Finally, the three SLR model scenarios (Table 2) are applied to the minimum, average and maximum global temperature scenarios (Fig. 2) computed from the PLASIM-ENTS emulator (See sect. 3.1) to generate 9 scenarios of SLR given in Fig. 3. For example, the scenario called MxAv refers to the SLR scenario assuming maximum temperature profile and average SLR parameters. Figure 3 shows that SLR curves are convex and smoothly increasing in time and resulting in SLR estimates between 0.6 m for the MnMn scenario and 1.1 m for the MxMx one by 2100.

The possible contribution of substantial ice sheet melt to future SLR does not have a close analogue in the recent past, so that our use of a semi-empirical fit to historical observations is conservative. The possibility of extreme ice sheet melting has not been quantified probabilistically, largely due to limited understanding of underlying processes (Krieglera et al. 2009), although rises in excess of 2 m by 2100 have been ruled out with high confidence (Lowe and Gregory 2010). Pycroft et al. (2014) considered a modified empirical fit that projects SLR of up to 2 m by 2100. Under this assumption, they estimated that the social cost of carbon increases by 10 to 14 US$/tCO2 (approximately 10 %) from their baseline.

3.3 Coastal Developments: Urban Areas and Population

Another important source of uncertainty regarding potential economic impacts of SLR is related to coastal evolution in terms of population density, urban areas and cropland areas. We

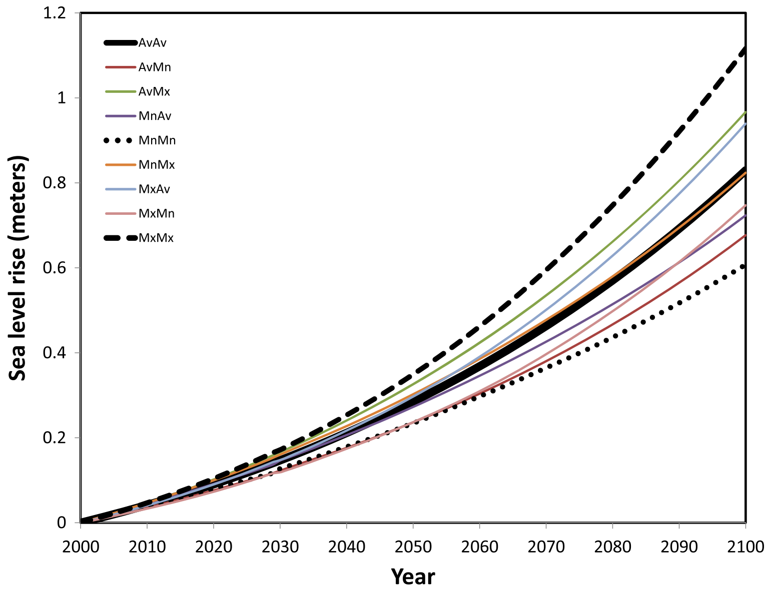

Fig. 3 Global sea-level rise in meters

have represented the possible evolution of these factors in terms of the relative concentration of activity in coastal areas through a set of relevant elasticities representing both physical and economic impacts. The elasticities are defined as:

- Percentage change in population living in coastal cities with respect to percentage change in population living in all urban agglomerations. The higher the population density in coastal cities, the higher the number of people affected and the higher the economic impacts.
- Percentage change of coastal urban areas with respect to percentage change of urban areas in the regions. We consider here that capital is mainly located in urban areas and that the economic impact of SLR is proportional to the affected urban surface.
- Percentage change of coastal cropland areas with respect to percentage change of cropland areas in the regions.

Let us now explain how we generate contrasted scenarios for the three aforementioned elasticities. For population density, we first estimate the coastal attractiveness in the past by using the World Urbanization Prospects from the United Nations (United Nations Department of Economic and Social Affairs, Population Division 191 2012). [7] The report estimates urban agglomerations with 750,000 inhabitants or more for the period 1950–2025 and indicates for each city if it is located in a coastal area.[8] For each region, we compute the number of people living in coastal urban agglomerations and the number of people living in urban agglomerations. We estimate the elasticity between these two values, and use it as a proxy

[7] Refer to http://esa.un.org/unpd/wup/index.html.

[8] Note that in this report the coastal areas were defined as areas between 50 m below mean sea level and 50 m above the high tide level or extending landward to a distance of 100 km from shore, including coral reefs, intertidal zones, estuaries, coastal aquaculture, and seagrass communities. While this definition will not be appropriate for all regions, it suffices to calculate an uncertainty range for global average elasticities used in this study.

Table 3 Elasticities concerning coastal developments

	Urban areas			Population		
	Low	Medium	High	Low	Medium	High
AFR	0.28	0.55	1.10	0.47	0.93	1.86
AUS	0.34	0.68	1.36	0.50	1.00	2.00
CAN	0.21	0.42	0.83	0.46	0.91	1.82
CHI	0.31	0.62	1.24	0.46	0.92	1.84
EEU	0.21	0.42	0.84	0.38	0.76	1.52
FSU	0.25	0.49	0.98	0.42	0.83	1.66
IND	0.26	0.52	1.04	0.46	0.92	1.84
LAT	0.32	0.63	1.26	0.46	0.92	1.84
MID	0.26	0.52	1.05	0.45	0.90	1.80
REA	0.30	0.66	1.19	0.49	0.97	1.94
RSA	0.26	0.52	1.05	0.50	0.99	1.98
SEA	0.36	0.72	1.45	0.50	0.99	1.98
USA	0.34	0.68	1.35	0.48	0.95	1.90
WEU	0.33	0.66	1.33	0.47	0.93	1.86

for coastal attractiveness. Table 3 gives these elasticities for coastal developments for each region. We observe that all elasticities are close to one for population growth in the medium scenario showing that, in the period covered, population growth in coastal areas has not been significantly faster than population growth in non-coastal zones. However in the future, the coastal attractiveness could increase either to support increased coastal tourism activities or as a result of other socio-economic factors. Although the available data are poor and there is limited systematic analysis, the study conducted by Nicholls (2002) uses a scenario where the coastal populations increase at twice the rate of national population, claiming that this is consistent with present trends. Based on our statistical analysis and existing studies we define three scenarios for migration to coastal areas:

- Medium scenario (ME): here we suppose that the past trends continue, and that the elasticity of the coastal population with the total population is the one reported in Table 3;
- High scenario (HI): in this case, we multiply the elasticity by two, following the assumptions used in previous studies (Nicholls 2002);
- Low scenario (LO): in this scenario, we suppose that the elasticity is divided by two, which could represent a proactive adaptation to SLR where the government takes incentive measures to limit the attractiveness of coastal areas.

Regarding the evolution of the coastal urban surface areas, elasticities (i.e., percentage change of coastal urban areas with respect to percentage change of urban areas in the regions) are calculated using the RCPs' land-use database (Hurtt et al. 2011). Medium elasticities (corresponding to the ME scenario) are reported in Table 3. They are estimated using the RCPs' land-use database for urban area from 2005-2100. However, one can expect these elasticities could change, hence low (LO scenario) and high (HI scenario) elasticity scenarios are also considered, using half and twice the derived values respectively.

For cropland elasticity, we consider only one scenario in view of the relatively low impact found to result from cropland area loss. As for surface area, values are calculated from the RCPs' land-use database for historical and future cropland area change.

Finally in order to generate a consistent set of scenarios for our sensitivity analysis, we assume that the elasticities for population density and urban area are correlated, i.e., an increase of density comes with an increase of urban area and vice-versa. Thus combining the three scenarios of temperature profile; the three semi-empirical relationships of SLR; the medium scenario for cropland elasticity; and the three (low, medium and high) elasticities for the development of coastal areas (density and surface), we end up with 27 scenarios. These are denoted as, for instance, LO_MnMx, which would refer to low elasticities for population and urban areas with minimum temperature profile and maximum parameters of the semi-empirical relationship for SLR.

4 Results and Analysis

4.1 Physical Impacts

Using the data and methods discussed in Sect. 2.3, we first examine the physical impacts of SLR separately on (1) the cropland area loss, (2) urban area loss and (3) number of people affected. Table 4 shows a global cropland area loss due to SLR by 2100 ranging from 73,397 km^2 in the LO_MnMn scenario to 138,846 km^2 in the HI_MxMx scenario. In the case of global urban area loss, it ranges from 7,296 km^2 in the LO_MnMn scenario to 53,814 km^2 in the HI_MxMx scenario. Globally, the total number of people affected due to SLR by 2100 ranges from 77.3 million in the LO_MnMn to 313.5 million in the HI_MxMx scenario. The study conducted by Rowley et al. (2007) found the number of people affected by 1 metre of SLR to be 107.94 million which is close to our ME_AvAv scenario. In our study, the expected number of people affected during the 2080s is predicted to be 0.09, 1.6 and 2.3 million in the LO_MnMn, ME_AvAv and HI_MxMx scenarios respectively in the European region (WEU + EEU). Similarly, Bosello et al. (2012) found that the number of people actually flooded increases over time and with increasing sea level if no adaptation is undertaken and it is large in absolute terms. For instance, these authors found that under the A2 (ECHAM4) scenario the expected number of people flooded per year in the EU without adaptation ranged from 0.22 to 1.4 million by the 2080s.

The share of coastal cropland area lost is greatest in South East Asia with an average loss of 3.6 %. In the case of urban areas and population, it can be seen from Fig. 4 that Australia and New Zealand, and South East Asia are the most affected regions. With the HI_MxMx scenario, the share of urban areas lost for South East Asia reaches 14.9 % and the share of population affected in Australia and New Zealand reaches 27.1 % (Fig. 4).

4.2 Economic Impacts

Economic consequences of SLR depend on the level of physical impacts discussed in the previous section. Details regarding the implementation of these physical impacts in GEMINI-E3 to analyse the economic implication of SLR are discussed in Sect. 2. In this section, first we consider welfare cost without adaptation and then with adaptation.

4.2.1 Welfare Effect Without Protection

On the basis of the physical impacts computed in Sect. 4.1, we sequentially introduce exogenous shocks on the factor endowments represented by land, capital and labour in GEMINI-E3. These shocks on factor endowments directly reduce the level of production with different

Table 4 Cropland area loss, urban area loss and number of people affected by 2100

	Cropland area loss (km^2)			Urban area loss (km^2)			Number of people affected (millions)		
	LO_MnMn	ME_AvAv	HI_MxMx	LO_MnMn	ME_AvAv	HI_MxMx	LO_MnMn	ME_AvAv	HI_MxMx
AFR	3430.6	4683.3	6302.8	285.2	1239.7	3666.6	11.1	30.7	131.8
AUS	2457.3	3354.7	4514.7	495.0	797.7	2205.9	2.8	5.1	15.9
CAN	590.0	805.4	1083.9	24.2	51.0	85.3	0.2	0.4	0.7
CHI	4760.8	6499.2	8746.6	533.5	2400.2	6135.4	7.0	8.1	8.4
EEU	1108.8	1513.6	2037.0	38.3	80.1	113.2	0.5	0.5	0.6
FSU	3510.0	4791.7	6448.6	94.4	264.4	332.1	0.8	1.0	1.3
IND	6613.6	9028.7	12150.8	127.0	600.1	1438.3	5.3	8.9	16.4
LAT	10775.1	14709.7	19796.3	765.8	1945.9	4984.6	7.8	10.6	20.5
MID	1286.6	1756.4	2363.7	126.1	515.1	1164.7	1.8	3.9	9.9
REA	595.7	813.2	1094.4	178.5	275.7	414.8	3.0	3.6	3.8
RSA	1026.8	1401.7	1886.4	52.5	385.3	738.6	2.5	3.6	8.4
SEA	26140.9	35686.6	48027.0	1202.1	4634.4	19360.2	23.6	34.5	65.0
USA	5845.9	7980.5	10740.2	2303.9	5068.8	10288.9	4.2	7.6	16.3
WEU	5254.9	7173.8	9654.5	1069.5	1941.9	2885.2	6.7	10.2	14.2
WORLD	73396.7	100198.3	134847.0	7296.1	20200.3	53813.9	77.3	128.6	313.5

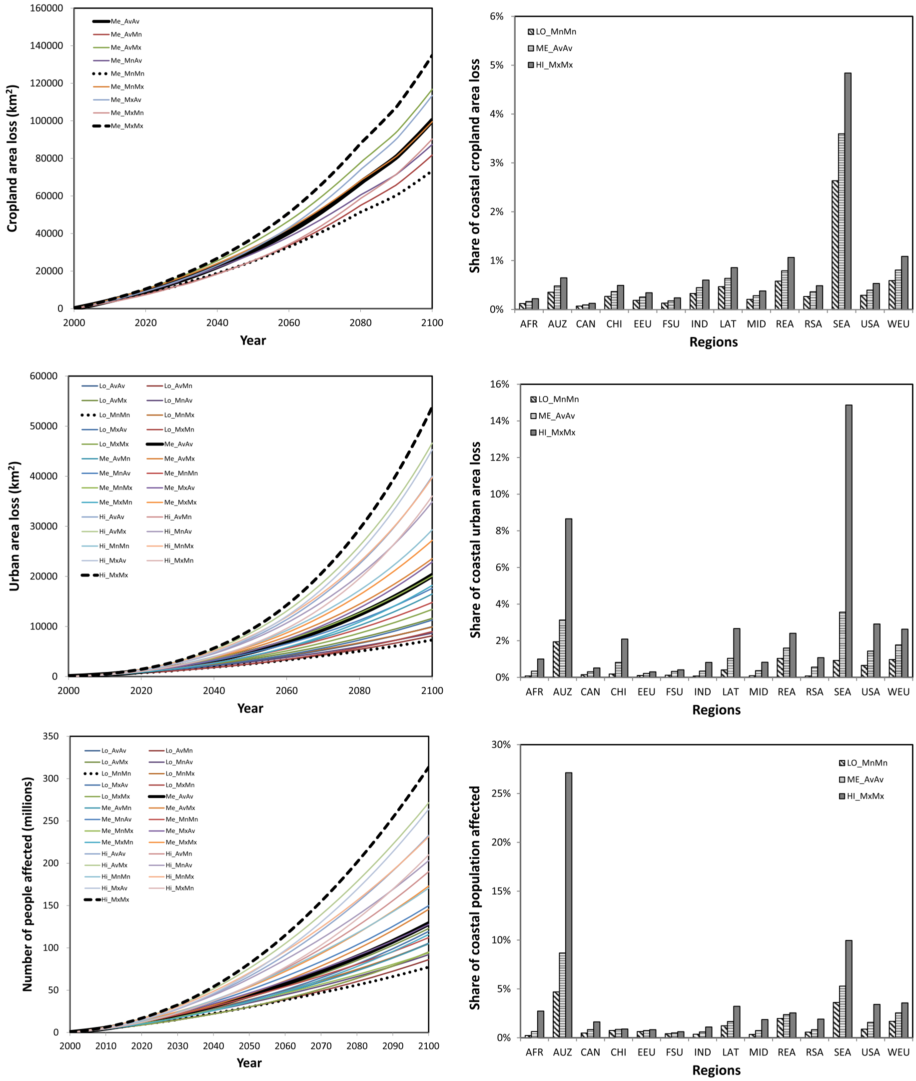

Fig. 4 Physical impacts of SLR on coastal cropland, urban areas and population at global and regional level for the year 2100

effects on sectoral outputs that are correlated to the contribution of these endowments to their productions. Loss of cropland area mainly impacts agricultural sectors, while sectors intensive in labour are more impacted by number of people affected. These decreases of production level induce loss of endowment remunerations (land rent, remuneration of capital and wages) that in turn reduce the household consumption. In the case of people affected another negative impact is generated by the costs of inhabitants' resettlement financed by the government through an increase of fiscal revenue that decreases household consumption. In our model, the welfare cost is measured by the households' surplus and represented by the compensating variation of income (CVI) expressed in US $.

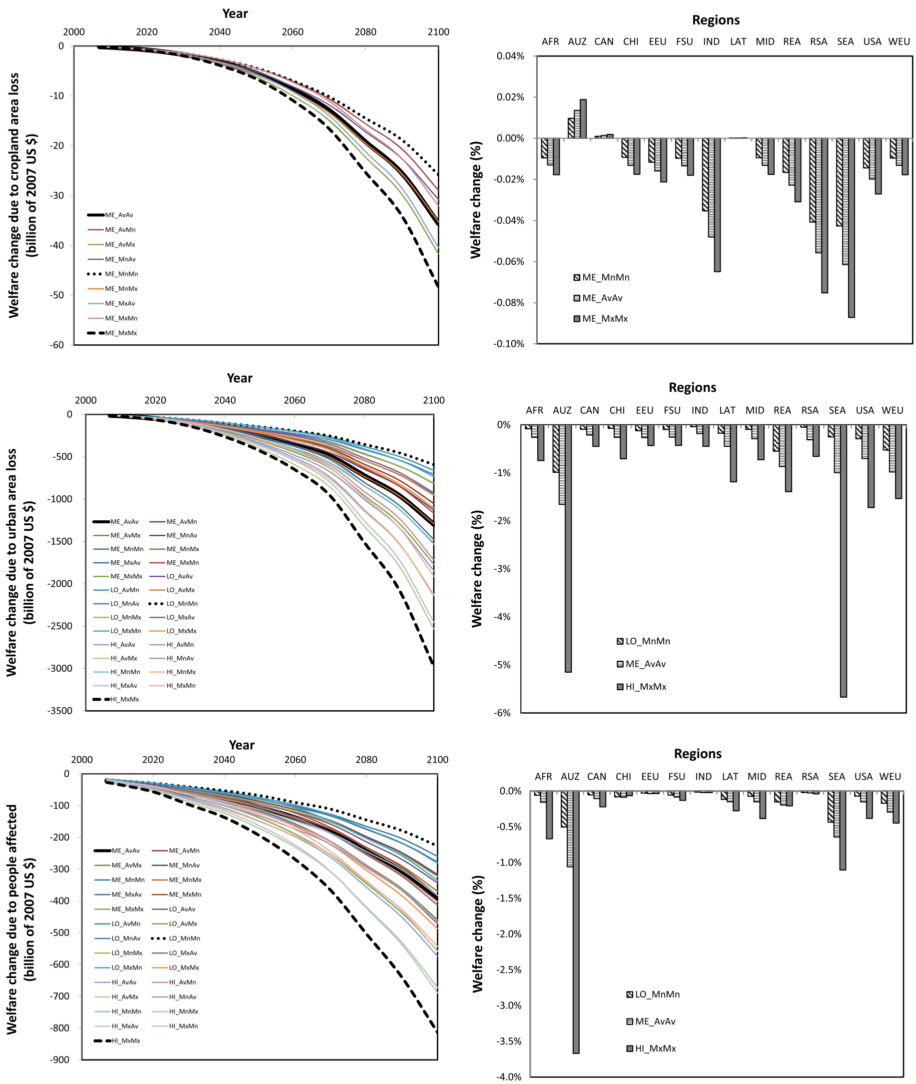

Fig. 5 Global welfare change (billions of 2007 US$) at different years and regional welfare change (percent of household consumption) for the year 2100

Figure 5 shows global welfare changes in billions of 2007 US \$ as compared to the baseline at different years and regional welfare changes in the year 2100 due to SLR without protection (i.e. without building dikes). Global and regional welfare loss due to cropland area loss is minimal. However, global and regional welfare loss due to urban area loss and population could have significant impacts. Welfare loss due to cropland area loss ranges from 30.79 billion US \$ (ME_MnMn) to 48.41 billion US \$ (ME_MxMx) in the year 2100. Some regions (AUS and CAN) have positive welfare change coming from gains of terms of trade. The study conducted by Bosello et al. (2012) which focused on the European level found that macroeconomic impacts (measured by GDP) are not in all cases negative but also in some cases positive. They state that this stems mainly from international trade and capital flows. However, our simulation results show that welfare cost due to loss of urban area and number of people affected could be very high at global level. For urban area loss, welfare loss ranges from 592.84 billion US $ (LO_MnMn) to 2975.20 billion US $ (HI_MxMx) in the year 2100. Similarly, welfare loss due to number of people affected ranges from 227.18 billion US $ (LO_MnMn) to 813.48 billion US $ (HI_MxMx) in the year 2100. Anthoff et al. (2010) estimated the global cost of 1 metre SLR in 2100 between 850 billion US $ and 1500 billion US $ taking into account three damage cost components (the cost of displaced people, value of dryland and wetland lost) using the FUND model. The study of Hallegatte et al. (2013) suggested that the present protection needs to be upgraded to avoid unacceptable losses of US $ 1 trillion or more per year in 2050. Much larger cost in this study is due to higher sea level rise, inclusion of subsidence and damage of assets. Moreover, they found that even if adaptation investments maintain constant flood probability, subsidence and SLR will increase global flood losses to US $ 60–63 billion per year in 2050.

In terms of regional welfare effects in absolute values, USA is most affected in terms of all the three factors: cropland area loss, urban area loss and people affected. Other regions that are most affected in the case of cropland area loss are Western Europe with 7.1 billion US $, India with 7.08 billion US $ and South East Asia with 3.95 billion US $. In the case of urban area loss, the regions most affected are USA, Western Europe, South East Asia, Latin America, Australia and New Zealand and Rest of East Asia (in these regions welfare loss is more than 100 billion US $). Welfare loss due to number of people affected is also significant in the region Australia and New Zealand and in Western Europe.

However, when welfare loss as a percentage of household consumption is examined, the most affected regions are India, Rest of South Asia and South East Asia in the case of cropland area loss with 0.05, 0.06 and 0.06 % respectively for the ME_AvAv scenario in the year 2100. While in the case of urban area loss, Australia and New Zealand, and South East Asia are the most affected regions with welfare losses of 1.66 and 1.00 % respectively for the ME_AvAv scenario in the year 2100. Similarly, in the case of number of people affected, Australia and New Zealand and South East Asia lose welfare by 1.06 and 0.64 % respectively for the ME_AvAv scenario in the year 2100. This can be expected as Australia and New Zealand, and South East Asia are the regions that have to bear most losses in terms of physical quantities in percent (Fig. 4). This is because these regions are highly urbanised and densely populated in the coastal areas.

4.2.2 Welfare Effect with Protection

Protection cost estimation It is extremely difficult to estimate the cost of all potentially relevant adaptation options, as the options available in terms of approaches and technologies depend on the specific context for each city (Hallegatte et al. 2013). Moreover, the study done by Nicholls et al. (2010) showed that protection by sea dikes is the major contribution to defence costs. Here, we consider dike construction as the only adaptation option, calculated as described in Sect. 2.4. In GEMINI-E3 this means that we impose an increase of government expenditure to build the sea dikes that is financed by an increase of the direct taxation on households, which impacts negatively on the household consumption. Furthermore, the negative shocks on factor endowments (land, capital and labour) are reduced with respect to scenarios without protection.

We estimate the global protection cost to be between 330 billion US $ and 470 billion US $ for medium protection cost assumptions by 2090 (see Table 5). Anthoff et al. (2010) found a cost of protection ranging between 150 billion US $ and 550 billion US $ for 1 m SLR by the year 2100. The regions that need most protection in our analysis are Western Europe, South East Asia, United States of America and Australia and New Zealand. Table 5 shows that 12,435 km of coastal length can be protected in Western Europe, 5112 km in South East Asia, 4138 km in United States of America and 2628 km in Australia and New Zealand for the ME_AvAv scenario. The estimated protection costs in these regions are less than total damage costs. The simulation results show that the coastal regions of Western Europe need to be protected more than any other region. This may simply reflect a higher concentration of urban population in coastal areas in these regions. With the possibilities to limit (or advance) the development of coastal cropland, urban area and population, there will be an increase in the need to protect coastal length for the HI_MxMx scenario and a decrease in the need to protect for LO_MnMn scenario. Similarly, limiting the development (i.e. LO_MnMn Scenarios) of cropland, urban area and population decreases the cost of protection by 14 percent while advancing the development (i.e. HI_MxMx scenario) increases the cost of protection by 23 percent in comparison to the ME_AvAv scenario. However, there are diverse regional impacts due to this limiting (or advancing) of the development of coastal regions. In the case of the region Australia and New Zealand, coastal development could have detrimental effects, increasing the protection cost by 132 % in the HI_MxMx scenario and decreasing it by 72 % in the LO_MnMn scenario in comparison to the ME_AvAv scenario. Protection substantially decreases cropland area loss, urban area loss and number of people affected in comparison to the no-protection scenario. Furthermore, the length of coastal region protected depends on the cost of protection which is shown in Table 6; the lower the protection cost the greater the length of coastal region protected and vice versa. Table 7 shows the share of cropland area loss, urban area loss and number of people protected by building dikes for medium protection cost. Given the cost of protection, which is low compared to the damage cost, it seems that most of the affected low-lying cropland areas, urban areas and population could be protected by the end of this century.

Welfare With Protection Global welfare cost with protection as a percentage of global welfare cost without protection gradually decreases and is considerably lower by the end of century (Fig. 6). Welfare cost without protection is relatively low in the first half of the century and increases exponential in the second half of the century. As the cost of protection is relatively low, this suggests to protect the coastal regions by the middle of this century. Figure 7 shows the comparison of welfare change for low, medium and high protection costs. Simulation results for the HI_MxMx scenario are more sensitive to the change in protection cost. High protection cost will result in relatively higher welfare loss compared to low and medium protection cost. In the HI_MxMx scenario with high protection cost, global welfare loss in 2100 could be as high as 500 billion 2007 US $ and in the LO_MnMn with low protection cost, global welfare loss in 2100 could be just 90 billion 2007 US $. The study conducted by Anthoff et al. (2010) estimated the global welfare cost between 750 billion US $ to 1000 billion US $ in 2100 with protection. The comparison of the dynamics of HI_MxMx with low and high protection cost scenarios is quite interesting. Surprisingly, in the middle of twenty first century the global welfare cost is higher in lower protection cost than in medium protection cost scenario. This is mainly coming from higher investments in coastal protection due to lower cost which temporally induces supplementary government expenditures. Another surprising result is that the global welfare cost of the HI_MxMx is lower than in the ME_AvAv scenario for the low protection cost scenario in 2100. The reason is that the coastal areas are protected more in HI_MxMx than in ME_AvAv scenario.

Table 5 Coastal length protected and protection cost by 2090 for medium protection cost

	Coastal length protected (km)			Protection cost (billions of 2007 US $)		
	LO_MnMn	ME_AvAv	HI_MxMx	LO_MnMn	ME_AvAv	HI_MxMx
AFR	927	1380	1769	10.69	15.91	20.40
AUS	744	2628	5868	8.58	30.31	67.67
CAN	612	699	911	7.06	8.06	10.51
CHI	1683	1691	1699	19.41	19.50	19.59
EEU	381	567	605	4.39	6.54	6.98
FSU	218	233	246	2.51	2.68	2.84
IND	566	622	690	6.52	7.17	7.96
LAT	704	928	1235	8.12	10.70	14.24
MID	139	143	213	1.60	1.65	2.45
REA	2248	2300	2360	25.92	26.52	27.21
RSA	290	462	702	3.35	5.33	8.09
SEA	4121	5112	6118	47.52	58.95	70.55
USA	3624	4138	5191	41.79	47.72	59.86
WEU	12,292	12,435	13,337	141.75	143.39	153.80
WORLD	28,548	33,337	40,946	329.20	384.43	472.16

Table 6 Percentage change in coastal length protected by 2090 compared to medium protection cost

	Low protection cost			High protection cost		
	LO_MnMn (%)	ME_AvAv (%)	HI_MxMx (%)	LO_MnMn (%)	ME_AvAv (%)	HI_MxMx (%)
AFR	24	21	26	−69	−30	−22
AUS	56	56	7	−44	−37	−92
CAN	68	96	302	−47	−40	−50
CHI	88	30	21	−66	−60	−49
EEU	123	88	103	−42	−59	−55
FSU	25	30	29	−29	−25	−30
IND	56	14	16	−32	−51	−30
LAT	37	44	26	−34	−31	−33
MID	73	70	698	−50	−40	−39
REA	376	12	13	−48	−87	−87
RSA	120	148	69	−60	−37	−62
SEA	343	529	68	−34	−34	−83
USA	20	20	15	−20	−13	−15
WEU	57	23	22	−85	−35	−20
WORLD	77	44	32	−60	−41	−58

Table 7 Share of urban area, cropland and people protected by 2090 for medium protection cost

	Cropland area			Urban area			People		
	LO_MnMn (%)	ME_AvAv (%)	HI_MxMx (%)	LO_MnMn (%)	ME_AvAv (%)	HI_MxMx (%)	LO_MnMn (%)	ME_AvAv (%)	HI_MxMx (%)
AFR	78.0	88.0	93.4	98.7	99.6	99.8	84.9	92.6%	96.0
AUS	25.5	27.0	32.1	99.7	99.8	99.9	85.8	88.1	99.4
CAN	28.7	35.8	43.4	97.6	98.4	99.1	72.1	74.5	81.3
CHI	96.6	98.2	98.2	99.6	99.9	100.0	95.6	96.2	95.5
EEU	89.2	93.4	94.5	99.2	99.5	99.7	64.5	78.3	80.0
FSU	98.0	98.5	98.9	99.4	99.7	99.9	91.8	91.8	91.8
IND	97.1	98.3	99.0	99.9	99.9	100.0	88.3	91.4	92.3
LAT	39.8	51.9	64.0	99.5	99.7	99.9	12.5	97.3	98.7
MID	99.5	99.9	99.9	100.0	100.0	100.0	99.9	100.0	100.0
REA	97.3	98.5	98.9	100.0	100.0	100.0	97.5	98.0	98.0
RSA	86.1	94.6	97.6	94.4	98.2	99.7	36.7	49.2	66.1
SEA	85.5	89.0	93.6	99.5	99.6	99.9	72.3	77.8	92.1
USA	97.6	98.7	99.1	99.9	100.0	100.0	97.8	98.6	99.4
WEU	90.4	93.7	95.6	99.8	99.9	100.0	95.9	97.7	98.4

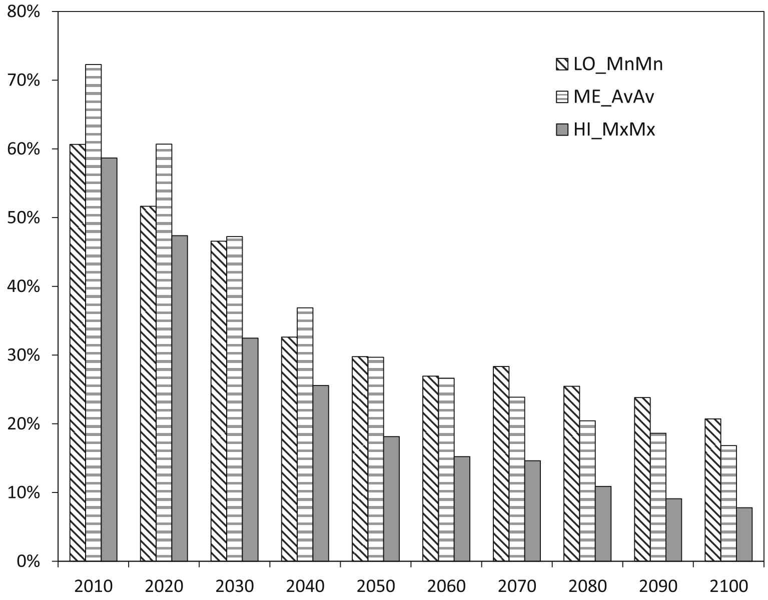

Fig. 6 Global welfare change (with protection) as percentage of global welfare change (without protection) for medium protection cost

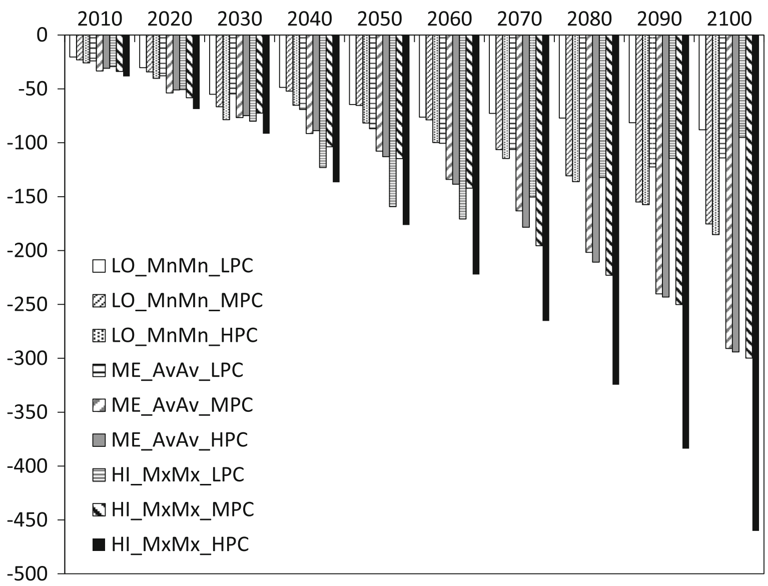

Fig. 7 Global welfare change (billions of 2007 US $) with for low, medium and high protection cost

Figure 8 shows that regional welfare loss (as a percentage of household consumption) with protection is significantly less than in the case without protection in all the scenarios. This study suggests that it is better to protect the coastal area by building dikes when damages for

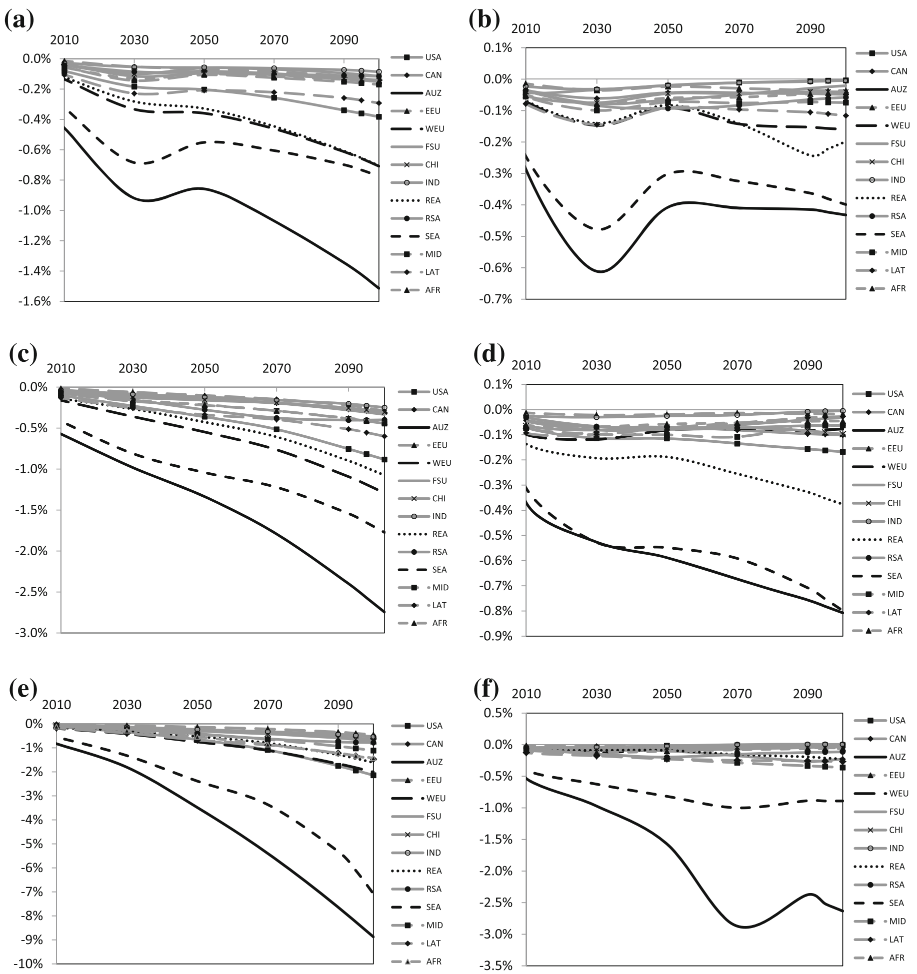

Fig. 8 Regional welfare change as a % of household consumption for with and without protection. **a** LO MnMn Scenario (Without protection). **b** LO MnMn Scenario (With protection). **c** ME AvAv Scenario (Without protection). **d** ME AvAv Scenario (With protection). **e** HI MxMx Scenario (Without protection). **f** HI MxMx Scenario (With protection).

cropland, urban areas and people affected are considered. Tol (2007) using the FUND model, have also shown that the benefits of adaptation (i.e. dike building) are substantial in terms of land loss prevented and economic damage avoided. Simulation results show that Australia and New Zealand and South East Asia are the most affected regions in terms of welfare loss (as a percentage of household consumption) both with and without protection. In the case of Australia and New Zealand, our calculations suggest welfare loss could be as high as about 9 % in the HI_MxMx scenario without protection or as low as 0.4 % in the case of medium protection cost. In terms of welfare cost in absolute values, USA is the most affected region. These regional insights are consistent with the study conducted by Anthoff et al. (2010), that found that East and South Asia are the most vulnerable countries and that the USA bears a substantial share of the total damage. Both eastern and western European regions show a significant welfare loss due to sea-level rise when adaptation is not considered; however with adaptation welfare loss is decreased significantly. These larger losses stem from the way coastal development (cropland, urban area, population) is considered in this study. As in the study by Bosello et al. (2012) in which only land area is protected, it is found that some European countries gain and some lose depending on the interplay between the initial land loss, the additional investment demand and the decrease and re-composition of private consumption demand. This might be the case in our simulation as well when Europe is disaggregated with many regions. Unlike other studies, it should be noted that the protection cost is estimated by comparing the damage cost at each coastal segment and at each decade. In this way, the costs of building dikes (and hence the welfare costs) could be significantly different from those estimated at national or regional level.

5 Conclusion

This study uses a CGE model with GIS tools to examine and analyse physical and economic consequences of SLR. One of the main objectives of the paper is to highlight the importance of incorporating uncertainties at different levels (temperature, the parameters of the semi-empirical relationship of SLR to temperature, and coastal development). Our simulation results show that it is important to consider uncertainties concerning development of future coastal regions as these uncertainties could have much larger economic consequences than uncertainties in SLR itself. Our simulation results showed that economic impacts due to loss in cropland without protection are low. In contrast, economic impacts of SLR due to loss of capital and number of people affected (change in labour supply and government expenditure on migration) are high when protection measures are not considered. Overall, we find that the economic impact of SLR could be significant for the coastal regions. Moreover, it is diverse across regions with South East Asia, Australia and New Zealand potentially the most affected regions. With protection, welfare change (as a percentage of household consumption) is still negative but much less than that without protection. This suggests that it would be beneficial to protect threatened coastal areas. In addition, this study also suggests that SLR impacts could be ameliorated by proper management of coastal developments (resettlement of coastal population and building infrastructure away from threatened coastline) in the coming decades.

A number of caveats should be raised. From a methodological point of view our novel approach that links a GIS tool and CGE model stresses the gain coming from such coupling. Nevertheless, further research should be considered to improve the coupling methodology by incorporating details of environmental and socio-economic factors at local level. The study consider only dike rising as an adaptation option, however, there is a multitude of protection options (beach/shore improvements, port upgrades and land use planning) that could be used to limit the impacts of SLR. The implementation of several adaptation options would improve the coastal management representation and the way the protection costs are introduced in the model. Another drawback of the CGE used in this study is the high level of aggregation that is required to have a manageable tool with the correlative issues of aggregation bias (Wing and Lanzi 2014). Of course the aim of this study is not to replace local case studies on coastal management but more to identify the regions that will be most affected by SLR and to stress the main uncertainties regarding these impacts. However, the use of a detailed GIS allows the integration of locally specific information into the CGE model and the coupling can be adapted at a regional level by analyzing for example the impacts of SLR on the 28 European countries. It is important to emphasize that the SLR impacts considered here are only a subset of the ways in which SLR could impact economies. Other potential consequences including saltwater intrusion of surface and groundwater, and coastal wetlands (such as salt-marshes and mangroves) could also have significant impacts. Ackerman and Stanton (2011) emphasizes that the real impact of climate on coastal regions can be understood only as the combination of permanent inundation from SLR and storm surge flooding from hurricanes and other major storms. Incorporating the effects of possible changes in intensity of storm surges and other occasional extreme events is likely to increase the economic impact of sea-level rise but these additional issues are beyond the scope of the present research. Nonetheless, we think that the added value of the integration of GIS with CGE is a promising approach.

Acknowledgements The research leading to these results has received funding from the EU Seventh Framework Programme (ERMITAGE FP7/2007-2013) under Grant Agreement no265170. The third author is also funded by the Qatar National Research Fund under Grant Agreement no6-1035-5-126. We would like to thank Stefan Rahmstorf and Richard S. J. Tol for their suggestions. We would also like to thank Florent Baume for his assistance in GIS analysis. Three anonymous reviewers are also gratefully thanked for their valuable comments and suggestions.

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