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REVIEW ARTICLE

What lurks below the surface? Exploring the caveats of sea level rise economic impact assessments

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Abstract This paper draws insights from multi-disciplinary research into sea level rise (SLR) in order to identify and critically evaluate the impact that assumptions underpinning SLR projections, damage assessment, and economic valuation have on the predictive accuracy of SLR economic impact assessments. The analysis demonstrates that economic models of SLR impact are, in the best case, guesstimates based on inexact data, and in the worst case, misleading works of politically infused fiction. In order to extract value from such studies and "speak truth to power", it is essential that critical assumptions associated with data that goes into the construct of such models are transparently disclosed to allow users of such assessments to fully understand the limitations to the modeling exercise and the inherent risks that may undermine the verity of projected outcomes.

Keywords Climate change · Sea level rise · Economic impact assessment

Introduction

In theory, economic modeling to evaluate policy alternatives has intuitive appeal. For any given policy challenge, there are a host of potential solutions and some basis is required to guide the decision-making process. In economic modeling, costs and benefits (economic, social, environmental etc.) associated with a given alternative are identified and assigned an economic value. Summing the costs and benefits of each alternative allows prospective solutions to be compared on a common basis.

In practice though, economic modeling of phenomenon in complex, adaptive systems is never as scientifically objective as economists hope, engendering often deserved criticism that economics has become scientific by becoming statistical (Schumacher 2010/1973). Critical assumptions that go into the construction of economic models may be erroneous or confounded by unanticipated developments, thereby undermining the predictive accuracy of the analysis (Cook and Campbell 1979). At the extreme, policy based on erroneous assumptions can be cataclysmic. Consider the Fukushima nuclear disaster of March 2011. The Fukushima Daiichi nuclear power plant was constructed with a sea wall barrier designed to protect the plant from tsunami waves up to 5.7 m high. The tsunami that plowed into the Fukushima plant on that fateful day in 2011 was estimated at 15 m tall. This one assumption made at the planning stage arguably meant the difference between minor damage and widespread disaster (Aldhous 2012). The geopolitical quagmire precipitated in large part by the US decision to deviate from United Nation Security Council consensus and send troops into Iraq in 2003 in pursuit of weapons of mass destruction represents another recent example of the cost of policy based on erroneous assumptions.

Even if the impossible were probable and the threat of modeling error could be eliminated, assigning economic value to non-marketable elements—the cost of a human life, the loss of leisure time, the extinction of species, the degradation of environmental endowments, polluted air etc.—is not just a subjective challenge, it can be a

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conundrum that is infused with ethical undertones (Perkins et al. 2006; Pieterse 2010; Thampapillai 2002; Valentine 2010). Accordingly, one should not be surprised that the development of economic models to compare the costs of adapting to sea level rise (SLR) is fraught with disputed assumptions, which serve as threats to analytical validity and fodder for politicization of response strategies.

The number of elements which confound the predictive accuracy of SLR economic impact assessments is staggering. Consider just three basic elements of an economic impact assessment and the challenges that can render it to be akin to an exercise of faith. First, projecting the magnitude of SLR over the next century depends on critical assumptions regarding climatic feedbacks, which are not well understood (McElroy 2002). Next, assessing the consequences of SLR depends on critical assumptions regarding environmental system dynamics, which also suffer from insufficient empirical understanding (Hoozemans et al. 1993; Keller et al. 2004). Finally, estimating costs depend on the abatement methods adopted, the verity of assumptions supporting selection of these methods and the efficacy with which such measures are eventually implemented (Kirshen et al. 2008). Overall, the validity of the modeling process is utterly dependent on the ability of scientists to accurately predict behavior in a highly complex adaptive system that is impacted by human behavior, which in itself is capricious and highly unpredictable (Keller et al. 2008). Given the potential for error that exists at virtually every stage in the modeling process, one could be forgiven for questioning if such modeling exercises should even be attempted. As E.F. Schumacher (Schumacher 2010/1973) has observed, “a man who uses an imaginary map, thinking it a true one, is likely to be worse off than someone with no map at all.”

This challenge of amassing reliable data to guide the decision-making process is exacerbated by politicization of quantitative data. In recent decades, there has been a predilection on the part of affected stakeholders to commission biased economic studies, reference partisan economic data in order to support positions on a given policy (Gerber and Huber 2010) or produce economic projections that exhibit “rational over-optimism” (Steen 2004). Given the scale and scope of financial interests associated with SLR mitigation and abatement efforts, it may be more accurate to conclude that the international community is faced with the challenge of choosing the least delusive from a host of imaginary maps.

The practical reality is that public policy decisions are largely made on economic merits. Fiscal budget constraints and the political need to justify the expenditure of public funds compel policymakers to demonstrate fiduciary competence through such economic assessments. This is not to say that policy decisions are solely predicated on economic outcomes; however, ceteris paribus, a policy decision that is supported by a positive economic analysis stands a greater chance of adoption and subsequent stakeholder support and insulates decision makers from charges of fiduciary negligence (Simoens 2010). Economic impact assessments, whether they are accurate or not, convey an image of applied due diligence and strategic intent. As Dwight. D Eisenhower is said to have observed, “no battle was ever won according to plan, but no battle was ever won without one.”

This paper embraces the premise that economic impact assessments in relation to SLR abatement can be of value in guiding policy decision-making, in spite of the likelihood that such studies will be fraught with inaccuracies. However, in order to be of value and “speak truth to power”, it is essential that critical assumptions associated with the construct of such models are transparently disclosed to allow users of such assessments to evaluate the extent to which outcomes could differ from expectations.

The goal of this article is to draw insights from multidisciplinary findings associated with SLR in order to explicate critical assumptions underpinning SLR estimates, SLR impact evaluation, and SLR abatement initiatives. To the best knowledge of the author, this has not been undertaken to date. As a result, modelers of SLR economic impact studies lack ready access to knowledge needed to adequately minimize model construct bias (Hoozemans et al. 1993; McElroy 2002). Furthermore, as a result of this paucity of knowledge, users of economic impact analyses pertaining to SLR impact and damage abatement lack the aptitude to adequately vet such studies; as such, they run the risk of being influenced by studies which are tainted by political bias. Accordingly, the contribution of this article is predominantly of an applied nature.

The layout of this article is as follows. “The challenge of estimating sea level rise” will focus on the factors which can confound the validity of SLR estimates. “The challenge of predicting physical damage” will examine the complexities associated with estimating consequences associated with given SLR estimates. “The challenge of economically estimating physical damage” and “The challenge of estimating and aggregating costs” explore the challenges involved in assigning economic value to SLR damage estimates, with “The challenge of economically estimating physical damage” focusing on the disparities that arise from choice of abatement strategy and “The challenge of estimating and aggregating costs” examining the disparities arising from the two prominent abatement strategies—retreat and engineered reinforcement. “Concluding Thoughts” summarizes the repercussions of risk associated with SLR economic assessments and concludes by re-iterating the need for transparency in regard to the critical assumptions underpinning economic impact assessments.

The challenge of estimating sea level rise

SLR estimates are contentious and disparate. The most recent Intergovernmental Panel on Climate Change (IPCC) assessment report (AR5) predicted a likely SLR of between 0.26 and 0.82 m by 2100, based on the four main representative concentration pathways (IPCC 2013). This in itself is a sizable range of variance given that many coastal cities could be severely impacted by SLR over 0.2 m or higher. Furthermore, critics of the IPCC SLR predictions argue that the projections are far too conservative and omit critical positive feedbacks that are already relatively known to be influential in SLR (Dasgupta et al. 2009; Hanna et al. 2008; Krabill et al. 2004; McElroy 2002).

The dominant variable which influences sea level rise is temperature (Burroughs 2007). Temperature influences sea level rise in two respects. First, higher global temperatures amplify the rate at which glaciers melt and snow runoff occurs. To give perspective to just how much SLR potential is locked in glaciers and ice fields, some experts contend that if all glaciers were to melt, SLR would rise by approximately 70 m on global average (Dasgupta et al. 2009; Leatherman 2001). Guillerminet and Tol (2008) estimate that the collapse of the West Antarctic Ice Sheets alone would cause a sea level rise of 5–6 m. Second, as temperatures rise, water bodies become warmer, and as result, expand in volume (Dasgupta et al. 2009).

There are two critical complications associated with estimating the impact of temperature on sea level rise. First, estimating global temperature change depends on the efficacy of climatic models to accurately predict trends in atmospheric greenhouse gas concentrations and this depends on the accuracy of assumptions made regarding human contributions to greenhouse gas concentrations. In short, modelers must be able to accurately predict the impact of technological evolution and demand pressures on greenhouse gas emission trends in areas such as agricultural practice, energy generation, transportation and industrial production. To emphasize just how complicated predicting developments in these areas can be, the reader is reminded that uncertainty in predicting changes in these areas underlies speculative activity in commodity and equity markets.

Second, even if anthropic greenhouse gas emissions can be accurately predicted, modelers face the seemingly insurmountable task of trying to predict how ecological, oceanic and climatic systems will respond to amplified emissions. For example, some researchers suggest that enhanced greenhouse gas concentrations may be somewhat attenuated by enhanced uptake of CO_2 in both terrestrial and marine fauna (McElroy 2002). Other researchers suggest that enhanced greenhouse gas concentrations will catalyze increases in oceanic temperatures which in turn may result in a substantial release of methane gas which is currently trapped at depth in our oceans (Harvey and Huang 1995). Yet other researchers have put forth various estimates regarding the scale, scope and pace of glacial melt (Guillerminet and Tol 2008; Harvey and Huang 1995; Oppenheimer 1998). The accuracy of one‘s estimate regarding how temperature (and in turn SLR) will be affected by changes in anthropic greenhouse gas emissions depends significantly on which scientific "evidence" one decides to integrate into the modeling exercise. In short, the Earth's climatic system is symbiotically tied to our terrestrial and marine ecosystems and the inherent complexity of interactive variables presents modeling challenges that only a few supercomputers on our planet can even attempt to model (McElroy 2002).

There is also a temporal dimension which further complicates the challenge of understanding and predicting how climatic, terrestrial and oceanic systems will respond as the planet warms. Temperature and sea level changes are nonlinear events (Guillerminet and Tol 2008; Keller et al. 2004). Regarding temperature rise, tipping points can accelerate the pace (Kearney and Rogers 2010; Keller et al. 2004). An example is the potential release of methane gas from oceanic deposits outlined earlier. It is believed that methane release is accentuated at certain oceanic temperatures and once these temperatures are reached, the release can be sudden and sizable, further amplifying radiative forcing (Harvey and Huang 1995). Regarding SLR estimates, research suggests that the melt rate of glaciers and ice sheets is exponentially related to temperature rise. It is believed that the melt rate of glaciers and ice sheets will accelerate at certain temperatures; and this could cause a significant change in SLR over a very short period of time (Guillerminet and Tol 2008). In summary, there are three inter-related challenges in estimating the impact of temperature on SLR—estimating greenhouse gas concentrations, estimating global temperature change in response to changing greenhouse gas concentrations and estimating the eventual impact that this will have on SLR—and each area is currently fraught with uncertainty (Fuentes et al. 2010).

The pace of SLR is arguably as important as estimating the aggregate scale and scope of SLR because, in addition to influencing the capacity for flora and fauna to adapt to change, pace influences the policies that are adopted to abate damage. It is intuitively understandable for policymakers to focus on abating near term-threats, those threats which could undermine re-election aspirations and sully political legacies (Moran et al. 2006). Therefore, estimating the pace at which SLR will occur is an essential first step to predicting the types of abatement policies that might be developed.

There is also a pragmatic reason for emphasizing short to medium-term planning horizons—major social problems are typically solved in a piecework manner that tends to begin with attenuation of the most severe impacts before progressively working toward complete mitigation of the problem. This engenders a degree of "path dependence" (cf. David 2000) that favors some solutions over others. For example, an estimate that SLR will reach 1 m over the course of 200 years may catalyze a decision to fortify an affluent residential area with sea walls. Consequently, this initiative sets the stage for the progressive development of more resilient flood fortifications. On the other hand, an estimate that SLR will reach 3 m over the course of 50 years may sire a coastal retreat strategy, wherein support is provided for families wishing to relocate from the threatened area but no support is provided to fortify the area from seawater intrusion. In order to anticipate policy responses, predicting the pace at which SLR will intensify is as important as predicting the aggregate level of rise.

All of the assumptions that go into the development of sea level rise estimates—GHG emission estimates, projections related to ecological and climatic responses to amplified GHG concentrations, estimates of melt rates of glaciers and snow caps in response to temperature change, speculation related to tipping points for key variables, and estimates regarding the pace of SLR—can produce dramatically dissimilar SLR impact estimates.

The challenge of predicting physical damage

Estimates regarding the pace, scale and scope of SLR allow modelers to utilize geographic information systems (GIS) to predict how much of a coastal region will be inundated by seawater. Unfortunately, an inherent weakness associated with the use of GIS is that the underlying contour data represent average elevations over a broad and frequently geographically disparate range. The actual elevation found along any contour line may be greater or less than average elevation depicted by the line (Dasgupta et al. 2009; Hoozemans et al. 1993). Any area of lower elevation represents a potential conduit for water incursion. In order to predict seawater inundation with a modicum of accuracy, high-resolution data are necessary (Cooper et al. 2008) and this typically requires costly field surveys to be undertaken. Only in the case of land with high economic value is such an exercise considered to be financially viable.

Predicting the erosion and accretion of marine, terrestrial and fluvial sediments also presents impact modeling challenges because one consequence of SLR is that coastal erosion patterns will change, thereby altering coastal geography (Cooper et al. 2008; Zhang et al. 2004). Some areas will experience elevated erosion rates while other areas might experience elevated accretion rates. In turn, physical changes to coastal geography influence the behavior of ocean currents and sediment sinks, which in a circuitous manner results in changes to patterns in which sediments are transported and deposited. To further compound the challenge of predicting how changes in sediment erosion and deposition will impact SLR damage, changes in sedimentation patterns can also positively or adversely affect the development of natural buffers which provide protection against storms surges.

Modeling the impact of storm surges adds complexity to the task of estimating physical damage associated with SLR. Given that significant economic damage can be caused by even temporary inundation of seawater, the challenge of accurately assessing the frequency and scale of storm surges is an integral part of modeling SLR damage. Temporary episodes of seawater inundation can destroy agricultural crops, degrade soils, flood roads and tunnels, damage machinery, degrade infrastructure and seep into man-made structures causing spoilage of stored materials (Gornitz et al. 2002; Kirshen et al. 2008). In extreme instances, storm surges can lead to costly, long-term evacuation of affected areas, as exemplified in New Orleans after the Hurricane Katrina storm surges.

Estimating the potential damage caused by storm surges is problematic even in stable sea level scenarios; however, as sea levels rise, the proclivity of storm surges to cause tangible damage amplifies because SLR amplifies the height of any given storm surge (Green et al. 2009). SLR can cause some storm surges to top established barricades and cause seawater intrusion to extend further inland causing more extensive damage (Fuentes et al. 2010). In extreme cases, SLR can weaken the foundation of established barricades (both natural and man-made); thereby, increasing the possibility of barricade collapse (Gornitz et al. 2002). To amplify the challenge of estimating the frequency and intensity of storm surges during a state of progressive SLR, some research suggests that thermal absorption in oceans in temperate regions may produce conditions conducive to the development of extreme weather events, implying that storms may be either more numerous, more damaging or both (Green et al. 2009; Kirshen et al. 2008).

Another challenge to SLR impact assessment involves the estimation of damage to coastal economic industries, the primary two being fisheries and tourism (Olivo 1997). As mentioned earlier, SLR can significantly alter patterns of sand and soil erosion, accretion and turbidity. This can disrupt existing marine habitats (particularly habitats of crustaceans, corals and other bottom dwelling marine life) by influencing the foraging patterns of fish or amplifying the mortality rate of marine fauna that depends on light for photosynthesis. Such events can alter the economic well-being of coastal fisheries (Cooper et al. 2008). In regard to tourism, SLR can cause erosion or complete submergence of beaches and enhance turbidity to the point where scuba diving and snorkeling activities are adversely affected. Overall therefore, the task of estimating damage to such coastal economic activities depends on accurate modeling of sedimentation patterns, as well as, on the accuracy of SLR and storm surge estimates.

A final category that should be included in any SLR impact assessment pertains to assumptions regarding damage to coastal infrastructure. SLR may negate the functionality of coastal piers, existing sea barricades, bridges (albeit temporarily) and drainage conduits; and this can have significant financial repercussions. For example, Olivo (1997) estimated that in Venezuela alone, the infrastructure and sunken capital at risk from a 1 m rise in sea level could be as high as US$7.8 billion (in 1997 dollars). In extreme cases, SLR can catalyze expensive fortification projects or even result in forced retreat from coastal areas and abandonment of valuable infrastructure (Kirshen et al. 2008).

To add perspective to the threat that estimation error poses, one in-depth study into SLR impact in New Jersey concluded that 1–3 % of the entire state will likely be inundated by seawater if SLR trends continue into the next century (Cooper et al. 2008). This 1–3 % range, when quantified, amounts to 220–660 km^2, which represents a sizable variance given that 60 % of the state‘s population live in coastal communities.

Hoozemans et al. (1993) caution, “the assessment of the risks, losses or changes for all relevant resources of the world’s coastal zones require detailed global information on the distribution, density and state of the resources and on the relevant hazardous events and corresponding probability distribution…(that) for many resources…is not available.” Therefore, there are numerous assumptions that feed into the development of physical damage assessments, with each assumption imbuing any related impact assessment models with a higher degree of risk of inaccuracy. The lesson that should be gleaned from this is that due to the estimation errors associated with estimating SLR scale, pace of development, impact on coastal geography, impact on sedimentation, changes to current patterns and storm surge activity, it is incumbent on the part of modelers to explicate these assumptions so those who are making decisions premised on the accuracy of these models can understand the extent to which statistical deviations might occur.

The challenge of economically estimating physical damage

Although errors associated with predicting physical damage associated with SLR represent the dominant influence on the accuracy of subsequent economic estimates of physical damage, economic analysis is further complicated by the need to establish ex ante what the damage abatement strategy should be. As this section will demonstrate, the choice of abatement strategy can lead to disparate economic impact estimates.

There are essentially three basic strategies for SLR damage abatement. The first is an “adaptation” strategy. Adaptation strategies are suited to circumstances where the economic value of the element being estimated is low and/or the cost of abatement is high (Kirshen et al. 2008). For example, if SLR leads to the erosion of a beach that is seldom utilized, it may be best to simply allow the damage to occur and base an economic analysis on any ecological damages caused. An adaptation strategy is also conducive to situations where alternative land uses can help to mitigate economic losses. For example, if SLR leads to the inundation of seawater onto a patch of land that was being used to cultivate vegetables, it may be possible—depending on the nature of the inundation and the soil conditions—for the land to be used post-inundation for cultivating sea vegetables (i.e. sea lettuce, nori, wakame etc.), halophytes, mangroves or undertake other natural aquaculture activities.

The second SLR damage abatement strategy is an “engineered reinforcement” strategy. Examples of engineered reinforcements include sea walls, dykes, gabions, tetrapods, accropodes, groynes, artificial reefs, drainage canals and natural buffer zones (Gornitz et al. 2002). This type of response favors conditions wherein the element being damaged is of high enough economic value to justify investment in preventing the damage from occurring. For example, one study posits that if SLR continues at the current pace, by 2100 New Jersey’s annual US$16 billion coastal tourism industry—with Atlantic City at its hub—could be severely damaged (Cooper et al. 2008). In areas of high economic value such as Atlantic City, it may be economically viable to implement engineering solutions to mitigate such threats (Kirshen et al. 2008) while in other less affluent areas (or countries) fortifying against SLR will be cost prohibitive (Carey and Mieremet 1992; Loucks et al. 2010).

The third damage abatement strategy is a “retreat” strategy. This involves relocating activities when possible and abandoning inundated areas (Kirshen et al. 2008). It is a viable strategy in situations where the cost of engineered reinforcement exceeds the costs associated with relocation and the damage is too great to adapt to. For example, if a cottage that has been built abutting a beach that will be flooded by seawater in response to a 1 m SLR, rather than erecting a seawall to protect the beach and the house, a more appropriate strategy may be to incur the cost of moving the house to higher ground.

The reason why the abatement strategy must be chosen prior to economic valuation is that the strategy frames the costs and benefits. For example, consider the challenge of how to place an economic value on a piece of farmland that is currently being used to cultivate vegetables and which will likely be inundated by seawater in the event of a 1 m rise in sea level. In applying an adaptation strategy, the decision might be made to switch to crops which are amenable to seawater intrusion. In this case, the economic loss associated with SLR would largely be comprised of any losses associated with the change in economic activity and any decrease in the value of the land. On the other hand, in applying an engineered reinforcement strategy, the most cost effective solution may be to build a levee made of reinforced sandbags in order to allow continued cultivation of vegetables. In this case, the economic loss associated with SLR would be the costs associated with erecting this barrier plus any decrease in land value. If a retreat strategy were applied to this scenario, the economic cost would be the price paid for acquiring and relocating operations to a similar parcel of land in a non-threatened area less any value that could be salvaged from the deserted plot. There could be a severe variance in costs among these strategies. For example, in a study into prospective SLR impacts in the Boston area, various abatement strategies (and SLR scenarios) resulted in abatement cost disparities that ranged from US$5.8 Billion to US$94 Billion (Kirshen et al. 2008).

In many economic studies on SLR damage, time and cost prohibit the economic evaluation of damages on a project by project basis. Consequently, more often than not, modelers choose one of the three basic strategies and apply it to all known economic activity in the affected area. For example, Leatherman (2001) estimated costs for coastal stabilization measures in response to a 1 m rise in sea level to be US$12 billion in the Netherlands, US$74 billion in Japan and as much as US$475 billion in the US. However, "coastal stabilization" may not be economically appropriate in all coastal regions in these nations. As the previous example of the vegetable farm further demonstrated, such a generic approach can lead to loss estimates that do not reflect true economic costs associated with actual likely responses.

The challenge of estimating and aggregating costs

Once a response strategy has been devised to abate or mitigate SLR impact, the economic modeler must then turn to the challenge of assigning an economic value to the "at risk" elements. As this section will demonstrate, the process of estimating costs associated with the two dominant SLR response strategies—retreat and engineered reinforcement—require a number of assumptions to be made that render accurate estimates difficult at the project level, highly complex at the regional level, overly costly at the national level and virtually impossible to implement to any degree of accuracy at the international level.

It is not the intent of this section to provide a comprehensive overview of the economic valuation challenges associated with these SLR response strategies. Instead, this section attempts to provide sufficient illustration of the complexities involved in economic valuation for each SLR response strategy in order to demonstrate just how subjective and complicated the valuation process can be.

Costs associated with the retreat strategy

On the surface, estimating costs associated with a retreat strategy on a project by project basis appears time-consuming but relatively straightforward. Seemingly, all one needs to do is to add up the costs of moving an enterprise or household to a "similar" site.

The reality is much more complex. Take for example the challenges of estimating site cost losses and moving costs—perhaps the two most prominent costs associated with a retreat strategy. Finding "similar" land in order to estimate site cost losses is not a simple process. For organizations, location can have strategic value and, therefore, altering location will have an impact on the firm's ability to carry out strategy as planned. For many households, current locations possess intangible value (i.e. memories) that requires subjective judgments to economically quantify. Similarly, costs associated with relocating a business or household are influenced by assumptions made in regard to how much equipment or furniture needs to be moved, the cost of local moving services and relocation distances.

In addition to challenges in estimating physical relocation costs, there are numerous other transitional costs that are even more difficult to quantify; yet, failure to integrate these costs into the costs of relocation can lead to severe under-representation of true costs. For example, firms that relocate may lose employees who are unwilling or unable to commute to the new location, might lose out on a favorable leases that are in place, might suffer from impaired revenue due to inferior access to customers and might suffer lower liquidity after having to finance such a relocation. For households that have to relocate, there are social costs associated with a move that need to be somehow translated into economic terms. The probabilities of these events transpiring all need to be estimated.

Each assumption made in regard to these types of costs undermines the likelihood of the estimate being accurate. When project specific estimates are then applied to the costs of relocating different types of industry or different types of households, the accuracy of the estimate is further eroded. If this estimation exercise is then applied to a regional level, regional cost disparities need to be recognized and factored into the estimate. If the estimation exercise is to be applied on a national scale, the level of quantitative complexity renders estimates to be extremely costly and of dubious accuracy. When the estimation exercise is then expanded to an international scale, one needs to factor in the possibility that in some nations, relocation is not economically feasible. In such nations, a forced retreat actually results in bankruptcies and displaced communities. Such possibilities must somehow be factored into international SLR impact estimates, in order to avoid under-representing the costs.

Costs associated with the engineered reinforcement strategy

An engineered reinforcement strategy does not entail relocation costs, so many of the challenges to predictive accuracy associated with estimating the cost of the retreat strategy are not relevant. However, estimating the cost of engineered reinforcement gives rise to at least three estimation challenges.

First, deciding on a reinforcement strategy requires engineering expertise, and a comprehensive understanding of the options available for reinforcing coastal areas from SLR damage. Very few economic modelers have sufficient engineering knowledge to adequately identify one reinforcement strategy, let alone evaluate a pool of options. Furthermore, each reinforcement strategy comes with pros and cons that need to be economically quantified. For example, on one hand, the use of indigenous natural material may be a cost effective and ecologically sensitive approach to protecting a coastline from storm surges. On the other hand, engineered sea walls may result in more effective protection. Trade-offs—such as that between ecological integrity and structural effectiveness—can have dire ecological and economic consequences.

Second, even if a suitable array of reinforcement options can be identified, the cost of reinforcement needs to be estimated. This requires additional subjective judgment. First, one needs to choose between estimates based on current market value and future market value. If future market value is the metric to be used, one needs to speculate on costs in an age where the demand for reinforcement services will likely escalate significantly due to demand pressures outpacing supply. Future market values will be higher; but estimating how much higher is far from an exact science.

Third, another significant threat to predicting the cost of engineered reinforcements relates to the possibility of failure. For example, if the economic modeler wishes to ensure with 95 % certainty that a given reinforcement strategy will effectively provide protection against SLR, very elaborate (and costly) reinforcement strategies must be chosen. If fail-safes are not sufficiently incorporated into an engineered reinforcement solution, there will be an elevated possibility of the solution failing, thereby, resulting in unanticipated damage to the economic entity that is being estimated. This means that for any given solution, the potential for failure needs to be estimated and the economic entity must be fully valued in order to estimate the cost of complete loss in the event of failure (which would then be multiplied by the probability for failure in order to estimate total loss associated with failure). Lamentably, both accounting for and failing to account for failure enhance predictive error. On one hand, if suitable fail-safes are incorporated into the reinforcement solution, the estimates of reinforcement will likely be exaggerated and unrepresentative of realized costs. On the other hand, if suitable fail-safes are not incorporated, the cost estimate will be significantly under-estimated in the event of reinforcement failure.

Finally, it should be pointed out that the process of consolidating cost estimates associated with engineered reinforcement strategies in order to derive regional cost estimates will likely result in severely overinflated cost estimates because as outlined earlier, engineered reinforcement is only justifiable where the economic (or ecological) value is high enough to warrant such an investment. Accordingly, an engineered reinforcement strategy will likely be most valid when applied to population centers where the cumulative value of existing infrastructure and property justifies safeguarding. This final point gives rise to additional complexity when considered in an international context because in some nations, existing infrastructure and property may be of significant value but governing authorities cannot afford to subsidize engineered reinforcement or private parties cannot be coerced to invest in engineered reinforcement strategies. In such cases, one might be justified in estimating costs based on engineered reinforcement; but in reality such engineered reinforcement will not take place. In such situations, the modeler has to decide whether the cost estimate should be based on the normative cost (engineered reinforcement) or on the most likely loss (from retreat).

Concluding thoughts

The analysis presented in this paper has underscored an important characteristic of SLR economic impact modeling exercises—they are underpinned by assumptions that confound predictive validity. However, inaccuracy does not mean economic assessments should be spurned.

Policymakers need to have some basis for guiding decisions related to SLR abatement; and any basis (ecological, economic or social) will be subject to the same confounding forces. As the discussion presented in this paper suggests, to be of value, the assumptions underlying SLR economic impact analysis must be transparently communicated to the reader so that the reader can understand the extent to which the economic assessment might be invalidated by unanticipated events or mistaken assumptions.

It is recognized that critics of this view could contend that economic models of SLR impact should not be the basis upon which policy decisions are made because the damage associated with severe levels of SLR is too high to contemplate any policy that allows for a remote possibility of cataclysmic disaster from occurring. In estimating SLR impact, the upper range for economic and ecological damage would include widespread loss of life, political turmoil, forced migration of millions, the complete elimination of some island states and widespread extinction of flora and fauna (Carey and Mieremet 1992; IPCC 2007a; Stern 2007). As Beck (1992) has observed, the impacts of some calamities are simply too severe to even contemplate assessing risk; they simply should not be allowed to occur.

It is difficult to find fault with this perspective. There are two extreme scenarios associated with SLR that could indeed produce cataclysmic results. The first is the possibility that the thermohaline circulation (THC) which is responsible for transferring heat from equatorial regions to temperate regions may weaken or even shut down if a massive infusion of fresh water as a result of glacial melt occurred (Kuhlbrodt et al. 2009; McElroy 2002). This could significantly alter climates around the world catalyzing enormous economic, environmental and social damage (McElroy 2002). It could also fuel enhanced SLR that some estimate could add 0.8 m to the IPCC estimates (Kuhlbrodt et al. 2009). The other catastrophic possibility is that the positive feedbacks associated with global warming (release of methane stored in oceans, reduced albedo as a result of reduced snow cover, release of CO_2 and methane stored in ice sheets etc.) could precipitate more rapid temperature rise and widespread melting of the world's glaciers in a very short period of time (Harvey and Huang 1995). Some researchers contend that break-up of the Greenland and West Antarctic ice sheets alone could produce 3–6 m SLR (Dasgupta et al. 2009; Guillerminet and Tol 2008) while global glacial melt could catalyze SLR of up to 70 m (Leatherman 2001). This would significantly alter the geography of our planet, diminish habitable areas and likely precipitate economic, social, political and environmental chaos. Although these are extreme scenarios which most researchers argue are unlikely (IPCC 2007a), even a remote possibility that such disaster could occur presents a strong case for application of the precautionary principle (Alley et al. 2003).

However, even proponents of this perspective must recognize that we live in a world where public policy is dominated by economic evaluation. Refusal to participate in such modeling practice simply cedes power to those who are willing to "play the game". SLR is too great of a threat for environmental scientists to remain on the sidelines in this game. Failure to adequately communicate risks associated with misguided SLR impact assessments implies that the status quo based on overly conservative impact assessments will continue to guide policy (Kahneman et al. 1991). This is an outcome that the vast majority of ecologists involved in climate change policy would like to avoid. In short, economic modeling may not represent endeavors that environmental scientists covet participation in, but without introducing science to the process, policymakers will continue to play the game without the appropriate tools. Only those with vested interest in preserving the status quo wish SLR impact assessments to be viewed as being scientific because they are statistical; the rest of the world needs SLR impact assessments to be informative because they are scientific.

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