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Climate change, sea level rise, and coastal disasters. A review of modeling practices☆

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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 zone 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.

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 (McGranahan et al., 2007; Small and Nicholls, 2003). 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$3000 billion, corresponding to around 5% of global Gross World Product (Nicholls et al., 2008a). Exposure is expected to increase with growing population and economic relevance of coastal cities, particularly in developing countries Nicholls et al., 2008a). 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 2 m increase in sea level by 2100 could occur under extreme assumptions then an increase of 0.8 m 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 et al., 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, 2007). However, the evidence connecting global warming and storms remains uncertain, although some studies found that warming could increase the intensity of tropical storms (Emanuel, 2005; Meehl et al., 2007; Webster et al., 2005).

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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 the shortcomings of various approaches and discusses the 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., 2008a). Climate drivers include global sea level rise, CO_2 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, 1992) 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 and 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 (Sections 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 Heberger 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 (Cardona 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, 1992). 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.[1] 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.

The large number of studies using the database or some of its components (Bigano et al., 2008; Bosello et al., 2007; Darwin and Tol, 2001; Hinkel and Klein, 2007; Hinkel et al., 2010; Nicholls, 2004; Nicholls et al., 1998, 1999, 2008a; Tol, 2007; Vafeidis et al., 2008) 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

[1] 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.