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Integrated assessment of sea-level rise adaptation strategies using a Bayesian decision network approach☆,☆☆

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ABSTRACT

The exposure to sea-level rise (SLR) risks emerges as a challenging issue in the broader debate about the possible consequences of global environmental change for at least four reasons: the potentially serious impacts, the very high uncertainty regarding future projections of SLR and their effects on the environmental and socio-economic system, the multiple scales involved, and the need to take effective management decisions in terms of climate change adaptation. Unfortunately, mechanistic models generally demonstrated a limited ability to characterise in appropriate detail how complex coastal systems and their constituent parts may respond to climate change drivers and to possible adaptation initiatives. The research reported here develops an innovative methodological framework, which integrates different research areas – participatory and probabilistic modelling, and decision analysis – within a coordinated process aimed at decision support. The effectiveness of alternative adaptation measures in a lagoon in north-east Italy is assessed by means of Bayesian Decision Network (BDN) models, developed upon judgments elicited from selected experts. A concept map of the system was first developed in a group brainstorming context and was later evolved into BDN models, thus providing a simplified quantitative structure. Conditional probabilities, quantifying the causal links between the direct and indirect consequences of SLR on the area of study, are elicited from the experts. The proposed methodological framework allows the integrated assessment of factors and processes belonging to different domains of knowledge. Moreover, it activates an informed and transparent participatory process involving disciplinary experts and policy makers, where the main risk factors are considered together with the expected effects of the adaptation options, with effective treatment and communication of the uncertainty pervading the SLR issue. Finally, the framework shows potentials for being further developed and applied to consider new evidences and/or different adaptation strategies, and it results sufficiently flexible to be adopted and effectively reused in other similar case studies.

1. Introduction

Global environmental change encompasses physical and biogeochemical modifications of ecosystems of natural or anthropogenic origin that have direct or indirect consequences on our societies. Given the relevance of coastal areas for a multitude of different reasons (density of human settlements, biodiversity richness, life support functions, etc.), sea-level rise (SLR) is considered as one of the most relevant phenomena of global change for its potential consequences on coastal habitats and ecosystems, but also on socio-economic activities (Klein and Nicholls, 1998; Smith and Raper, 2000; EEA, 2004). Biogeophysical effects of sea-level rise, such as increase in flood frequency, erosion, saltwater intrusion, etc., directly impact on ecosystems and coastal habitats, and directly or indirectly damage socio-economic activities and infrastructures.

In many coastal areas, unsustainable development and overexploitation of natural resources have increased the vulnerability to the natural dynamics and effects associated with sea-level variability, by decreasing the system's resilience, in terms of its "ability to cope with additional pressures" (Klein, 2002). Global environmental change can potentially enhance the stress on systems that are quite often already under significant pressures. In particular, the exposure to SLR risk emerges as a challenging issue for at least four

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reasons: (i) the potentially serious impacts, (ii) the very high uncertainty, (iii) the multiple scales involved, and (iv) the need to take management decisions in terms of climate change adaptation, which should guarantee at least against the risk of potential future negative side effects (so called "maladaptation").[1]

Several drivers influence sea levels, and they change if we consider long or short-term timescales, and the global or local scales. Global environmental change and its cascade of effects on water dynamics, density, ice masses, etc. is one of the most relevant drivers over long-term projections (Chu-Agor et al., 2011) and the human dimension plays an even greater role (Moser, 2005). In order to prevent the negative consequences of SLR, and to assess and plan the possible measures to adapt to their impacts, several studies have been carried out, estimating the future trends of the main factors that affect sea-level variability, and their interactions with coastal ecosystems and our societies (IPCC FAR, 2007a; Antonioli and Leoni, 2007; Church et al., 2004; Mcleod et al., 2010).

The high number of variables and processes to be considered when assessing sea-level dynamics, and the complex system of interactions among them, result in a widespread uncertainty in the estimates and in future projections of sea-level variability. The global mean sea-level scenarios prepared by the IPCC for the Fourth Assessment Report (IPCC FAR, 2007a) indicate a range of growth comprised between +0.18 m and +0.59 m by 2100, reflecting some progress towards reduced uncertainty with respect to the Third Assessment Report (IPCC, 2001), which indicated a range between +0.09 m and +0.88 m. Nevertheless, the spread of global projections is still very high and local sea-level changes may significantly depart from the global mean, due to regional variations in oceanic level and geological uplift or subsidence. Local climate characteristics, such as temperature, precipitation, wind and pressure patterns, as well as variations in ocean circulation and water density, also affect sea-level variability.

Nicholls and Leatherman (1995) classify the physical impacts of sea-level rise into different categories, reorganised into the list of biogeophysical effects identified by Klein and Nicholls (1998): (i) erosion and sediment deficit; (ii) saltwater intrusion into internal aquifers; (iii) increased flood frequency; (iv) inundation of low-lying areas; (v) rising of water tables; and (vi) consequent biological effects. Coastal erosion could cause wetland loss, affecting the peculiar natural habitat, and could also have impacts on economic activities, such as tourism, due to beach erosion. Saltwater intrusion into freshwater systems, and in particular into aquifers, would have relevant ecological implications, leading to significant modifications of the habitats of various animal and plant species. Those impacts can also negatively influence agriculture, through soil salinization and salt contamination of irrigation water, and would finally represent a risk for public health and more broadly for human welfare.

In general, the increased frequency of flooding and the inundation of low-lying areas represent the two most evident impacts of sea-level rise. The degree of risk will depend also on the susceptibility of human settlements on the coast and on the effectiveness of existing defensive structures.

Adaptation to the impacts of sea-level rise is thus an important component of countries' strategies to cope with the expected negative consequences of global change (EC, 2007; IPCC CZMS, 1990; IPCC, 2007a; Klein and Nicholls, 1998; Klein et al., 2000, 2001; Evans et al, 2004; Brooks et al., 2006; Levina and Tirpak, 2006). The classification of adaptation options proposed by the report of the Coastal Zone Management Subgroup of the International Panel on Climate Change (IPCC CZMS, 1990), is still a reference for the development of local adaptation plans:

- *Protection*, based on the defence of vulnerable areas where population settlements, economic activities and natural resources are located, by decreasing the probability of occurrence of a negative event and increasing the robustness of infrastructural designs and long-term investments;
- *Accommodation*, which involves the continued use of vulnerable areas, and the enhancement of society's ability and flexibility to cope with the impacts and its resilience to recover after possible hazardous events;
- *Retreat*, which implies the abandonment of vulnerable areas and the resettlement of inhabitants and activities, in order to limit the potential damage and to improve the resilience of coastal wetlands, allowed to migrate inland.

The inadequate knowledge of coastal conditions, due to lack of long-term data for key coastal descriptors, is only one of the numerous impediments to the success of climate change adaptation in coastal areas. The main difficulties concerning the definition and especially the implementation of efficient adaptation strategies to SLR impacts are linked to the complexity of coastal systems, where natural and human factors dynamically interact. The limited ability to characterise in appropriate detail how those systems, and their constituent parts, evolve and respond to climate change drivers and to adaptation initiatives increases the uncertainty and the difficulty to define and choose appropriate adaptation options. Fragmented institutional arrangements, weak governance, and societal resistance to change, further complicate the implementation process (IPCC, 2007b).

There are also important trade-offs between the possible adaptation strategies, as in the following examples. Hard protection measures might be able to control or reduce the impacts of sea level on socio-economic systems, but at the same time they would damage the associated natural ecosystems due to coastal squeeze (Knogge et al., 2004; Rochelle-Newall et al., 2005; IPCC, 2007b). Managed retreat could represent an alternative solution, but its consequences on socio-economic systems should be taken into account. In general it is clear that decisions on adaptation options will need to consider and integrate social, economic and ecological concerns (Adam, 2002).

As suggested by Morgan and Henrion (1990), the analysis of climate change policy should aim at being "comprehensive and analytic, encompassing as much as possible of the causal chain that connects human actions to their influence on global climate, and carrying out probabilistic numerical estimates". Several models to analyse the potential impacts of SLR have been developed over recent years (Mcleod et al., 2010), but they are not always able to characterise and simulate with appropriate detail the dynamics through which extremely complex coastal social and ecological systems may respond to climate change drivers and to possible adaptation initiatives. Moreover, in many cases the data requirements of models cannot be fully satisfied, and thus growing attention is being paid to the knowledge owned by disciplinary experts. Techniques for gathering ("eliciting") the experts' knowledge are thus increasingly applied in environmental analyses and policy support, in cases of particularly complex phenomena and lack or scarcity of data (see for example in the climate change field Nordhaus, 1994; Morgan and Keith, 1995; Morgan et al., 2001).

[1] One of the most comprehensive and widely adopted definitions of adaptation is probably the one indicated in the IPCC Third Assessment Report: "adjustment in ecological, social, or economic systems in response to actual or expected climatic stimuli, and their effects or impacts. This term refers to changes in processes, practices or structures to moderate or offset potential damages or to take advantage of opportunities associated with changes in climate" (IPCC, 2001). "Maladaptation" can thus be intended, in brief, as any response to climate change showing significant negative side effects.