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Climate Change, Sea Level Rise, and Coastal Disasters. A Review of Modeling Practices

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Summary

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Keywords: Climate Change Impacts, Adaptation, Sea Level Rise

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Abstract.
The climate change impacts on sea level rise and coastal disasters, and the possible adaptation responses have been studied using very different approaches, such as very detailed site-specific engineering studies and global macroeconomic assessments of costal zones vulnerability. This paper reviews the methodologies and the modeling practices used by the sea level rise literature. It points at the strengths and weaknesses of each approach, motivating differences in results and in policy implications. Based on the studies surveyed, this paper also identifies potential directions for future research.

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1. Introduction

The impacts of coastal erosion and sea flooding in densely populated and infrastructure-rich coastal cities have received a lot of attention by the climate change impact literature. Coastal areas are characterized by high concentrations of human settlements: population density is on average three times the global mean (Small and Nicholls 2003; McGranahan et al. 2007). Large numbers of people and assets are already exposed to coastal flooding. There are 136 major port cities hosting more than one million inhabitants each, thirteen of which are in the top 20 most populated cities in the world. In 2005, the total value of the assets across these cities was estimated at US$3,000 billion, corresponding to around 5% of global Gross World Product (Nicholls et al. 2008). Exposure is expected to increase with growing population and economic relevance of coastal cities, particularly in developing countries (Nicholls et al. 2008; Hanson et al. 2009, 2012). Accordingly, climate change impacts in coastal areas and cities are a major reason for concern (Handmer et al. 2012).

Nonetheless, future sea level rise remains highly uncertain. Important sources of uncertainty are the dynamics of large ice sheets in Greenland and Antarctica and the interaction between mean sea level, extreme water levels, and storm characteristics (Seneviratne et al. 2012). The Fourth Assessment report of the Intergovernmental Panel on Climate Change (IPCC) (AR4) projects sea level rise to range between 0.18 and 0.38 m for the B1 scenario of the Special Report on Emissions Scenarios (SRES) and between 0.26 and 0.59 m for the A1FI scenario by the end of the century (Meehl et al. 2007). These projections mostly reflect the effect of thermal expansion of seawater and do not account for the instability and potentially large discharges from the Greenland and West Antarctica ice sheets which could add a further 10 to 20 cm to sea level rise projections by the end of the century. The AR4 also acknowledged that a larger contribution could not be ruled out. Since the publication of the Assessment Report 4 (AR4) by the IPCC, several studies using statistical methods to relate observed variations in global sea levels and global temperature, suggest that global mean sea level rise could be higher than what was described in the AR4. For instance, Kopp et al. (2009) suggest that, during the Emian period, when climatic conditions and ice sheet configurations were comparable with present ones, global sea level might have risen by 6-9 m above the present level, because of extensive melting of the ice sheets as a response to a global mean warming of 1–2°C. According to Vermeer and Rahmstorf (2009) and Rahmstorf (2007) the AR4 climate change scenario range is consistent with 0.5 to 1.9 m of sea level rise for the 21st Century. Pfeffer et al. (2008) use a model of glaciers to conclude that if a 2m increase in sea level by 2100 could occur under extreme assumptions then an increase of 0.8m is likely in any case. Overpeck and Weiss, (2009) conclude that sea level rise could exceed 1 m by 2100. In addition, observed sea level rise has been following a trajectory close to the upper bound of the Special Report on Emission Scenarios (SRES; Nakicenovic 2000) scenarios that include land ice uncertainty (Cazenave and Nerem 2004). Sea level rise can interact with mid-latitude storms and tropical cyclones, exacerbating water level increases, waves, erosion, and the risk of flood and defense failures (Nicholls et al. 2007). However, the evidence connecting global warming and storms remains uncertain, although some studies found that warming could increase the intensity of tropical storms (Meehl et al. 2007; Emanuel 2005; Webster et al. 2005).

The impacts of sea level rise and to a lower extent of coastal disaster and storm surge, and the possible adaptation responses, have been vastly studied using very different approaches. These range from very detailed site-specific engineering studies to global macroeconomic assessments of the vulnerability of costal zones. The objective of this paper is to review the methodologies and the modeling practices used by the sea level rise literature and to indicate the strengths and weaknesses of the different approaches which motivate differences in results and in policy implications. Based on the studies surveyed, the paper also identifies potential directions for future research. The remainder of this paper is organized as follows. Section 2 reviews the current status of impact modeling and adaptation research, distinguishing between bottom-up (Section 2.1) and top-down (Section 2.2) approaches (general equilibrium models and optimization models). Section 3 discusses the modeling of disasters and extreme events to the extent they relate to coastal areas and interact with sea level rise. Section 4 summarizes shortcomings of various approaches and discusses potential areas for future research. Section 5 concludes and discusses the policy implications of different modeling procedures.

2. A Review of the Modeling Approaches

The drivers of actual impacts in coastal zones depend on a number of climate and non-climate factors (Nicholls et al. 2008). Climate drivers include global sea level rise, CO2 concentration, sea surface temperature, storm characteristics, runoff, and changes in wind and precipitation patterns. Non-climate drivers include uplift/subsidence due to human or natural processes and socioeconomic trends (of population and Gross Domestic Product (GDP), coastward migration, tourism, land use and aquaculture, infrastructure and port developments, use of marine renewable energy). Direct impacts of sea level rise include inundation, flood and storm damage, wetland losses, erosion, saltwater intrusion, rising water tables, and impeded drainage. These clearly affect many socioeconomic and environmental aspects of life in coastal zones such as tourism, agriculture, biodiversity, health, freshwater resources, and infrastructure (Nicholls et al. 2010).

The literature investigating these impacts and the related adaptations has been dominated by engineering models and by approaches based on Geographical Information Systems (GIS). Following the methodology outlined by the IPCC (IPCC CZMS, 1991) and focusing on direct effects, early assessments have estimated areas, people and activities at risk. In the survey we refer to this typology of modeling as bottom-up studies of coastal systems, as they basically neglect the interaction between the coastal system and the rest of the economy. Bottom-up studies have been conducted with different scales and the literature offers assessments with global, regional, as well as site-specific coverage. The investigation unit in global or regional analyses is usually the coastal segment with varying sizes. Adaptation measures are usually compounded in broad categories, such as dike building and beach nourishment. Site-specific assessments focus on delimited locations and specific impacts and measures are analyzed with much higher detail. Bottom-up studies do not account for the feedback of sea level rise on the macroeconomy and social context. Rather, they focus on exposure and vulnerability analyses (Section 2.1.1) and at best include cost-benefit considerations (Section 2.1.2 and 2.1.3). Top-down models have been used to estimate indirect costs, which refer to the higher-order implications of the direct effects. Generally speaking, indirect costs are related to the secondary or collateral effects of sea level rise and coastal storms (see Herberger et al. 2009 for a review). When considering top-down models we refer specifically to economy-wide costs, which are the costs reflecting macroeconomic, market-induced adjustments ultimately affecting income, GDP or welfare. Although top-down models are generally less detailed in the spatial and technical description of the coastal system, they better capture market interaction or growth effects. They complement bottom-up technical assessments with a broader economic evaluation of sector-specific impacts and adaptation. Economy-wide sea level rise impacts have been estimated using computable general equilibrium (CGE) models (Section 2.2.1) by shocking key parameters and model inputs, such as land and capital endowments of the economic systems concerned, and by tracking the market reactions and the final effects on a given country's economic performance. Dynamic optimization models (Section 2.2.2) are another type of top-down models used to analyze the long-run growth implications of sea level rise. These models include reduced form equations representing sea level rise impacts and adaptation costs that allow determining the optimal protection levels. In principle, top-down studies should be grounded on evidence provided by bottom-up approaches. In practice, there is a gap between the two approaches, both with regard to impacts and adaptation cost estimates.

2. 1 Bottom-up studies

2.1.1. Exposure and vulnerability approaches

In this paper we define exposure as the inventory of elements located in an area in which hazard events may occur. Vulnerability refers to the propensity of exposed elements such as human beings, their livelihoods and assets to suffer adverse effects when impacted by hazardous events. While the literature and common usage often mistakenly conflate exposure and vulnerability, they are distinct. Exposure is a necessary, but not sufficient, determinant of risk. Vulnerability is related to predisposition, susceptibilities, fragilities, weaknesses, deficiencies, or lack of capacities that favor adverse effects on the exposed elements (Cadorna et al. 2012).

Two approaches have emerged as established methodology to assess sea level rise impacts on coastal areas at the global scale. The first is the methodology introduced with the Global Vulnerability Assessment (GVA) (Hoozemans et al. 1993). The second is grounded on the Dynamic Interactive Vulnerability Assessment (DIVA) model and database. DIVA can be considered the successor of the Global Vulnerability Assessment (GVA1) and is the main source of bottom-up information regarding sea level rise impacts and adaptation costs for nation-wide and global studies (see Section 2.1.3). The GVA1 is an application at the global scale of the Common Methodology for assessing the Vulnerability of Coastal Areas to Sea-Level Rise (IPCC CZMS 1991). The methodology was introduced in order to provide guidelines to identify the population and assets at risk with respect to a number of vulnerability indicators. The key concepts in GVA1 are exposure and risk. A key indicator is Population at Risk (PaR). It measures changes in population living in the risk zone (coastal flood plain) considering the flood frequency due to sea level rise and the protection standards. What drives sea level rise impacts is relative sea level rise, which takes into account surge characteristics and subsidence. Numbers of people in the hazard zone are then computed using the average population density for the coastal area. Fundamental assumptions concern the characteristics of a flood zone and the occurrence of flooding[2]. As a last step, the standard of protection is used to calculate PaR. The standard of protection is often estimated indirectly, by mapping protection classes (low, medium, high) to Gross National Product (GNP) per capita categories (less than 600US$, between 600 and 2400US$, above 2400US$). GVA1 provides the data for 192 polygons of varying size. In most cases they correspond to individual countries, though some countries are represented with more than one polygon.

[2] Common assumptions are that coastal flood plain has a constant slope, and the population is distributed uniformly across the coastal zone. If a sea defense is exceeded by a surge, the entire area behind it is flooded.

The large number of studies using the database or some of its components (Nicholls et al. 1998; Nicholls et al. 1999; Darwin and Tol, 2001; Nicholls, 2004; Nicholls et al. 2008; Bosello et al. 2007; Tol 2007; Bigano et al. 2008; Vafeidis et al. 2008; Hinkel and Klein, 2006; Hinkel et al. 2010) indicates the value and also the need of such an informative support. GVA1 is still one of the most influential in the field, used by both bottom-up and top-down assessments (see e.g. Nicholls et al. 2010 on dike costs). Yet, a number of shortcomings can be pointed out:

1. Simplified treatment of impacts, flood risk, wetland losses, and changes in coastal rice yields. Lack of non-climate drivers and of socioeconomic factors. Population and GDP are assumed to remain constant at 1990 levels.
2. Poor representation of climate drivers. Only 1 m global sea level rise is considered. Surge characteristics are assumed constant over time and extreme events are not considered.
3. Simplified treatment of adaptation. Protection costs are estimated indirectly by using GNP per capita in 1989 as an indicator of the ability-to-pay parameter for a chosen level of protection. The level of adaptation is arbitrary. All areas with a population density above 10 persons/km^2 are considered as fully protected.
4. Coarse spatial resolution. For example, subsidence is assumed to be uniform across coastal zones. Results are valid only at regional or global scales, as they have been validated against national-scale vulnerability assessments (Nicholls et al. 1995).

A first improvement of the GVA methodology was proposed by Nicholls et al. (1999), who introduced a dynamic approach and a richer database. Different global sea level rise scenarios are derived from two Global Circulation Models (GCMs) developed at the Hadley Centre (UK). The main factors that influence the incidence and risk of flooding evolve dynamically over time. Population density in coastal regions is assumed to change at rates that are double the rates for national population growth. Estimates of protection costs, which are the same classes of Hoozemans et al. (1993), have been revised to include deltaic regions where protection is more expensive. The study also introduces a module for assessing coastal wetland losses (salt marshes, mangroves, and associated unvegetated intertidal areas). Wetlands responses to sea level rise are nonlinear and losses arise only above some thresholds. Low tide zones are more vulnerable and wetland losses can be compensated by some inland wetland migration as accommodation space is calculated. The study considers two alternatives with and without inland wetland migration and develops a non-climate trend as a benchmark for comparison. With all these modifications the estimated risk of a flooding from a 1 m sea level rise increases. GVA1 estimated that 60 million people would be affected by a 1 m sea level rise induced flooding in 2100. Nicholls et al. (1999) suggest that this number could triple as a sole consequence of population and population density increase (Table 1, first row). The additional effect of sea level rise on top of the socio-economic development is minor, about 10% in 2080. The study also suggests that protection can be very effective, which is a finding that will be reiterated in all the subsequent studies.

Table 1: Global results from Nicholls et al. (1999).
Effectiveness of different protection measures on exposure

	No protection	**Constant Protection**	**Evolving Protection (increasing with GNP per capita)**	**Protection effectiveness**	
	PHZ (People in the hazard zone, millions)	AAPF (Average annual people flooded, millions)	AAPF (Average annual people flooded, millions)	Constant Protection	Evolving Protection
2080s (no sea level rise)	575	36	13	-94%	-98%
2080s (HadCM2 40cm sea level rise)	636	237	93	-63%	-85%

**PHZ: people at risk. AAPF: average people flooded*

In a further development Nicholls (2004) adopted a scenario-based approach to highlight the role of non-climate drivers. Global sea level rise under the SRES scenarios ranges between 22 (B2) and 34 (A1FI) cm in 2080s. Population growth assumptions determine population at risk (PAR), which is greater in the A2 and B2 scenarios in which population grows faster. Population and economic growth assumptions determine the average annual people flooded (AAPF). Growth assumptions become relevant when for instance protection capacity is assumed to increase with income. Residual damage is very low in the fast growing scenario, while it remains higher than 1990 levels in the A2 scenario where income is the lowest in 2080. Table 2 highlights the role of socioeconomic drivers. As in Nicholls et al. (1999), the additional effect of sea level rise is quite minor, about 9% in the scenario with the highest sea level rise, A1F1. With sea level rise, the additional number of people flooded is the highest in the A2 and B2 scenarios, even though A1FI has the largest sea level rise. The last column in Table 2 highlights that the assumption concerning the timing of protection (evolving versus lagged evolving where there is a 30-year time lag between income per capita and protection standard improvements) is quite relevant and can lead to very different impacts, especially in the low-growth heterogeneous scenario.

Table 2: Regional results from Nicholls et al. (2004) without considering sea level rise.
The role of socioeconomic drivers

					Low pop	**High pop**	**Constant protection**	**Evolving protection**	**Lagged evolving protection**
	Coastal population change	Pop	GDP	Sea level rise	PHZ	PHZ	AAPF	AAPF	AAPF
A1FI	High	7.9	416	34	286	439	15-25	0.00	0-1
A2	Low	14.2	185	28	521	840	30-49	11-19	18-30
B1	High	7.9	289	22	286	439	15-25	0.00	1-2
B2	Low	10.2	204	25	374	552	22-34	0.01	3-5

Nicholls and Lowe (2004) extend the analysis beyond 2080, when sea level rise would be affected by other climate drivers, in particular ice sheet dynamics. They exclude adaptation to focus on mitigation scenarios that stabilize CO_2 concentration in the 22nd Century.[3] The

[3] These are the IPCC scenarios S550 and 750 and some other SRES scenarios. Although SRES scenarios do not include mitigation, some of them (B1 and B2) are consistent with various level of mitigation in the 22nd Century.

analysis shows that mitigation can significantly reduce impacts under medium or high climate sensitivity. However, the effects are visible only after 2080, suggesting that adaptation will remain important, especially under high climate sensitivity scenarios. The analysis also suggests that protection could be more effective in managing coastal flooding while mitigation would play a more important role in the presence of low probability/high impact events such as the collapse of the West Antarctic Ice Sheet (WAIS) or the loss of the Greenland ice sheet (Lenton et al. 2009). The interaction between sea level rise impacts plus geological and socioeconomic mechanisms certainly goes beyond what can be captured by SRES scenarios. Land-use change, income distribution, and urbanization rates are some other important elements. Kirshen et al. (2008) in the analysis of sea level rise and storm surge impacts on the Metro Boston Area (USA) make the point that adaptation also affects exposure and should be considered in risk analyses. Structural protection is more effective in highly developed areas whereas less developed areas should be protected with more environmental friendly measures.

Although the focus of this review is on global modeling approaches, a number of site-specific studies based on exposure-vulnerability methodologies are worth mentioning. The local analyses considered below are of particular interest, because they provide a sort of benchmark against which global models can be reviewed more critically. This is not to say that those case studies have no limitations on their own, but they certainly do a better job at characterizing local vulnerability and the indirect or secondary effects of sea level rise impacts and coastal disasters.

Hallegatte et al. (2011) introduce a five-step methodology to evaluate people and insured asset exposure to sea level rise and storm surge in Copenhagen and in a virtual city. The study also estimates the direct and indirect costs associated with economic activity disruption. The exposure assessment only considered insured assets and population. Damages to un-insured assets are not available for the case study considered and estimates from the Katrina landfall are used to approximate infrastructure losses. For the vulnerability assessment, direct costs are measured as repair and replacement costs of damaged buildings and equipment, using insurance company records. Secondary costs are approximated by the produced value-added dedicated to reconstruction, business interruption in the aftermath, and loss of housing services. These were computed by applying the Adaptive Regional Input-Output ARIO model (Hallegatte 2008) that describes the changes in production capacity due to capital productivity losses and adaptive behaviors in disaster aftermath. The study highlights that direct costs are a very poor proxy of overall costs. Nonetheless, indirect costs are found to be a small fraction of total costs even though they tend to increase non-linearly with direct costs through macroeconomic multiplicative effects. The policy implication is that adaptation measures should focus on direct costs.

Heberger et al. (2009) provide a more exhaustive analysis of exposure. They consider population, infrastructure, ecosystems, and population at risk using Geographic Information System (GIS) techniques and overlaying inundation and erosion geodata with socioeconomic geospatial data in order to assess the impacts of sea level rise for the Californian coast. They also provide estimates of the costs of structural measures, such as seawalls and levees. The study is close to the exposure and vulnerability assessments that have been undertaken by Nicholls and coauthors or by applications of the DIVA model (see Section 2.1.3), but being focused on one single region, it can be more detailed in the components characterizing exposure and vulnerability. In particular, the study evaluates the risk affecting a number of facilities: roads, utilities, schools, healthcare services, power plants, and natural resources, such as wetlands. The study tries also to account for the interaction with socioeconomic mechanisms, demographics, and environmental justice. It provides a breakdown of the affected population by race and it examines how residential tenure, income, and linguistic isolation affect the ability to undertake preventive measures. Results suggest that social and economic disparities matter, confirming that aggregated indicators, such as population at risk (PaR) or GDP, can only partially account for changes in exposure and vulnerability. These studies raise the question of scalability or replicability of case studies. The analysis of a virtual city as performed by Hallegatte et al. (2011) (in the specific case of a city with the same exposure as Copenhagen, but with lower protection levels) might be one way to proceed.

2.1.2 Cost-benefit approaches

The aforementioned studies are bottom-up assessments of exposure and risk that make ad hoc exogenous assumptions about adaptation levels and effectiveness. Fankhauser (1995) is probably the first in introducing a cost-benefit algorithm that allows the endogenous computation of the areas which are economically optimal to defend. The fraction of the vulnerable coasts to be protected is derived from the comparison of the value of land at risk and the protection cost. The optimal protection level minimizes the total sea level rise costs, including the net present value of protection costs, dryland, net wetland, and capital loss. Adaptation options are retreating (abandoning the area), accommodating (accepting the greater flooding), or protecting (building dikes). There is a trade-off between these strategies, as well as between dryland and wetland protection. Wetland cannot be directly protected, but wetland adjustments (inland migration) can be halted by dryland protection (coastal squeeze). Introducing the concept of optimality, protection is no longer uniform as assumed in previous studies, such as GVA1. Higher level of protection (100%) is observed in cities and harbors, where the value of land is high. Protection ranges between 75% and 80% in open coasts, and between 50% and 60%, in beaches.

Fankhauser’s methodology has been amply used in global assessments (Tol 1999; Tol 2002a; 2002b; Tol 2007; Nicholls and Tol 2006; Anthoff et al. 2010). Nonetheless, it has been criticized noting that the optimal protection levels being estimated appear to be unrealistic (much higher) when compared to those resulting from local studies for the UK (for example, Turner et al. 1995). High protection levels are ultimately driven by the high land and property values assumed. Moreover, they can also reflect the inability of the methodology to factor in the ability of real estate markets in order to anticipate the future hazards posed by sea level rise. As noted by Yohe (1991) and Yohe et al. (1996), if properly considered, these two elements should reduce the level of protection, because anticipation depreciates the value of the lost structure to zero at the future time of inundation. Wei-Shiuen and Mendelsohn (2005) apply the idea of Yohe to ten selected sites in Singapore and use the results to extrapolate a pattern for the country. They find very high protection levels even though they motivate the result with the increase over time of the value of the land at risk, already scarce in the sites considered, and with their optimistic assumptions about adaptation costs (they do not account for some components that could make protection much more expensive, such as disruptive effect of seawalls, time required to build seawalls).

The hypothesis of perfect foresight might work well in the case of erosion and gradual sea level rise, but it might become less appropriate when considering coastal storms, which are less predictable. In this case, the no-foresight assumption (which practically means to assign a positive value to the property or structure threatened) might be more realistic as insurance schemes are more likely to be inefficient or imperfect. West et al. (2001) argue that cost-benefit approaches, similar to Yohe et al. (1996), can still be used to evaluate the economic impacts of sea level rise and storms. The expected damage of storm can be assessed using insurance premium. That study highlights that sea level rise can induce indirect effects that amplify the damages of storms. In the same vein, Yohe et al. (2011) superimpose coastal storm to long-term sea level rise. They compare efficient insurance (foresight) versus unavailability of insurance (no foresight) and evaluate the effect of insurance availability on the ranking and comparison of two adaptation options, soft- (natural defenses characterized by a flow of expenditure over time) and hard-adaptation (characterized by large up-front investment costs) measures. The availability of an efficient insurance, by reducing or eliminating individual risk aversion, would reduce the value of adaptation and postpone the date at which big investment projects should start. Soft- rather than hard-adaptation is thus preferred. Should efficient insurance schemes not be available, risk aversion would increase the value of adaptation and the opposite would happen. Regarding scalability of case studies, Wei-Shiuen and Mendelsohn (2005) argue that the cost-benefit approach pioneered by Yohe et al. (1996) could in principle be applied to any number of locations within a given country, building a sample that could be used to extrapolate nation-wide estimates.

2.1.3. Combining exposure-based approaches and cost-benefit analysis

Coupling an exposure-vulnerability analysis (Section 2.1.1) with an optimization criterion (Section 2.1.2) at the global level would be a natural and desirable development of the socioeconomic analysis of sea level rise. The most notable effort in this direction is represented by the DIVA[4] model and database (Vafeidis et al. 2008). DIVA includes a global coastal database, a set of consistent climatic and socioeconomic scenarios, and a simulation model that allows evaluating the effect of climate and socioeconomic changes and adaptation of natural and human coastal systems at different scales, from regional to global. Both physical and economic impacts can be estimated. In the DIVA database and model, the world's coastal line is divided into segments that are homogeneous in terms of potential impacts and vulnerability to sea level rise[5]. The database gathers information on coastal topography (elevation, geomorphic type, tidal range, and landform type), population, protection status, and wetland. The model has a modular structure[6] and each module represents a specific coastal subsystem. DIVA can quantify the direct impacts of sea level rise both in physical (Km^2 of land lost) and economic (value of land lost and adaptation costs) terms. Different adaptation levels can be considered. Optimal adaptation reflects a cost-benefit comparison of sea level rise costs and adaptation costs. The costing and adaptation module computes the economic impacts of sea level rise and determines the level of adaptation. Table 3 summarizes the information for physical and economic impacts and for the adaptation options which are modeled.

[4] The DIVA tool is the output of the European Union (EU) project DINAS-COAST, funded by an EUFP5 project (DINAS-COAST Consortium 2006).

[5] The criteria used in the segmentation of the coastline are: (i) geomorphic structure of the coastal environment, (ii) potential for wetland migration, (iii) locations of major rivers and deltas, (iv) population density classes and (v) administrative boundaries. The model counts 12,148 segments with average length of 70km.

[6] The modules included are internal drivers for socioeconomic scenarios, relative sea level rise, river effect, wetland change, flooding, wetland valuation, indirect erosion, costing and adaptation, and World Heritage Sites.

Table 3. Impacts and adaptation options in the DIVA model as described in Hinkel and Klein (2006) and Hinkel et al. (2010)

	Physical/social impacts	Economic impacts	Adaptation options
Sea-Flooding	Flooding due to sea level rise and storm surge can be computed. Impacts can be computed in terms of *people in the hazard zone*, (people at risk), *average annual people flooded* (expected number of people subject to annual flooding) - people to respond, and *forced migration* (the number of people forced to relocate). Forced migration is computed from the coastal area permanently flooded times the population density in the areas.	Dry land loss is evaluated using the value of agricultural land, which has the lowest value. Inundated land for industry and housing usages will be converted into agricultural land. The value of agricultural land is a function of income density. The cost of floods depends on the expected damage and is logistic in flood depth. The costs of migration are calculated on the basis of loss of GDP per capita.	Costs of building dikes depend on the dike heights and are taken from Hoozemans et al. (1993). Benefits are influenced by several cultural and socioeconomic factors. A demand for safety, which drives the demand for dikes and dike height, increases with per capita income and population density and decreases in the cost of dike building. Dikes are not applied where there is very low population density (< 1 person/km^2) and above this population threshold an increasing proportion of the demand for safety is applied.
Erosion	Direct erosion on the open coast is computed according to the Bruun Rule (Bruun 1962). Indirect erosion (loss of land, sand, and demand for nourishment) is calculated using the ASMITA model (Kragtwijk et al. 2004), modified to account for beach nourishment. It assumes a linear relationship in sea level rise and beach nourishment. Marginal benefits of beach nourishment are constant. Only long-term sea level rise erosion is considered.	Dry land loss is evaluated by associating the dry land lost with the value of agricultural land. Tourism increases the value of land and a more expensive beach nourishment procedure will become optimal (as opposed to the shore nourishment which is cheaper and less immediate in its effect). The number of tourists and their spending is based on the Hamburg tourism model (Bigano et al. 2005).	Beach nourishment occurs if the costs (which are linear in sand supply) are less than the benefits (the value of the land protected from erosion). Nourishment costs are constant over time, since the technology is considered mature. They can vary across countries. Shore nourishment (when sand is placed below low tide) is substantially cheaper than beach nourishment when the sand is placed directly on the intertidal beach, but the benefits are not immediate.
Wetland loss and change	Total area of wetland loss compared to 1990. Wetlands comprise saltmarsh, freshwater marsh, mangroves, low and high unvegetated wetlands. The emergence of new wetlands (after 1990) is not considered.	Losses are monetized using the wetland valuation method of Brander et al. (2003), based on the meta-analysis of wetland valuation literature, which consider wetland type, size, location, national GDP, and population density	Wetland nourishment
Salinization	The span of salt water intrusion into the river and the land area affected by salinity are calculated. Intrusion of salt into the ground or surface water used for agriculture can reduce the yield.	The cost of salinity intrusion into river deltas is calculated in terms of the agricultural land affected. Saline agricultural land is half as valuable as non-saline land.	None

Applications of the DIVA model have mostly focused on Europe, though there are a number of ongoing applications to other regions[7]. Analyses based on the DIVA model have also provided widely-used inputs to top-down models (Agrawala et al. 2010; Bosello et al. 2012; Ciscar et al. 2012; Bosello et al. 2012; see Section 2.2). The PESETA project (Projection of economic impacts of climate change in sectors of the European Union based on bottom-up analysis) uses this version of the DIVA model (Vafeidis et al. 2008) to estimate the physical and monetary impacts of climate change on coastal systems in Europe (Richards and Nicholls 2009). The increase in sea levels considered ranges between 25.3 and 58.5cm for the A2

7 See for example the study for Japan and China, http://www.scribd.com/doc/70494572/Sea-Level-Rise-Impacts-and-Adaptation-Costs-for-Japan-ROK-and-PRC, or for Tanzania http://economics-of-cc-in-tanzania.org/images/Tanzania_coastal_report_draft_vs_2_1_.pdf accessed 13 August 2013.

scenario and 19.4 and 50.8 cm for the B2 scenario. A high sea level case of 88 cm is also analyzed. The analysis indicates that adaptation (beach nourishment and dikes) can reduce both land loss and people flooded by an order of magnitude between two and three (Table 4), with increasing positive net benefit since 2020. PESETA also offers a general equilibrium assessment of the related GDP implication, which is presented in Section 2.2.1

Table 4: Physical and economic impacts of sea level rise in Europe as estimated in the PESETA study for Europe.

	People		**Damage**		**Adaptation**	
	Flooded (thousands per year)		Cost (million/euro, 1995 values)		Cost (million/euro, 1995 values)	
Medium sea level rise scenario from the ECHAM4 model (43.8 cm in the A2 scenario and 36.7 in the B2 scenario)	A2	B2	A2	B2	A2	B2
2080s without ada	674	404	13796	12532	0	0
2080s with ada	35	24	1275	960	1300	990
	-95%	-94%	-91%	-92%		
High sea level rise scenario from the ECHAM4 model (58.5 cm in the A2 scenario and 50.8 in the B2 scenario)	A2	B2	A2	B2	A2	B2
2080s without ada	1420	909	18632.3	16097.3	0	0
2080s with ada	36	25	1453.5	1026.3	1717	1288.4
	-95%	-97%	-91%	-92%		

Hinkel et al. (2010) use a more recent version of DIVA with improved data on elevation[8] and higher resolution. Impacts are simulated for the A2 and B1 scenarios[9]. As shown in Table 5, Hinkel et al. (2010) find that the sum of damage and adaptation costs is significantly lower than damage costs without adaptation, in accordance with the PESETA simulations. The study also highlights the contribution of different impacts, with sea-flood and salt water intrusion being the most important in the short-run and migration becoming the main cost item in the second half of the century. The study also stresses the interaction with tourism. The rise in tourism increases the demand for protection in the form of beach nourishment as beaches become more valuable.

[8] What actually matters for sea level rise impacts is the relative sea level rise, which depends on vertical accuracy. Data from digital elevation models (Rabus et al. 2003) used in this paper are currently the most accurate, taken from the shuttle radar topography mission (SRTM).

[9] The climate module is another difference compared to PESETA. While Hinkel et al. (2010) used the DIVA default climate module CLIMBER-2, the PESETA project used the ECHAM4 and HADCM3 GCM, essentially for internal consistency.

Table 5: Physical and economic impacts of sea level rise in Europe as estimated in the Hinkel et al. (2010) study for Europe.

	People Flooded (thousand/year)		**Land Loss (km²/year)**		**Damage Cost (million euro/year)**		**Adaptation Cost (million euro/year)**		**Total Cost (million euro/year)**	
	A2	B1	A2	B1	A2	B1	A2	B1	A2	B1
2100 without ada	776.2	204.5	16.4	12.2	16,933	17,496	0	0	16,933	17,496
2100 with Ada	3.4	1,8	0	0	2,291	1,917	3,536	2,621	5,827	4,538
	-100%	-99%	-100%	-100%	-86%	-89%			-66%	-74%

Nicholls and Tol (2006) combine exposure-based approaches and an economic analysis with the FUND model (Section 2.2.2). The two methodologies are combined in a sequential manner. Anthoff et al. (2006) follow a similar approach, but improve the exposure analysis. A GIS method is used to overlay geophysical (elevation and tidal range) and socioeconomic data (population, GDP, national boundaries). The combination of different databases allows for a better description of the flood zone characteristics, which crucially affects the computation of exposure indicators.[10] It emerges that while East Asia and Europe are the most affected regions in terms of GDP, South Asia and East Asia are the most exposed in terms of population. Table 6 summarizes the basic characteristics of the most influential studies that apply bottom-up approaches. The next section reviews top-down approaches.

10 Results are still subject to a number of limitations that are involved when managing and overlying different global databases, such as matching data layer boundaries, variable resolution, data resampling, and input quality.

Table 6: Bottom-up approaches to sea level rise exposure, vulnerability, impacts and protection levels.

	Local, site-specific	Regional\Global
Exposure and vulnerability approaches	Yohe (1991) outlines an accounting methodology aimed at quantifing the net benefit of protection for the US coastal area of Long Beach Island, NJ (economic vulnerability). Kirshen et al (2008) in the analysis of sea level rise and storm surge impacts on the Metro Boston Area (USA) makes the point that adaptation also affects exposure and should thus be considered in risk analyses. Structural protection is more effective in highly developed areas, whereas less developed areas should be protected with more environmental friendly measures. Heberger et al. (2009) assess population, infrastructure, ecosystems and population at risk using GIS techniques and overlaying inundation and erosion geodata with socioeconomic geospatial data in order to also assess the impacts of sea level rise on ecosystems for the Californian coast. They also provide estimates of the costs of building structural measures, such as seawalls and levees. The study also tries to account for the interaction with socioeconomic mechanisms and demographics and environmental justice. The study provides a breakdown of the affected population by race and also examines how residential tenure, income, and linguistic isolation affect the ability to undertake preventive measures. Hallegatte et al. (2011) introduces a methodology based on 5 steps to evaluate people and asset exposure to sea level rise and storm surge, to assess the direct and indirect costs associated with economic activity disruption.	Global Vulnerability Assessment (GVA1, Hoozemans et al. 1993) provides the first global database to compute exposure and protection costs. Nicholls et al. (1999) builds on GVA1, but adds considerations based on future population and GDP. Nicholls (2004) estimates exposure for different SRES scenarios. Nicholls and Lowe (2004) extend the time horizon beyond 2080.
Cost-benefit approaches	Yohe et al (1996) build on their 1991 study, but also illustrate the decision to protect at 50x50 grid cell levels for various US coastal areas. West et al. (2001) show that, for each individual structure in a hypothetical community in the USA, sea level rise could have indirect effects that amplify storms damages, whose expected damages could be evaluated using insurance premium. Yohe et al. (2011) illustrate how the decision to protect, in terms of extent and timing, depends on the availability of efficient insurance and how risk aversion affects the value of adaptation. Two zones in the Boston areas are considered. Wei-Shiuen and Mendelsohn (2005) apply Yohe's methodology to ten sites in Singapore and find large value of protection levels, reflecting the increasing value of land due to land scarcity.	Fankhauser (1995) introduces a cost-benefit framework to evaluate optimal protection levels, which are found to be very high, because of the high damages assumed and lack of foresight. Hallegatte et al. (2007) develops a single-region Solow-type model to illustrate how equilibrium dynamics and constraints on reconstruction resources following a disaster affect the macroeconomic consequences of extreme events. They also define the economic amplification ratio.
Exposure and vulnerability approaches with a cost-benefit algorithm		Vafeidis et al. (2008) and more recently Hinkel et al. (2010) develop a global database (DIVA) that gathers information on coastal topography (elevation, geomorphic type, tidal range, landform type), population, protection status, and wetland and a model structured in modules that allows to perform exposure and vulnerability analyses under different adaptation levels, including optimal adaptation based on cost-benefit analysis.

2.2 Top-Down models

2.2.1. Computable General Equilibrium models

Computable General Equilibrium (CGE) analyses of sea level rise are usually part of broader integrated assessment exercises and they represent the end-of-pipe economic evaluation step of a soft-linking approach. The generation of scenarios for climate variables, the assessment of the physical impacts, and the economic evaluation derive from different modeling exercises, connected in a sequential process. Climate models generate sea level rise scenarios, which are used as inputs in coastal bottom-up models (such as DIVA) that generate changes in physical and biophysical indicators, such as loss in land or capital stock, and estimates of protection costs. Physical and biophysical indicators and protection costs are finally translated into shocks of key economic parameters represented in CGE models. The macroeconomic response to these shocks represents the economic assessment of the economy-wide impacts of sea level rise[11].

A seminal effort of coupling sea level rise and CGE is represented by the work of Darwin and Tol (2001). The FARM CGE model is used to assess the GDP implication of a 0.5 m sea level rise with and without optimal protection. The optimal land area to be protected is computed using the module of the FUND model (Tol 2002a, 2002b), which is based on the Fankhauser (1995) optimality condition. FARM offers a quite sophisticated representation of land and its value, which is not only differentiated by classes and uses, but also geographically as the model includes a GIS module. Sea level rise in FARM is simulated by reducing land and capital quantities by uses and classes. The cost of protection, the fixed capital and land lost are instantaneously subtracted from regional endowments, reducing the amount available for the final production of goods and services. In the no protection case, the annuitized total cost for 50 cm of sea level rise in 2100 reaches nearly US$66 billion globally. The highest losses occur in OECD countries (nearly US$7 billion in Europe). Asian economies as a whole would lose US$42 billion. The direct costs of optimal protection are a tiny percentage of the regional GDP. However, the impact on welfare, measured in terms of equivalent variation, is 13% greater, though distributed unequally. Welfare effects are larger in the developed regions (8 to 43%) rather than in the developing regions (4 to 10%). International trade tends to redistribute losses from high-damage to low-damage regions. The main limitation of the study is the comparative static nature. The sea level rise scenario is imposed on the 1990 socioeconomic situation and, therefore, economic impacts are likely to be underestimated.

Deke et al. (2002) use a dynamic recursive general equilibrium approach to study the implications of coastal protection costs, ignoring the physical direct impacts on land and capital loss. The costs of coastal protection are subtracted from investments, which reduces the capital stock, and hence economic output. According to their estimates, in order to cope with a 13 cm sea level rise in 2030, direct protection costs range from 0.003% of GDP in Western Europe to 0.01% in North Africa and the Middle East. The final GDP loss ranges from 0.006% of GDP in Western Europe and 0.087% in North Africa and the Middle East.

[11] Soft-linked approaches are amply used in integrated assessment as they can reach a high detail in the representation of each different dimension involved in the analysis. Nonetheless, the link between the different parts may show inconsistencies and non-converging solutions. In addition, the computational burden is high. This often precludes the possibility of fully performing intertemporal optimization exercises.

Bosello et al. (2007) also use a static CGE model to evaluate general equilibrium costs of 0.25 m of sea level rise and total protection. Differently from Darwin and Tol (2001) and Deke et al. (2002), protection costs are not subtracted, but rather added to investments with a displacement effect on consumption. In addition, the shocks are imposed on a projected economic system in 2050. When sea level rise is implemented as a loss of productive land, GDP losses are negligible and peaking at 0.03% in the China and India aggregate. When capital losses are also included, albeit remaining moderate, they increase significantly. The highest increase of about 10 times is experienced in developed regions, which have a higher value of capital at risk. Japan loses the most, incurring a cost of 0.054% of GDP. When total protection is assumed, GDP expands as forced higher investment inflates the economy. However, utility is smaller than in the case of no protection since consumption is reduced. Direct effects tend to be smaller than the final economy-wide impacts and the regional distribution is also different.

Bosello et al. (2012), within the PESETA project, highlight the vast gap between the direct costs estimated by the DIVA model and the economy-wide cost estimated with a static CGE model, when only the loss of land is considered. In 15 out of 25 countries, the direct costs of land losses are higher than the GDP costs, and their distribution also changes. Market mechanisms explain the cost redistribution. Land and agricultural prices increase, with a benefit for net food exporters such as the EU. The net GDP loss at the World level reduces the demand of energy commodities, causing a reduction in their prices, with negative effects on energy exporters. This leads to an improvement in the terms of trade of the EU. The authors offer some guidelines for interpreting the results. The static nature of the CGE model fails to capture the multiplicative effect of coastal-related investments and property losses. By modeling sea level rise as a loss of productive land, the effect primarily falls on the land-intensive agricultural sector. When effects on infrastructure and population are accounted for, impact estimates are much higher. Ciscar et al. (2012), within the PESETA project, apply the static CGE model GEM-E3 to analyze the joint impacts of climate change on tourism, agriculture, river floods and coastal system on the EU economy. The temperature increase considered ranges from 2.5°C to 5.4°C and sea level is assumed to rise from 0.49 m to 0.88 m, respectively. Resulting impacts are imposed on today's economy. Effects of sea level rise consist in floods and forced migration. Flooded areas and people displaced are taken from the DIVA model and they are implemented in the CGE model as loss of productive capital and additional household expenditure, respectively. This additional expenditure does not provide a welfare gain, but it represents a welfare loss since households are forced to migrate. Under these modeling assumptions, sea level rise represents a considerable share of welfare and GDP losses. In Europe, climate change can induce a welfare loss ranging between 0.22 and 0.98% and between 72 and 47% of them are due to the impacts on the coastal systems. They are particularly severe in Central and Northern Europe and reach 80% of total losses in the British Isles.

Sea level rise, by changing the availability and quality of coastal land, could affect tourism flows. An attempt to analyze the interaction between sea level rise and tourism has been made by Bigano et al. (2008). Their paper analyzes the economic implication of climate-induced sea level rise and tourism impacts. Tourism impacts are simulated with an exogenous change in market services demand. The economic impacts associated with tourism dominate the economic impacts associated with land loss due to sea level rise by roughly one order of magnitude. Only in South and South East Asia do the impacts lead to comparable economic losses. This suggests that demand-side impact, by affecting the composition of services consumption and thus production, is far more relevant than the relatively small supply side shock due to land loss, which prevalently affects agricultural industries. The study also shows that the GDP loss of joint impacts is greater than the sum of the GDP effects of the two impacts considered separately.

Bosello et al. (2010, 2012) within the CIRCE and the Climate Cost projects propose a similar analysis for the Mediterranean and the EU, respectively, using a dynamic CGE model. CIRCE analyzes impacts on sea level rise, tourism and energy demand impacts. The Climate Cost project also includes health, agriculture and river flooding. Both projects take input information on land lost from an updated version of the DIVA model. According to the CIRCE study the GDP loss would be 0.4% and 0.1% for Northern and Southern EU, respectively. According to the Climate Cost study the GDP loss would be 0.2% and 0.025% for Northern and Southern EU, respectively. The North African shore of the Mediterranean would have impacts somewhat in between North and South Europe. Compared to the static approaches, recursive dynamic models amplify the negative impacts through the multiplicative effect of disrupted investment that mimics infrastructural losses.

CGE assessments need information on biophysical losses of land, capital, and labor, and they cannot provide information regarding the optimal level of protection, if they are not through an iterative process that simulates different levels of protection and compares the associated welfare effects. They are also not able to provide information about the trade-off between adaptation and mitigation since they do not include a climate module and they do not model adaptation investments as a choice variable. Issues related to the optimal level of adaptation and the trade-off with mitigation can be addressed with top-down integrated assessment models, which are reviewed in the next section.

2.2.2. Optimal growth models

The first analysis of coastal protection in an optimal growth modeling framework has been developed by Tol (2007). The Solow-type FUND model version 2.8n[12] is used to simulate scenarios for population and economic growth. In the presence of climate change, they will follow a different path, as climate-induced migration and GDP losses are related to changes in temperature level. A stylized climate module (Tol 1999) translates emissions into temperature increases. As a part of the climate impact module (Tol 2002a, 2002b), coastal protection choices are based upon Fankhauser (1995). Therefore, FUND computes optimal protection by comparing projected protection costs with wetland and dryland losses and values.[13] The main finding of the study is that in sea level rise, adaptation is much more

[12] Version 2.8n runs at its maximal spatial resolution, 207 countries. This model version 2.8 has instead 16 regions.

[13] Land loss is linear in sea level rise;[13] the value of dryland is linear in income density; wetland values are logistic in per capita income; migration is a function of land lost and average population density. Migration costs are three times the regional per capita income per migrant. The migration costs, however, are low compared to sea wall construction costs. Wetland losses are caused by both the rising sea level and the building of protection measures. Anthoff et al. (2006) and Nicholls et al. (2008) suggest that the average slope of the coast increases above 1 m elevation (relative to high water). A linear assumption therefore is likely to overestimate impacts.

effective and viable than mitigation. Due to the slow reaction of sea level to temperature, mitigation can reduce sea level rise impact by 10% at most, while coastal protection can cost-effectively eliminate almost all negative impacts. Mitigation can also reduce adaptation costs. However, by reducing GDP, it also reduces the potential to adapt through an income effect which is more pronounced in rich countries.

Anthoff et al. (2010) enrich the FUND model in order to study the effect of "sizable sea level rise" (up to 2 m per century at the regional level). Protection costs are modified to be a function of the rate of sea level rise and the proportion of protected coast. They are calibrated to grow much more rapidly if sea level rise is faster than 1 cm per year. The study shows that total damages increase less than protection costs, nonetheless protection remains cost efficient. Among the cost components considered (dryland loss, wetland loss, migration, and protection costs) the most important in size are protection costs and wetland losses. Indeed, while wetland losses increase with per capita income, the other damage components decrease, because more protection is implemented. The study shows that adaptation reduces damages more effectively in the case of moderate sea level rise. The study also recognizes the risk of overestimating protection levels, which is generally shared by optimization, aggregate studies,[14] and underestimating the importance of retreating. This adaptation option could be favored if other environmental concerns, such as wetland preservation, or the risk of increased flooding and extreme events, which have been neglected by most modeling analyses, were taken into account.

Nicholls et al. (2008a) suggest that retreating could become preferable when considering the acceleration in global sea level rise associated with the collapse of the West Antarctic Ice Sheet. By coupling an exposure analysis (based on GIS data analysis) with an economic assessment based on the FUND model, their paper shows that when sea level rise increases above 2 m, the optimal protection rates fall from 85 to 50%. Nevertheless, protection costs increase dramatically to US$30 billion per year. They also discuss that such increase in protection investments would displace significant resources for other usages, an effect that cannot be captured by the FUND model.

3. Extreme events in coastal areas and sea level rise

Sea level rise is only one of the hazards coastal zones are exposed to and interactions with other natural (e.g. hurricanes) or climate- and human-induced geophysical changes (e.g. intensified hurricanes and subsidence) can exacerbate their reciprocal effects. For instance, mean sea level rise is likely to contribute to an increase in extremely high coastal water levels, which will affect exposure and sea level rise impacts. Analogously, more intense storms (in terms of maximum wind speed) and characterized by heavier precipitations, (Emanuel 2005; Webster et al. 2005; IPCC 2012) can strengthen the impacts of coastal flooding due to an average long-term trend in sea level rise.

The coupled impact of storm intensification, storm surge, and gradual increase in sea level rise is recent research. Physical factors have been assessed through tide/storm surge models on the Atlantic coasts of Europe and Canada (Gonnert, 2004, Danard et al. 2003; Demernard et al. 2002; Lowe et al. 2001). Characteristic of this modeling approach is the spatial detail, as

[14] Turner et al (1995) show that, although the protect strategy is economically justifiable on a region-wide basis in most scenarios, on a more localized scale 'do nothing and retreat' might be an optimal response.

spatial heterogeneity matters even within the boundary of a country (as an example see Lowe et al. (2001) for the UK). Extreme surge height could increase due to meteorological factors, but also due to changes in mean sea level, which is the dominant factor in most areas. McInnes et al. (2009) and Brown et al. (2010) examine the relative impact of mean sea level rise in Australia and wind speed in Ireland, concluding that sea level rise has a larger potential than meteorological changes to increase extreme sea levels. Mousavi et al. (2011) use a hydrodynamic model for hurricane and flood elevation in order to evaluate the effect of warming (sea surface temperature) on hurricane intensity and the impact of hurricane surge on flooding. Sea surface temperature projections are obtained from the MAGICC/SCENGEN model (Wigley, 2004) for three IPCC future climate scenarios B1, A1B, and A1FI, varying the climate sensitivity. Future hurricane intensity scenarios were developed by combining projected sea surface temperatures and historically observed pressures for three selected historical hurricanes. The study shows that in some areas hurricanes could contribute to flooding and damage as much as sea level rise. These studies just inform about the changes in the hazard that could be posed to exposed areas. The remainder of this section reviews the studies that analyzed the combined exposure and vulnerability to sea level rise and storm surge.

Nicholls et al. (2008) estimate and rank the exposure of major coastal cities with more than 1 million inhabitants in 2005 to coastal flooding due to high wind and storm surge. They combine the effect of a global sea level rise of 0.5 m with subsidence and the intensification of storms. The latter effect is captured by a storm enhancement factor that reflects the potential increase in extreme water levels due to more intense storms. The enhancement factor is set at 10%, based on Walsh and Ryan (2000), who estimated that a 10% increase in tropical cyclone intensity leads to a 10% increase in 100-year storm surge level. Depending on the region, areas can be exposed to extreme water levels between 0.5 and 1.5 m. Having computed city population, elevation data are used to derive population exposed. Assets exposed are computed by multiplying exposed people and per capita income. The analysis is based on exposure, and it does not consider the effect of protection, except for the few cities with known protection standards. The study indicates that sea-level rise alone leads to larger exposure compared to storm intensification. Nicholls et al. (2010) using the DIVA model find that the additional protection costs due to a 10% increase in tropical cyclones would be 9% in 2040. Though this could be higher (13%) in some regions, it remains low compared to the overall additional costs due to high sea level rise.

Dasgupta et al. (2009) apply a similar methodology globally. GIS analysis is used to estimate the impact of future storm surge increases associated with more intense storms and a 1 m sea level rise. Data on coastal attributes and surge are from DIVA. After delineating future inundation zones, this information is overlaid with indicators for coastal populations, settlements, economic activity, and wetlands. Results clearly stress that highly vulnerable, large cities and losses are concentrated at the low end of the international income distribution. The major limitation of this study is to assume population, socioeconomic and land use patterns which are constant at today's values. The study also excludes small island states from the analysis, which are particularly vulnerable due to the large fraction of land at low elevation.

To our knowledge the macroeconomic effects of coastal disaster and sea level rise together have not been analyzed yet. However, a number of recent top-down analyses of extreme events have introduced new approaches that could be useful for that purpose.

For instance, CGE models have been also used to evaluate ex post the economic impact of a particular extreme event. Farinosi et al. (2012) combine a detailed spatial analysis of flood exposure and vulnerability with a CGE model for Italy. GIS techniques are used to estimate the direct costs of floods which are also the input to the CGE model that computes the indirect or general equilibrium costs. This specific study considers land loss for agriculture, capital loss in industry, commercial, residential services and infrastructure damages, and labor productivity loss due to suspension from work. Sue Wing et al. (2013) use a regional CGE model and scenarios for the ARkstorm model (Porter et al. 2010) to study flood effects in California. That study introduces impacts as changes in total factor productivity (loss in agricultural output rather than in land) and accounts for the lifeline losses by imposing an adverse neutral productivity shock on the Armington supplies of utility services in each county. An interesting result is that as long as markets can adjust immediately and completely with no frictions, the shocks imposed on capital are absorbed quickly, through price-induced substitution among production factors and consumed goods (Lanzi and Sue Wing 2013). Also growth models have been applied. Hallegatte et al. (2007) use a single-region Solow-type model to compare the economic consequences of an extreme event on two similar economies, but with different economic dynamics. One of the two economies is on the balanced-growth path, while the other experiences a transient disequilibrium. They also explore the implications of constraints on the financial resources that can be mobilized for reconstruction every year. The paper shows that both assumptions significantly increase the economic costs of extreme events. Moreover, the recovery from a shock becomes much longer (extended by three years under realistic assumptions), especially under limited reconstruction investments.

Top-down, long-term models, as well as exposure and vulnerability-based studies cannot be expected to reproduce the total effects of an extreme event and this would probably apply to coastal disasters as well. Both approaches under-represent indirect effects (migration and consequent long-run effect on growth, see for example Zissimopoulos and Karoly 2007[15]), social and institutional aspects (political stability, inequality, education, trade openness, financial development, government burden) and more generally elements that are difficult to translate into monetary values. Cavallo and Noy (2011) show that only disasters followed by political revolution have a persistent (lasting 10 years) effect on economic growth, indicating that the political stability of a country and institutional conditions certainly influence a country's vulnerability to disasters.

[15] To our knowledge only Ciscar et al. (2012) make an attempt to account for forced migration due to sea level rise.

Table 7: Top-down approaches to sea level rise and extreme events impacts and protection costs.

Sea-level rise				
Study/CGE model	**Sea level rise impacts (source of input data)**	**Time treatment**	**Protection costs**	**Estimated GDP change**
Darwin and Tol (2001)	Land and capital loss (GVA and Bijisma et al. 1996) reduce endowments.	Static	Optimal protection provided by the FUND model based on Fankhauser (1995) module. Land loss and protection costs (GVA and Bijisma et al. 1996) reduce capital endowment.	Max annuitized costs of a 50m sea level rise reported in OECD (Europe, 7bn).
Deke et al. (2002)		Recursive-dynamic	Protection costs (from survey of 23 case studies) reduce investments for capital accumulation equation.	Economy-wide costs (0.087% and 0.01% in Western Europe and Northern Africa and Middle East, respectively) are larger than direct costs (0.003% and 0.006%, respectively) for a 13 cm sea level rise in 2030.
Bosello et al. (2007)	Land and capital loss (GVA and Bijisma et al. 1996) reduce endowments.	Static	Protection costs (GVA and Bijisma et al. 1996) increase investment, but displace consumption.	Economy-wide costs smaller than direct costs. Max cost of 0.25 m sea level rises when capital loss is accounted for occurs in Japan (0.054%).
Bigano et al. (2008)	Land loss (GVA and Bijisma et al. 1996) reduces endowments and tourism expenditure increases market services demand.	Static	Not included.	Impacts associated with changes in tourisms are larger than the direct impacts of sea level rise (max cost of a 25 cm sea level rise 0.1% of GDP vs. 0.5% of GDP of the hit region).
Bosello et al. (2012)	Land loss (DIVA, PESETA project).	Static	Protection costs (DIVA) increase investment, but displace consumption.	While sea level rise has negative and huge direct economic effects, overall effects on GDP are quite small (max -0.046% in Poland).
Ciscar et al. (2012)	Capital loss (DIVA, PESETA project) reduces endowments.	Static	Migration costs. Forced migration increases household expenditure.	Welfare effects of sea level rise impacts range between 72 and 47% of total impacts, which vary between 0.22 and 0.98% of GDP).
Bosello et al. (2012)	Land and capital loss (DIVA, Vafaeidis et al. 2008) reduce endowments.	Recursive-dynamic	Not included.	Max costs about 0.3% in South Asia, yet much lower than direct costs, about 4%.
Extreme events				
Study/CGE model	**Sea level rise impacts (source of input data)**	**Time treatment**	**Protection costs**	**Estimated GDP change**
Farinosi et al. (2012)	Spatial analysis of flood exposure and vulnerability with a CGE model for Italy.	Static	Not included	Country level (Italy): 0.08% Industry: -0.106%
Sue Wing et al. (2013)	ARkstorm	Recursive-dynamic	Protection costs (from survey of 23 case studies) reduce investments for capital accumulation equation.	Economy-wide costs (0.087% and 0.01% in Western Europe and Northern Africa and Middle East, respectively) are larger than direct costs (0.003% and 0.006%, respectively) for a 13 cm sea level rise in 2030.

4. Shortcomings and directions for future research

In the context of sea level rise impact analysis, the tendency to combine bottom-up risk assessments with macroeconomic analyses is becoming more prominent. This methodology has been applied in several European projects with a European (PESETA, Ciscar et al. 2012, Climate Cost, Bosello et al. 2012) and Mediterranean (CIRCE, Bosello and Shechter, 2013) focus. An effort to link the DIVA model with the MIT IGSM-EPPA model on a global scale is also under development (Sugiyama et al. 2008). In the context of extreme events, an emerging methodology is also to combine scenarios of a particular event in a specific location with CGE models of regional economies (Farinosi et al. 2012, Sue Wing et al. 2013).

At least three issues which are not yet satisfactorily resolved remain to be tackled by future research. First, improve the accuracy of the bottom-up, risk assessments. Second, improve the detail and resolution of top-down assessment. Third, and probably most importantly, improve the communication between bottom-up and top-down methodologies. On the one hand, this requires developing consolidated practices to translate bottom-up results into inputs suitable to top-down models. On the other hand, it requires tailoring top-down models to receive inputs from bottom-up studies, minimizing the information loss.

4.1 Exposure and vulnerability based approaches

Exposure and vulnerability assessments have mostly focused on people and a narrow definition of assets at risk, which basically coincide with building and land property. Often the definition of future exposure is determined by projections of population and GDP. The appeal of this methodology is its obvious simplicity. However, it clearly neglects the interaction of sea level rise with other socioeconomic components. For instance, it does not consider trends regarding urbanization, income and population distribution within a given area, race and segregation, insurance coverage, legal residency status, residential tenure, quality of housing which do affect vulnerability and the ability to respond or to put in place preventive measures (Heberger et al. 2009). Moreover, future policies would also influence the evolution of the aforementioned variables with an impact on adaptive capacity that needs to be considered.

The topical example of these limitations is the DIVA model. Although, if compared with seminal efforts, it greatly improved the spatial resolution,[16] the modeling of impact categories and adaptation options, yet it presents many shortcomings. For instance, the response of each coastal segment is assumed to be homogenous within each segment. Land-use patterns are assumed constant throughout the century. The database does not include information on the distribution of capital on coastal areas nor on coastal socioeconomic dynamics. Coastal GDP and population are assumed to grow at the same speed as the national country average. Adaptation options represent still a limited subset of those available. Protection costs are proportional to protection levels and they neglect issues of materials and resource scarcity, such as sand.

[16] Compared to GVA, the first global assessment on coastal vulnerability, the number of coastal segments has increased from 191 to 12,148.

To date, only some sub-national analyses (such as that of the aforementioned Herberger et al. 2009) attempted to overcome these limitations.

4.2 Top-Down Studies

The challenge top-down models are confronted with is twofold and concerns first, which processes are represented and second, how to model the associated effects. To date top-down studies have incorporated the information provided by bottom-up studies only in part. These are generally land loss, capital loss, migration, and change in tourism flows. For example, none of the CGE analyses reported in Table 7 includes salt water intrusion and wetland losses, which could represent a significant and possibly one of the largest components of damages (Anthoff et al. 2010; Dasgupta et al 2009; Nicholls 2004; Sugiyama et al. 2008). The aggregation from national or sub-national scale to macro-regions makes it difficult to account for local damages and adaptation characteristics.

The modeling choices made to represent and translate bottom-up inputs into top-down models are not neutral either as, for example, illustrated by the different economy-wide estimates by Ciscar et al (2012) and Bosello et al. (2012) in the context of the PESETA project. For instance, the same phenomenon of migration induced by sea level rise can be modeled either by increasing unproductive household expenditure or by reducing labor productivity-supply, leading to different outcomes. Similarly, the costs of coastal protection can be modeled as an expenditure displacing investments in national capital stocks, thus not contributing to the production of GDP (Deke et al. 2001), or as a forced investment, increasing capital stock, but crowding out final consumption (Bosello et al. 2007) .

Top-down models are also ill-suited to capture frictions in adjustments as both optimal growth and CGE models tend to assume a fixed or increasing possibility to substitute factors of production. This might be reasonable in the case of long-term smooth sea level rise. When considering coastal disasters however, the event itself and the consequent lifeline interruptions might impair factor substitution especially with respect to the lost capital with other inputs. Reduced substitutability will likely increase short-term impacts of extreme events. This might also explain, more generally, the low impact estimates from top-down assessments. Another motivation hinges on the use of GDP as a measure of losses. It is well known that it is a flow measure that captures only indirectly property losses, which are among the main cost item associated to sea level rise. In addition, models based on economic equilibrium and efficient markets tend to underestimate protection costs. Even though investments are considered, operation and maintenance expenses or other auxiliary cost components (such as expensive gates to maintain harbor activity or pumps to complement dikes) are often omitted. Similarly, possible negative effects associated with especially hard protection measures, such as visual impact of dikes with negative impacts on tourism, the loss of ecosystems, are rarely accounted for. The implication is a tendency to overestimate optimal protection levels and to underestimate the advantages of the retreat option. This adaptive response could be favored if environmental concerns, such as wetland preservation or the risk of increased flooding and extreme events, or of accelerating sea-level rise were taken into account (Turner et al. 1995; Nicholls et al. 2008a).

The optimization approaches that have been proposed in the literature (mostly by Tol and coauthors) based on the optimality condition initially suggested by Fankhauser (1995), can be improved along many directions (Suygima et al. 2008). Other forms of protection, such as beach nourishment, and of impacts, such as wetland loss can be added. Protection levels can be made time-varying. Sea level adaptation can then be built as a choice variable within the optimization process of models themselves, following the procedure used to model adaptation in Integrated Assessment Models, such as the AD-DICE/AD-RICE/AD-WITCH (Agrawala et al. 2011). Adaptation to sea level rise could be combined with the reduced form module for sea level rise impacts introduced by Nordhaus (2010)[17] and with the module to represent extratropical cyclone damages developed by Narita et al. (2010) or Mendelsohn et al. (2012). Coupling the effect of storms and sea level rise requires a link between the two (Walsh and Ryan 2000). This link could be retrieved from Mousavi et al. (2011) whose model formulation is simple and could be implemented in virtually all integrated assessment models that have a climate module. Some issues to be resolved would still remain linked to the use of statistical methods proposed by Narita et al. (2009) and Mendelsohn et al. (2012) to estimate reduced-form relationships between the entity of the damage and storm characteristics and between selected endpoints and damage. Firstly, the selection of the dependent variable is not straightforward. Natural candidates are indicators of number of lives lost or of economic damages as reported in Emergency Disaster Database EM-DAT, which however should be used with particular attention (Loayza et al. 2009). But sea-level rise and coastal disaster affect many sectors and activities Secondly, the use of statistical approaches itself can be problematic when, as in the case of sea level rise, the change is very long-term (Vermeer and Rahmstorf, 2009; Rahmstorf, 2007). Thirdly, a reduced-form module for sea level rise would still have a limited ability to capture the spatial characteristics of sea level rise and storm surge and its sectoral implications.

The analysis of sea level rise and coastal disasters impacts in the presence of uncertainty also needs more research. While there is extensive economic literature related to climate change, damage uncertainty and mitigation policies[18] the adaptation literature has only marginally studied the effect of risk and uncertainty on adaptation choices. Some indications are offered by the theoretical work by Kane and Shogren (2000), Ingham et al. (2007) and Yohe et al. (2011), which focuses on coastal adaptation under uncertainty. They focus on efficient insurance (foresight) versus unavailability of insurance (no foresight) and evaluate the effect of insurance availability on the ranking and comparison of two adaptation options, soft- (natural defenses, characterized by a flow of expenditure over time) and hard-adaptation (characterized by large up-front investment costs) measures. They highlight how the availability of an efficient insurance, as a way of reducing/eliminating individual risk aversion, would reduce the value of adaptation and postpone the date at which big investment projects should start. Should efficient insurance schemes not be available, risk aversion would increase the value of adaptation.

Finally, a general remark pertains to the information exchange between top-down and bottom-up studies and the appropriate form for this connection. What is the suitable form also depends on the purposes for which different approaches are made. In our view, top-down models should not be used to determine which and where a specific adaptation measure has to be adopted, but rather to inform about the economic consequences of implementing the

[17] The module distinguishes the contribution of thermal expansion, glaciers and small ice caps, as well as the Greenland and the Western Antarctic Ice Sheet.

[18] The literature on mitigation under uncertainty has pointed out two policy responses, hedging and wait-and-see. Yohe et al. (2004) suggest that some degree of early mitigation (hedging) is rational. Nordhaus (2007) suggests that for moderate risk aversion and moderate smooth damages the optimal abatement does not significantly deviate from the deterministic, expected value policy. As a consequence, uncertainty about gradual sea level rise and about coastal storms and disasters might have different policy implications.

measures suggested by bottom-up models or approaches. This has two major implications. The first concerns the spatial resolution and process representation of top-down assessments. The level of country or macro-regions is too coarse to represent the richness of spatially-resolved bottom-up studies, therefore finding ways to maintain part of the geographical detail would offer an important improvement. The second concerns the use and interpretation of the results generated by top-down, optimization exercises. Those should aim at offering cost-efficiency comparisons and rankings of alternative adaptation types rather than quantitative and practical advice on how different measure should be implemented in various locations.

5. Conclusions

This paper has surveyed the modeling approaches used to assess the climate change impacts and adaptation to sea level rise and extreme events related to coastal areas. We have identified five major approaches, each of them with specific pros and cons: exposure and vulnerability approaches, cost-benefit approaches, an attempt to combine risk analysis and cost-benefit policy evaluation on a global scale, general equilibrium assessments, and integrated modeling assessments.

We classify the first three approaches as bottom-up, because they provide spatially-resolved information, but generally do not account for the feedback of sea level rise coastal impacts on the macro-economy and on the social context, especially when the study is global in scope. However, more recent studies have made some progress in extending the coverage of secondary effects, to include also socioeconomic components and demographic effects. The last two approaches belong to the category of top-down, macroeconomic models. They provide an economic assessment of the economy-wide costs of sea level rise and extreme events. These analyses are less detailed in the spatial and technical descriptions of coastal characteristics, impacts, and adaptation, but characterize economic behavior and macroeconomic interactions either in terms of the market adjustments or in terms of the long-term, growth dynamics.

Although the two methodologies were initially separate, the tendency toward integrated risk analyses with computable general equilibrium approaches to track market reactions and adjustments is becoming a prominent methodology of analysis. Yet there are a number of areas where future research could improve both methodologies. Most exposure and vulnerability assessments still neglect many social or even sociological aspects playing a role in impact determination, such as urbanization, income and population distribution, race and segregation, insurance coverage, legal residency status, residential tenure, and quality of housing. These issues are partially considered site-specific case studies. An issue that remains to be solved is that of scalability to national level and the replicability to other cases. Top-down models can highlight some macroeconomic implications of sea level rise, but they are very stylized in the representation of the processes that bottom-up studies can consider and are even unable to model many of those processes. Most top-down models, based on economic equilibrium and efficient markets, are still ill-suited to capture frictions and delay in adjustments, implicitly assuming huge adaptation potentials and underestimating protection costs. Moreover, the spatial detail of top-down models is still too coarse to allow a really informative integration with bottom-up researches.

Notwithstanding all these limitations, caveats and differences in results, some robust policy implications can be highlighted. In general, coastal protection appears to be a very cost-effective strategy. This has been highlighted by different studies, conducted with different methodologies. This broad consensus needs to be interpreted in the light of local conditions though. For instance, more recent research indicates that retreating might be an option that should deserve more attention than what early studies suggested, especially in the presence of accelerating sea level rise, of the risk of flooding and extreme events. However, in many regions the resources needed for planning and investing in coastal protection may not be available, and financial and institutional barriers could hinder the actual implementation or the effectiveness of adaptation projects.

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