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THE VALUE OF FLEXIBILITY IN ADAPTING TO CLIMATE CHANGE: A REAL OPTIONS ANALYSIS OF INVESTMENTS IN COASTAL DEFENSE

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Adaptation to climate change is likely to be a significant challenge for developing countries. We examine whether a real options approach that recognizes uncertainty and maintains future flexibility can provide an improved adaptation investment strategy. We use a Monte Carlo model to test four strategies for defending against sea level rise. Two of the strategies are inflexible, with the coastal defense fully specified in the first year of analysis. The other two strategies are flexible real options that allow adjustments in the coastal defense over time. We emphatically show that a real options strategy has the potential to increase the benefits of proactive adaptation. Our results prove to be location-dependent, underscoring the need for location-specific analysis. We find that the quality of the information obtained over time has an important bearing on option value and that a country's institutional capability and the specific mechanisms of international development assistance may affect implementation.

Keywords: Adaptation; climate change; real options; coastal defense; multilateral environmental assistance.

1. Introduction

1.1. Global context

Continued warming of the climate appears unavoidable, leading the Intergovernmental Panel on Climate Change (IPCC) to conclude that at least some adaptation will be necessary (IPCC, 2007a). Particularly in low-income countries, decisions about adaptation will be made in the face of scarce resources and competing development priorities (IPCC, 2007d). The World Bank estimates that by 2050, adaptation to 2°C of warming could cost such countries \$70–\$100 billion per year (2010). Many developing countries are located in low-latitudes, where climate impacts are expected to be more severe (Mendelsohn *et al.*, 2006).

Decisions about adaptation will be made under substantial uncertainty. IPCC (2007c) notes several key uncertainties in our understanding of the causes and effects of climate change. For example, greenhouse gas emissions are driven by many difficult-to-forecast forces. Significant uncertainty also exists about the relationship between emissions and impacts, and about the nature, magnitude and regional

distribution of those impacts. Finally, as the climate changes, individuals, firms and governments will make hard-to-predict choices about how to adapt.

The scientific understanding of global climate change and its impacts has improved in recent years (National Research Council, 2010). The IPCC began its peer-reviewed assessments in 1990; the 2007 assessment contains several instances in which important uncertainties have been reduced (IPCC, 2007b). For example, the Panel now states “unequivocal[ly]” that the climate is warming, whereas in 1990, natural variability could not be ruled out, forcing the Panel to conclude that the “unequivocal detection of the enhanced greenhouse effect from observations is not likely for a decade or more” (IPCC, 1990). Other areas where scientific progress has been made, relative to the 2001 assessment, include:

...large amounts of new and more comprehensive data, more sophisticated analyses of data, improvements in understanding of [climate] processes and their simulation in models, and more extensive exploration of uncertainty ranges (IPCC, 2007b, p. 2).

Progress in reducing uncertainty will likely continue. The IPCC, for example, recently launched its fifth synthesis of the literature (IPCC, 2010). As a result, our understanding of important scientific phenomena and of the impacts of localized climate change will almost certainly improve. Even if scientific research yields no new insight, the passage of time will allow for additional direct observation and measurement of the impacts of climate change.

Today’s policymakers thus face a dilemma. Should they make irreversible investments in adapting to potential climate change? Or should they take the risk of delaying action until uncertainty has been reduced and actual climate impacts are experienced? Perhaps there is a middle course in situations where investments made today create the opportunity, but not the obligation, to take future action to adapt to climate change.

In our view, a framework for adaptation decisions should comprise several elements. It should explicitly incorporate uncertainty about the future conditions that will determine the value of today’s adaptation investments. It should recognize that such uncertainties are likely to diminish over time, thanks to improvements in forecasting techniques and to the passage of time during which climate impacts can be observed. In addition, if flexibility exists to modify adaptation investments in the future, then such investments should not to be seen as “now-or-never” investments. The framework should also recognize that adaptation decisions are rarely “all-or-nothing” investments, but instead are choices along continua of costs, risks and benefits. Finally, the framework should acknowledge that delayed investment in adaptation may increase the risk of climate-driven damages. We concur with Weyant (2008, p. 88):

Climate change is a long-run problem that will provide us with many opportunities to learn and to revise our strategy over many decades. Thus, it is best conceived of as a problem requiring sequential

decision-making under uncertainty rather than requiring a large, one-shot, “bet-the-planet” decision.

1.2. Characterizing investments in adaptation as real options

This paper explores whether a real options approach can be used to inform adaptation decisions. We begin this section by describing key concepts and then explain our focus on sea level, review relevant literature, and pose the research questions that motivate the analysis.

1.2.1. Conceptual explication

Real options are similar to financial options in that both give the option holder the right, but not the obligation, to take a future action if doing so is advantageous based on future conditions. For a financial option, the opportunity for action typically involves a time-limited right to buy or sell a financial asset for a specified price. By contrast, “real options” exist when the underlying asset is a real asset such as land, a business opportunity, valuable information, or in the present case, enhanced protection against the impacts of climate change. Real options exist when future outcomes are uncertain, uncertainty is likely to diminish over time, flexibility exists to take future action as uncertainty is resolved, and the future action can reduce costs or increase benefits when it is taken (Triantis, 2003). Real option analysis has been applied in many contexts including research and development, oil and gas exploration, mergers and acquisitions and real estate development (Shockley, 2007; Triantis, 2001; Vonortas and Desai, 2007).

If a real option exists but is not properly valued, then the traditional decision criterion of maximizing net present value may yield a suboptimal choice (Copeland and Antikarov, 2003; Shockley, 2007; Triantis, 2003). In the typical cost-benefit analysis, uncertainty is captured with expected values based on the means of the relevant probability distributions. This approach effectively attaches a “now-or-never” quality to the investment choice; this quality is appropriate if no flexibility exists to adjust today’s decision in future time periods, but if such flexibility exists, then the net present value framework will tend to under-value it.

Many potential adaptation investments have option-like qualities. For example, development of new cultivars suitable to a changed climate can create an option for the agricultural sector in a vulnerable region. If the regional climate changes as expected, the new cultivars can be quickly deployed (i.e., the option would be exercised). If the climate remains unchanged, then the new cultivars would not be used (i.e., the option would expire). In this case, the R&D cost is the purchase price of the option and the cost to deploy the new cultivars is the exercise price.

1.2.2. Sea level rise

We chose to examine a real options approach for adaptation to sea level rise for several reasons. First, there is uncertainty about the extent of sea level rise (IPCC, 2007b;

Lowe and Gregory, 2010; Rahmstorf, 2010). Second, storm surges are recognized as the event during which rising seas are most dangerous; such surges have historically exhibited substantial variability. Third, from a cost-benefit perspective, the resources to be protected from sea level rise — economic assets and vulnerable populations — are not static, but evolve over time, thereby introducing a dynamic element into the analysis. All of these uncertainties combine to make adaptation to sea level rise a phenomenon particularly well suited to real options techniques.

We also focus on sea level rise because of the threat posed to developing countries. A World Bank review identified “very heavy potential losses that are much more concentrated in some regions and countries than others” and a “concentration of highly vulnerable large cities at the low end of the international income distribution” (Dasgupta *et al.*, 2009). About 11 million people live in port cities in low-income¹ countries that are threatened by coastal flooding (Nicholls *et al.*, 2008). We recognize that the threat to coastal areas does not originate solely in climate change; other drivers include development that puts populations and economic assets in harm’s way, local land subsidence, inadequate warning systems, failure to invest in sufficient protection measures and non-climate-related variability in sea levels and storms. The catastrophic 1900 flooding in coastal Galveston, Texas — presumably not attributable to climate change — is a case in point (Rosenberg Library, 2003).

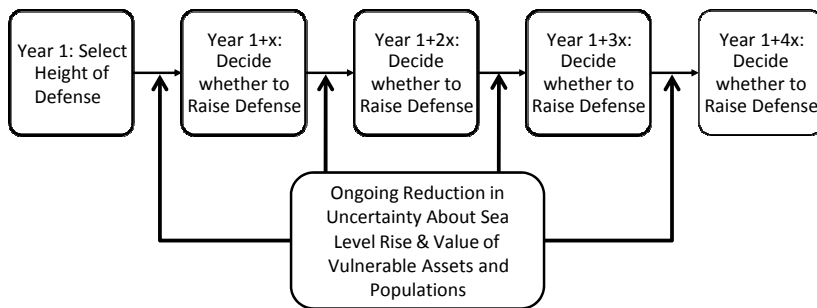
Coastal planners face a dilemma: Insufficient protection may lead to inundation but excessive protection may lead to wasted resources. In addition, as the value of vulnerable assets changes over time, the value of protection also changes. One approach is to conduct a single analysis at time zero, given the information then available, that assesses the probabilities of all relevant future events, and then to select the level of coastal defense with the highest expected net social benefit. As an alternative, Fig. 1 re-frames the problem as a real option in which multiple decisions are made over time as uncertainty is resolved and more information becomes available. This contrast between a one-off decision and a series of sequential decisions demonstrates how planning for sea level rise might be enhanced by a real option approach.

1.2.3. *Prior literature*

There exists a small body of literature that links real options analysis to investments in adaptation to climate change.² Government guidelines in the United Kingdom, for example, suggest that the option analysis be used to appraise adaptation projects that entail “uncertainty, flexibility and learning potential” (HM Treasury, 2009, p. 14). In its Synthesis Report on the Economics of Adaptation to Climate Change, the World Bank (2010, p. 100) also makes a brief reference to real options as a “practical approach” for addressing uncertainty in investments in adaptation. Real options analysis

¹Defined as having a per-capita GDP of less than \$3500 per year, on a purchasing power parity basis.

²There also exists a literature, not reviewed here, that addresses real option analysis of measures to mitigate climate change.



X = Number of years between periodic planning decisions.

Figure 1. Applying sequential decision making to coastal defense planning.

has been applied to adaptation to climate change in the rain-fed agriculture sector in Yemen (Scandizzo, 2010), in the residential housing sector in the Mekong Delta of Vietnam (Dobes, 2010), in the agricultural sectors in Australia (Hertzler, 2007) and Mexico (World Bank, 2009), and in flood management strategies for the Thames Estuary (Woodward *et al.*, 2011).

The first economic analyses of coastal defense appear to have emerged in the Netherlands after the 1953 North Sea Flood. Van Dantzig (1956) identified the key management decision as a cost minimization problem, where risk reductions from enhanced protection are balanced against the increased costs of such protection. He characterized the optimum dike height as one that minimizes the sum of dike costs and flood damages. A related body of work developed in the United States in the 1970s, but focused more broadly on the economics of natural hazards such as snow storms, drought, tornadoes and earthquakes (Cochrane, 2010). Exemplars of this line of thinking are Russell (1970) and Howe and Cochrane (1976), whose studies identified the optimal strategy as the one that minimizes the expected value of the sum of protection costs and residual damages. More recently, Mendelsohn (2000) identified an economically efficient adaptation strategy as one that equates the marginal benefits and marginal costs of adaptation.

While this earlier work typically envisioned a single decision in time (which would not comprise a real option), Eijgenraam (2007) extended the framework to consider periodic improvements in coastal defenses in response to economic development and changes in sea levels. The Dutch government is currently in the process of updating its flood protection standards based on Eijgenraam's extended framework (Jonkman *et al.*, 2009) and such a framework is consistent with the real option approach taken in this study.

1.2.4. Research question

We define our core research question as follows: To what extent would framing investments in coastal protection as real options lead to better use of resources? We

take as given the objective of maximizing net social benefits. We assume no benefits to climate change in vulnerable coastal communities, but two types of benefits from investments in adaptation. The first is the ongoing productivity of the assets protected from inundation and the second is the value of avoiding fatalities and displacement among vulnerable populations. Weighed against these benefits are the costs of coastal defenses. We define the first-best outcome to be the solution to a dynamic programming problem that selects investments in coastal defenses at each time t , given the information then available to maximize the present value of aggregate expected net social benefits on an ex-ante basis. At time t , the present value of aggregate expected net social benefit is

$$A_t = \left\{ \sum_{i=t}^{t+n} \frac{E(\text{GLP}_i - M_i - K_i | I_t) - C_i - O_i}{(1+r)^i} \right\} + \left\{ \frac{E(V_{t+n} | I_t)}{(1+r)^{t+n}} \right\}, \quad (1)$$

where n is the length of time over which investments are analyzed, GLP_i is the gross local product of assets in the vulnerable area in year i , M_i is the monetized value of fatalities and displaced persons in year i , K_i is the capital investment in productive assets in the vulnerable area in year i , C_i is the capital investment in coastal protection in year i , O_i is the recurring cost for coastal protection in year i , r is the discount rate, and V_{t+n} is the terminal value of the productive assets in the vulnerable area at the end of the analysis period (i.e., at time $t+n$). More broadly, $E(\text{GLP}_i - M_i - K_i | I_t)$ is the expected value of the net benefits that occur in year i , given the height of the coastal defense and conditional on the information (I_t) available to the policymaker at time t . $E(V_{t+n} | I_t)$ is the expected terminal asset value conditional on the same factors.

We observe that computation of both $E(\text{GLP}_i - M_i - K_i | I_t)$ and $E(V_{t+n} | I_t)$ requires specification of a probability distribution for inundation and its impacts, rather than a single-point estimate from that distribution. Accordingly, this approach is more data intensive than a strategy based on adapting to a single point estimate of, say, a 0.5 m increase in sea level. The need for this additional complexity is inescapable owing to two factors: The stochasticity over time of the economic and environmental phenomena of interest and the nonlinearity of the relationships between climate conditions and consequent damages. Several scholars have noted that the greatest climate risks likely originate in low-probability but high-consequence events in the “fat tails” of relevant probability distributions (Kousky and Cooke, 2010; Weitzman, 2009). The entire distribution of potential climate outcomes is thus relevant to choices about coastal defenses.

Our net benefit maximization framework departs somewhat from the cost-minimizing approach common in the literature.³ Both approaches entail optimization, but our approach allows for a more expansive analysis of the consequences of inundation. Rather than conceptualizing vulnerable assets as a stock, damages to which are a cost,

³Mendelsohn (2000) does frame adaptation as a net benefit maximization problem, but many other scholars do not.

we instead focus on changes in the flows of benefits from those assets, and treat increases in such flows as a benefit of adaptation. Doing so allows us to consistently measure the impacts of adaptation strategies that may vary widely with respect to the extent and timing of asset and population growth, asset destruction and re-building and capital and recurring investments in coastal protection.

The value of applying a net benefit maximization framework, rather than a cost minimization framework, can be illustrated with a simple example. If one were interested only in minimizing costs, the optimal strategy might be to invest very little in defenses, thereby allowing the destruction of vulnerable assets, and then do nothing to restore the economic productivity of the vulnerable area. The cost of re-building assets would enter the cost minimization framework, but the benefits generated by those assets would be ignored. In short, because a more robust coastal defense creates the potential to accrue such benefits, net benefit maximization is the appropriate decision metric for selecting the extent of the coastal defense.

The only instance in which we consider stocks rather than flows is in the final year of the analysis, where we attach a terminal value to the capital stock that remains in the vulnerable area. As a practical matter, the analysis must be truncated at some point in time; ignoring the size of the asset base at that point would render the decision framework incomplete.

We assume policymakers are risk-neutral when endeavoring to maximize net social benefits, based on the principle that government policymakers, investing on behalf of taxpayers across multiple diverse projects throughout the economy, ought to be risk-neutral (Arrow and Lind, 1970). Two caveats, however, must be kept in mind. First, if coastal planners display risk aversion when adapting to climate change, then simulation of their behavior should reflect such considerations. Second, some scholars have identified concerns about the application of risk-neutrality to public decisions (Broadman *et al.*, 2006). Particularly relevant is Weyant's observation (2008, p. 90) that "there may need to be some premium [added to the discount rate] to reflect that climate change is a big enough potential problem to make even whole economies risk averse". We plan to address risk-aversion in future work.

2. Methodology

A coastal planner aiming to implement the first-best approach implied by Eq. (1) faces significant data needs and complex analytic methods. Accordingly, we compared four distinctly different decision strategies that a boundedly rational coastal planner might use to defend against rising sea levels, two based on economic optimization, and two driven by natural phenomena. In turn, we estimated the present value of aggregate net social benefits likely to accrue from each strategy. We used a Monte Carlo model to simulate physical, economic and decision-making processes. This approach, unlike many option valuation methods, can accommodate multiple sources of uncertainty and does not require that uncertainties fit any particular statistical distribution (Triantis,

2003). We analyzed two cities, one in a riverine delta, Dhaka, Bangladesh, and the other on an ocean coast, Dar-es-Salaam, Tanzania.⁴

2.1. Strategies analyzed

In addition to the four strategies for constructing coastal defenses, we also examined a “Do Nothing Baseline” in which policymakers make no new investments in defending against sea surges. Instead, the consequences of inundation are driven solely by natural processes, existing coastal defenses, and evolving land-side populations and asset values.

To characterize the performance of each decision-making strategy, we applied an ex-post perspective to a 100-year time frame and used the Monte Carlo model to estimate — across the probability-weighted set of relevant cost and benefit drivers — the average net benefit of that strategy. For each iteration, x , of the model, we estimated the present value of net social benefits (NPV) for each strategy, s ,

$$NPV_{sx} = \left\{ \sum_{i=0}^{100} \frac{GLP_i - M_i - K_i - C_i - O_i}{(1+r)^i} \right\} + \left\{ \frac{V_{100}}{(1+r)^{100}} \right\}. \quad (2)$$

We then computed the average NPV of each strategy over 5000 iterations of the model,

$$NPV_s = \frac{\sum_{x=1}^{5000} NPV_{sx}}{5000}. \quad (3)$$

The strategy with the highest average NPV should be preferred by the policymaker as the best of the four strategies for using the resources available for adaptation to climate change.

The first strategy, based on meteorological and natural phenomena, is an inflexible one and not a real option. It assumes a single decision about the height of the coastal defense at the start of a 100-year planning process. The protection height is selected based on the 100-year surge event, plus a 0.5 m safety factor. For the 100-year event (sometimes referred to as having a 100-year annual recurrence interval), there is a 1% chance of a sea surge higher the specified height in any one year, with an average of 100 years between surge events that exceed this height. Many coastal defense strategies, such as the Dutch Delta Programme, can be characterized by the annual recurrence interval they are designed to accommodate (Ministry of Transport, 2010). We refer to our version of this approach as the “100-Year Event Strategy.”

The second strategy is also an inflexible one but differs from the first in two respects. First, policymakers use a limited cost-benefit calculation to determine the optimal height of the coastal defense at the start of the 100-year period. Second, rather

⁴While the data used in the model are loosely based on these cities, readers are cautioned that a number of simplifications and data imputations mean that our results should not be seen as identifying a recommended course of action for either city.

than being built only in Year 1, coastal defenses are constructed to the target height in five equal increments. For example, if 5 m were identified in Year 1 as the optimal height, one meter would be added to the structure in years 1, 21, 41, 61 and 81. We refer to this as the “Decide Once & Build in Stages Strategy.”

We assume a decision maker who, owing to data and analytic limitations, does not endeavor to identify the first best solution implied by Eq. (1), but instead aims to minimize the present value of the sum of the protection costs and the expected value of the residual damages that occur despite the presence of the protection,

$$Z = \left\{ \sum_{i=0}^{100} \frac{C_i + O_i + D_i}{(1+r)^i} \right\}, \quad (4)$$

where C_i is the capital investment in coastal protection in year i , O_i is the recurring cost for coastal protection in year i , D_i is the expected annual residual damage in year i , and r is the discount rate. In this strategy, D_i is a constant, calculated based on Year 100 asset values that are in turn calculated by applying point estimates of population and economic growth rates to the Year 1 values. The current (i.e., Year 1) probability distribution for sea surges is then applied to Year 100 asset values to compute the expected value of annual residual damages (i.e., the constant D_i). This approach implicitly assumes a far-sighted coastal planner who bases current decisions about coastal protection on the future value of the assets to be protected. Operationally, the planner is assumed to calculate Z for each possible protection height from zero to 10 m, in one meter increments, and select the height with the lowest value of Z .

The third strategy is a real option that uses the same simplified cost-benefit methodology as the second. The analysis, however, is done at five points over the 100-year period, rather than just once. Planners thus have the option, but not the obligation, to raise the protection height in years 1, 21, 41, 61 and 81. Each planning decision (other than the first) is based on extrapolations from observed changes in sea conditions, assets and populations which are then used to predict the conditions expected over the next 20-year interval.⁵ Unlike the second strategy, the value of D_i is not constant over the 100-year period, but changes every 20 years, based on the annual expected residual damage at the end of each 20-year planning period. Under this strategy, for example, the decision made in Year 40 uses 40 years of observations of sea level rise and population growth to project conditions for Years 41 to 60. As with the Decide Once & Build in Stages Strategy, planners have no assurance that their projections will prove accurate; however, in this strategy, planners predict only 20 years, rather than 100 years, into the future. Their sequential decisions also reflect increasing amounts of information about how sea levels, populations and assets are changing. We call this approach the “Predict & Respond Strategy.”

⁵The Year 1 decision is made in the same manner as in the Decide Once & Build in Stages Strategy, except that the planning horizon is 20 years rather than 100 years.

The fourth strategy is a real option that gives local planners the option of raising the height of the defense in any year. No economic optimization is involved; instead, planners observe maximum sea levels in relation to the height of the existing defense. If the maximum sea level comes within 0.5 m of the height of the defense, then it is raised in the subsequent year. The new height is the observed maximum sea, plus a 0.5 m safety factor. Such observations, rather than predictions about future sea levels or the value of vulnerable assets, drive decisions about whether to raise the height of the defense. In addition, to create a minimum level of protection in Year 1, the height of the defense is initially raised to that of the 10-year surge event, plus a 0.5 m safety factor. While these parameters are somewhat arbitrary, they are necessary to operationalize a strategy that gives local planners substantial flexibility yet does not demand extensive data collection and analysis. Such approaches have recently begun to appear in the literature. Our approach is inspired by the work of Hoekstra and De Kok (2008), who studied an approach they call the self-learning dike. We refer to our version as the “Sense & Respond Strategy”.

2.2. Model

We used a stochastic simulation model to analyze the adaptation strategies. Implemented as an Excel spreadsheet, the model uses Oracle’s Crystal Ball add-in to execute the Monte Carlo analysis. We simulated 5000 iterations, with each iteration comprising an analysis of the 100-year planning period. The model includes six components, each described below. Figure 2 illustrates how the model is built around a standard risk assessment paradigm.

2.2.1. Simulation of coastal defenses

We use the concept of a coastal defense to describe a generic barrier — a seawall or dike — of a certain height that can restrain storm surges below that height and prevent inundation of assets on the land-side of the defense. The prospect of a failure of the barrier is not considered; inundation is assumed to occur only if the barrier is overtopped by the sea.

The height of the coastal defense, as well as all references to sea levels and storm surges, is expressed relative to the mean local high tide over the course of the year prior

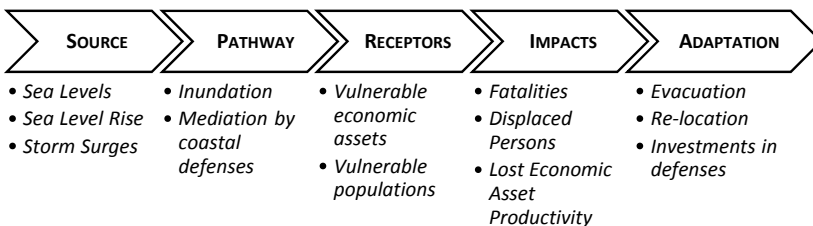


Figure 2. Framework for assessing adaptation to sea level rise.

to the start of the 100-year simulation. The model includes the height of both freeboard and constructed defenses. Freeboard — as we use that term here — refers to the protection afforded by natural beaches, bluffs and rocky shorelines. It refers to the vertical distance between the water level and the lowest level at which vulnerable assets or populations exist. The base of the constructed defense is assumed to match the top of the freeboard; hence, the total protection height is the sum of the freeboard and the defense height.

We estimated the costs of coastal defense based on [Yohe et al. \(1999\)](#) who, after reviewing eight studies, applied a unit cost of \$750 per linear foot (1990\$) for a 1-meter high sea defense and assumed that defense costs rise as the square of the height. We updated the unit cost to 2009 using a price index for fixed investments in nonresidential structures ([U.S. Council of Economic Advisors, 2011](#)).⁶ The model estimates the capital cost (C) of the coastal defense⁷ as a function of its height,

$$C = \$5617 * [H_n^2 - H_e^2] * L, \quad (5)$$

where H_n is the height of the new structure in meters and H_e is the height of the existing structure, if any. L is the length, also in meters, of the coastal defense. Owing to the trapezoidal shape of the typical defense structure, capital cost rises exponentially with height. The same algorithm is used to estimate the cost of raising an existing defense as well as constructing a new structure; in the latter case, the H_e term is set to zero (e.g., the cost of constructing a 3 m high defense is the same as the combined cost of first constructing a 1 m high defense, and then later raising the height by 2 m). Like [Yohe et al. \(1999\)](#) we assume annual maintenance costs equal 4% of the historical capital investment. A similar approach was applied by [Ng and Mendelsohn \(2005\)](#) to their analysis of coastal protection in Singapore.

Visual inspection of the relevant maps led us to assume a length of 75,000 m for coastal defenses in Dar-es-Salaam and 66,000 m in Dhaka. Based on a database compiled by a consortium of researchers, we assumed that the existing height of the protection is 1.5 m in Dar-es-Salaam and 3.0 m in Dhaka ([Valfedis et al., 2004](#)). We assumed this height was split equally between naturally occurring freeboard and constructed coastal defenses.

2.2.2. Simulation of annual maximum sea levels

The maximum sea level in any year is a function of three variables, one a constant and the other two simulated stochastically. The first, local sea level rise (LSLR), occurs at a constant rate and captures the net effect of changes in location-specific land elevation, which may increase due to forces such as geologic uplift or decrease due to forces such

⁶We recognize that both the unit cost and price index may not be directly applicable to developing countries; accordingly, these estimates should be viewed as first approximations of these values.

⁷Unless otherwise noted, all monetary values used in this analysis are expressed in real terms, as 2009 US\$.

as subsidence. In Dar-es-Salaam, LSLR is assumed to be -1.58 mm per year, i.e., land elevation is increasing (Kebede and Nicholls, 2011). For Dhaka, we assumed the historical subsidence rate of 0.65 mm per year reported by Milliman and Haq (1996) is a reasonable proxy for future subsidence.

Global sea level rise (GSLR) is treated stochastically, using a two-step process. At the start of each iteration, the model selects a single value for the entire 100-year analysis period to represent the underlying trend in average annual change in sea level. This value is drawn from a normal distribution with a mean of 3 mm per year and a standard deviation of 2 mm.⁸ Then, to capture annual variability, the actual GSLR in any given year is drawn from a uniform distribution with a mean equal to the simulated underlying 100-year trend for that iteration and a range of plus or minus 50% of the mean. This annual simulation assumes independence of each year from all other years, so there is no serial correlation.

The third element in the annual calculation of the maximum sea level is an extreme value distribution that captures variability in storm surges experienced each year. Information on sea surges for the two studied cities was provided to us by Robert Nicholls of the University of Southampton who, with colleagues, studied the vulnerability of port cities around the world to sea level rise (Nicholls *et al.*, 2008). Information was provided, as of 1995, on the surge height associated with four annual recurrence intervals (ARI): 1-, 10-, 100- and 1000-year events. The ARI represents the average time interval in years between surge events that exceed a given level. Because such events are assumed to be statistically independent, it is possible to have a 100-year event more than once every 100 years. For purposes of stochastic simulation, it was necessary to convert the ARIs to annual exceedance probabilities (AEPs). We used the approach specified by the Australian Government's Bureau of Meteorology (2011) in which:

$$\text{AEP} = 1 - e^{-\frac{1}{\text{ARI}}} \tag{6}$$

The probability of the 1000-year event in any one year is 0.1% . For the 100-, 10- and 1-year events, the probabilities are respectively, 1.0% , 9.5% , and 63.2% .

We also updated the 1995 surge heights for 15 years of global sea level rise (assumed to be 3 mm per year), and 15 years of local sea level rise which, as described above, differs between the two cities. We next took the four point estimates of sea heights (and the associated AEPs) and matched them to a Gumbel maximum extreme value distribution,

$$f(x) = \frac{1}{\beta} \cdot e^{\frac{x-\mu}{\beta}} \cdot e^{-e^{\frac{x-\mu}{\beta}}} \tag{7}$$

⁸As a sensitivity analysis, we also test a normal distribution for GSLR with a mean of 5 mm and a standard deviation of 4 mm.

Table 1. Extreme value distribution for storm surges.

Annual exceedance probability	Annual return interval (years)	Annual maximum sea (meters)			
		Dar-es-Salaam		Dhaka	
		Base case	Sensitivity	Base case	Sensitivity
0.001	1000	3.30	5.51	5.21	11.43
0.002	500	3.25	5.24	5.06	10.65
0.004	250	3.19	4.96	4.90	9.86
0.010	100	3.12	4.59	4.70	8.84
0.020	50	3.06	4.31	4.54	8.05
0.039	25	3.01	4.03	4.38	7.26
0.095	10	2.94	3.70	4.19	6.32
0.181	5	2.88	3.40	4.02	5.48
0.393	2	2.81	3.03	3.82	4.45
0.632	1	2.75	2.75	3.66	3.67
<i>Scale parameter (β)</i>		0.080	0.400	0.225	1.125
<i>Location parameter (μ)</i>		2.752	2.752	3.661	3.661

where β is the scale parameter and μ is the location parameter. The Gumbel distribution is often used to characterize flooding events (Kotz and Nadarajah, 2000). Table 1 displays selected values from the extreme value distribution used in this analysis, along with the values of β and μ .

Our analysis does not capture the possibility that the frequency or intensity of storm events is affected by climate change; instead, the parameters underlying the extreme value distribution are stationary for the 100-year analysis period. Because several scientists have suggested that climate change may lead to more intense tropical cyclone activity (IPCC, 2007a), we adjusted the distribution to increase the probability of more extreme sea levels. These adjustments are simply for purposes of sensitivity analysis and do not reflect any particular scientific prediction. As shown in Table 1, the scale factor (β) was increased fivefold, from 0.08 to 0.40 for Dar-es-Salaam and from 0.225 to 1.125 for Dhaka. The effect in Dar-es-Salaam is to raise the 100-year event from 3.1 to 4.6 m. The 100-year event in Dhaka is increased from 4.7 to 8.8 m.

To simulate the maximum sea in any given year, our model integrates these three variables (LSLR, GSLR and maximum surge) as follows. First, the cumulative sea level rise to date is computed as the combination of the deterministic LSLR and the stochastic GSLR. Second, the maximum sea surge for the year being analyzed is simulated and added to the cumulative sea level to yield the maximum sea level to which the coastal defense is exposed. If this level is less than or equal to the height of the coastal defense (plus the freeboard), no inundation occurs and the model moves to simulation of the next year. If the maximum sea level exceeds the height of the defense, then at least some inundation is simulated to occur.

2.2.3. Simulation of inundation events

The extent of inundation depends on the degree to which the maximum sea level is above the protection height. For example, if the maximum sea is 3.2 m and the protection height is 2.0 m, then the difference of 1.2 m determines the extent of inundation. The terrain of the vulnerable city is segmented based on its susceptibility to inundation. The first segment comprises all land susceptible to flooding in the event of an over-topping of coastal defenses of 0.5 m; the second segment comprises lands susceptible to inundation from an over-topping of 1.0 m. This framework continues in half-meter increments, up to the tenth segment, which comprises the area vulnerable to flooding from a vertical over-topping of 5.0 m. If the sea over-tops the protection by 1.2 m, the model would assume complete inundation of area of the first and second segments and partial inundation of the third.

The population within each segment in the first year of the analysis is a model input. Dr. Nicholls provided 2005 population data for the two cities in one-meter intervals (Nicholls *et al.*, 2008); we simulated half-meter intervals by taking the mid-point between the one-meter intervals. Data were adjusted to 2009 using city growth rates (World Bank Databank, 2011).

To estimate asset values within each vulnerable area, we used an approach sometimes applied by the insurance industry in which assets are estimated at five times per-capita GDP (Kebede and Nicholls, 2011).⁹ Because per-capita GDP is higher in urban areas than in rural areas, we developed city-specific estimates of per-capita GDP. We began with 2008 GDP (purchasing power parity, or PPP) for Dar-es-Salaam and Dhaka (Pricewaterhouse Coopers, 2009) and updated the values to 2009 using the national GDP growth rate (World Bank Databank, 2011). (We could not locate city-specific GDP growth rates.) Each city's GDP was then divided by its population (United Nations Secretariat, 2009) to yield an estimate of 2009 per-capita GDP-PPP of \$5841 for Dhaka and \$2669 for Dar-es-Salaam. Table 2 integrates these data and analyses to report population and asset values by area.

If a segment in the city is flooded, then all assets in that segment are assumed to be destroyed. If a segment is only partially flooded, then the asset loss is calculated on a pro-rata basis. Population impacts from the flooding of a segment of the city are divided between fatalities and "displaced persons". Based on a review of available literature and international data on storm events, Jonkman and Vrijling (2008, p. 46) conclude that a "1% mortality value can be used as a first rule of thumb to estimate the number of fatalities for large scale coastal flood events". Accordingly, we assume that 99% of the affected population becomes displaced persons; the remaining 1% are counted as fatalities.

⁹Given that this relationship is an industry heuristic, it is hard to verify its direct applicability to developing countries. Thus, it should be viewed as a first approximation of the relationship between population and asset values in the two cities.

Table 2. Vulnerability as a function of vertical quantity (Q) of over-topping of defenses (estimated for 2009).

	Segment									
	1	2	3	4	5	6	7	8	9	10
Q (m)	0.5	1.0	1.5	2.0	2.5	3.0	3.5	4.0	4.5	5.0
<i>Dar-es-Salaam</i>										
Value of assets (\$m)	244	263	297	331	438	545	732	919	1278	1636
Population (thousands)	18	20	22	25	33	41	55	69	96	123
<i>Dhaka</i>										
Value of assets (\$m)	1390	4754	5602	6450	7297	8145	11,491	14,836	24,220	33,603
Population (thousands)	48	163	192	221	250	279	393	508	829	1151

2.2.4. Simulation of changes in vulnerability

The size of the populations and assets at risk of inundation do not remain constant in the model. Instead, they are assumed to vary stochastically over time. Population growth is simulated based on U.N. projections of urban growth rates by country for five-year intervals between 2010 and 2050 (United Nations Secretariat, 2009). For simulation purposes, we assumed a simple triangular distribution with a minimum equal to the lowest five-year growth rate, a peak equal to growth rate over the full 40 years, and a maximum equal to the highest five-year growth rate. We assume the same rates hold for periods after 2050. Table 3 provides the population growth rates used for the simulation, along with the implied mean of the distribution. While the underlying population growth trend remains constant over the 100-year analysis period within a single model iteration, it is initially selected stochastically based on the distributions shown in Table 3. To reflect year-over-year fluctuations, the actual change in population in any given year is drawn from a uniform distribution with a mean equal to the simulated underlying trend for that iteration and a range of plus or minus 50% of the mean.

Table 3. Annual population growth rate distributions (triangular).

	Dar-es-Salaam	Dhaka
Minimum	3.09%	1.67%
Peak	4.01%	2.50%
Maximum	4.74%	3.13%
Implied mean	3.95%	2.43%

When it comes to estimating changing asset values over time, we again use the heuristic that asset values equal five times per-capita GDP. We combined data on projected GDP growth between 2010 and 2025 (Pricewaterhouse Coopers, 2009) with city-specific population growth rates from the U.N. (United Nations Secretariat, 2009) to derive a GDP per-capita annual growth rate of 3.68% for Dhaka and 2.20% for Dar-es-Salaam. We assumed that this growth rate would persist over the 100-year simulation. As population fluctuates over time, the model estimates asset values as a function of population size and simulated per-capita GDP.

In the year of an inundation, these population and asset growth rates are not applied. Instead, the process of asset destruction and population displacement determines the assets and population that remain at the end of that year. Then, in the following year, the model simulates re-population as the displaced persons return. Displaced persons do not return only to the segment of the city from which they were displaced, but instead are assumed to spread themselves across segments of the city in the same proportions as the population was previously distributed prior to the inundation. Having estimated the post-inundation population in the city, the model then derives the post-inundation asset values using the relationship between population and asset values described above.

2.2.5. Valuation of vulnerable assets and populations

To ensure consistency in the comparison of alternative adaptation strategies (which may exhibit wide variations in the extent and timing of asset creation and asset destruction), we do not focus on changes in asset values, but instead concentrate on changes in the stream of benefits associated with those assets. Given the premise that an asset's value equals the present value of all net benefit streams emanating from it over time, we do not sacrifice analytic rigor by doing so. We also estimate the investment costs incurred when new assets are created. We do not attach a direct cost to the destruction of an asset by flooding because the asset value is a sunk cost funded with capital investments in prior periods. (As explained below, however, the benefit stream from an asset ceases if the asset is destroyed by flooding.)

Of note is that our approach does not allow for fluctuations in the market value of assets as a function of location-based attributes, microeconomic factors, or the potential impacts of climate change. Instead, asset values are assumed to equal the cumulative historical investments in their creation or, put another way, that market value equals book value.

Based on Mello's review of 95 countries between 1970 and 2000, we use an estimate of 7.9% for the marginal product of capital (2009). The annual benefit derived from the capital stock in any given year is thus equal to the value of the stock times 7.9%. This estimated benefit is reduced by the cost of any capital investment simulated to occur in that year. Such investments can occur in one of two ways. First, due to natural population growth and increases in per-capita GDP, the asset stock may

increase on a year-over-year basis; such increases are treated as capital costs. Second, in the year after inundation, asset values also increase but not through natural growth. Instead, the algorithm for re-population leads to increases in the capital stock; again, such increases are treated as capital costs.

For purposes of this analysis, we value a fatality at \$0.320 million in Dar-es-Salaam and at \$0.701 million in Dhaka. These values reflect Miller's review of 68 studies of the value of statistical life (VSL) conducted across 13 countries and his finding that the typical value is about 120 times per-capita GDP (Miller, 2000). In addition, because per-capita GDP grows over time, the value of a statistical life grows commensurately in our analysis. We are not aware of estimates of the value of a displaced person; hence, we simply assume the value to be 5% of the VSL. We make no normative claims about these values; rather, we use them only to reflect the likelihood that planners consider more than vulnerable economic assets in planning coastal defenses.

Finally, we note that each adaptation strategy can differentially affect the value of vulnerable assets at the end of the 100-year analysis period. A strategy which makes large investments in coastal defenses, for example, may result in a markedly larger asset base in Year 100 than one that makes only modest investments in defenses. Although using the marginal product of capital to estimate benefit streams does capture such differential effects during the 100-year analysis period, it does not capture the residual value of a larger asset base after Year 100. Accordingly, we estimate the terminal value of the asset base as a perpetuity that reflects conditions as of Year 100. The annual amount of the perpetuity comprises three elements: The marginal product of capital times the Year 100 asset base, the O&M cost in Year 100 and the expected value of the residual damages based on sea levels, vulnerable populations, and vulnerable assets as of Year 100. This perpetuity is valued with the same discount rate used throughout the analysis.

2.2.6. *Compilation of results*

All adaptation strategies are simulated simultaneously within each iteration. This ensures that annual sea levels and population growth rates remain constant as each strategy is assessed. (Across iterations, these variables are allowed to vary stochastically.) For each year, the model records the product of the asset stock, the spending on coastal defenses, whether the protection height has been raised, whether an inundation occurs, and if inundation occurs, the number of fatalities and displaced persons. It also records the Year 100 terminal asset value.

At the end of the analysis period, the present value of costs and damages are computed and the numbers of inundations, fatalities and displaced persons are tallied. After 5000 iterations, statistics are generated on key model outputs. Appendix A illustrates the simulation model.

We applied discount rates of 3% and 7% (U.S. Office of Management and Budget, 2003) and considered two scenarios for climate change. In the *base climate scenario*,

global sea level rise reflects a normal distribution with a mean of 3 mm and a standard deviation of 2 mm. Three millimeters per year is approximately the average of the mid-points projected in the IPCC Fourth Assessment Report (2007b); the standard deviation of 2 mm is a speculative judgment about uncertainty in the average rate of sea level rise. In the intensified climate change case, the mean is 5 mm and the standard deviation is 4 mm. In other words, sea level rise is both faster and more variable in the latter case. For the *intensified climate scenario*, as noted previously, we also adjusted the extreme value distribution to increase the magnitude and likelihood of extreme sea surge events. This scenario is a sensitivity analysis, not based on specific scientific forecasts.

3. Results

We first describe our results for the base climate scenario and then turn to the intensified climate scenario. We next consider the explicit value of flexibility in planning for coastal defenses and conclude with an overview of the limitations of our approach.

3.1. Performance of adaptation strategies: Base climate scenario

Table 4 presents the net benefits of each strategy and ranks them from highest to lowest benefit. Table 5 shows, for each strategy, the number of years in which inundation occurs, the number of times the defense is raised, and the average height of the defense.

The Do Nothing Baseline tends to perform quite poorly and is one of the least beneficial strategies, except in the case of Dar-es-Salaam where, at a 7% discount rate, it dominates all other strategies. Other than in this one case, vulnerable assets and

Table 4. Results: Base climate scenario. Mean present value (\$M) of net benefits* over 100 years (5000 iterations).

City/Discount rate	Result	Inflexible strategies			Real option strategies	
		Do Nothing Baseline	100-Year Event	Decide Once & Build in Stages	Predict & Respond	Sense & Respond
Dar-es-Salaam 3%	Net benefits	\$6,118	\$5,340	\$19,431	\$111,919	\$112,935
	Strategy rank	#4	#5	#3	#2	#1
Dar-es-Salaam 7%	Net benefits	\$1,123	-\$773	\$257	-\$2,216	-\$2,494
	Strategy rank	#1	#3	#2	#4	#5
Dhaka 3%	Net benefits	\$292,839	\$1,737,087	\$1,995,410	\$2,408,507	\$2,375,890
	Strategy rank	#5	#4	#3	#1	#2
Dhaka 7%	Net benefits	\$31,771	\$55,029	\$54,290	\$59,050	\$59,630
	Strategy rank	#5	#3	#4	#2	#1

*Net benefits = [Ongoing asset product – Investments in assets coastal defenses – Value of fatalities & displaced persons + Terminal asset value]

Table 5. Characteristics of coastal defenses: Base climate scenario. Mean value over 100 years (5000 iterations).

City - Discount rate	Do Nothing Baseline			100-Year Event Strategy			Decide Once & Build in Stages Strategy			Predict & Respond Strategy			Sense & Respond Strategy		
	# of inundations	# of height increases	Avg defense height (m)	# of inundations	# of height increases	Avg defense height (m)	# of inundations	# of height increases	Avg defense height (m)	# of inundations	# of height increases	Avg defense height (m)	# of inundations	# of height increases	Avg defense height (m)
Dar-es-Salaam — 3%	100.0	0.00	0.75	82.63	1.00	2.00	34.67	5.00	2.67	0.40	1.70	3.11	0.00	2.20	3.15
Dar-es-Salaam — 7%	100.0	0.00	0.75	82.63	1.00	2.00	45.31	5.00	2.18	4.76	1.28	2.93	0.00	2.20	3.15
Dhaka — 3%	100.0	0.00	1.50	8.42	1.00	3.00	4.14	5.00	4.76	0.04	2.71	5.44	0.26	3.23	3.95
Dhaka — 7%	100.0	0.00	1.50	8.42	1.00	3.00	4.14	5.00	4.76	0.54	3.13	5.09	0.26	3.23	3.95

populations are sufficiently large, and the probability of inundation sufficiently high, to justify additional investment in protection. The case of Dar-es-Salaam, however, demonstrates that, as discount rates increase, yielding to a rising sea and suffering the associated consequences, may be preferable to investing in the near term to prevent inundation in the long term.

The performance of the 100-Year Event Strategy is mixed. In one case, it has the lowest benefits; in other cases, its performance is in the middle of the other strategies. Setting aside the Do Nothing Baseline, the 100-Year Event Strategy results in the lowest level of protection (i.e., 2 m in Dar-es-Salaam and 3 m in Dhaka) and, in turn, the highest rates of inundation (i.e., 83 in Dar-es-Salaam and 8 in Dhaka). This strategy has lower construction costs, but its savings are offset by increased damages from the lower level of protection. In addition, because all construction costs are incurred in Year 1, there is no opportunity for discounting to reduce present value costs as would be the case if construction were postponed.

The Decide Once & Build in Stages Strategy outperforms the 100-Year Event Strategy in three cases and, in a fourth case (Dhaka at a 7% discount rate), performs about the same. Contributing to its performance is the inclusion of a cost-minimization algorithm that selects an average protection height greater than the 100-Year Event Strategy (e.g., in Dhaka, 4.76 m rather than 3.00 m), thereby significantly reducing the number of inundations in comparison to the 100-Year Event Strategy. In addition, by staging the construction of the defense over 100 years, discounting reduces the present value of costs relative to a strategy in which the full investment is made in Year 1. Undermining the performance of the Decide Once & Build in Stages Strategy, however, is the lack of a learning mechanism that detects and acts on changing sea conditions. While construction costs are spread over time, the protection height is selected in Year 1. Therefore, in iterations where sea level rise is less than expected, the protection height (and the associated costs) are higher than necessary, and when sea levels are higher than expected, the protection height is insufficient to prevent inundation.

The first of the real option strategies — Predict & Respond — outperforms the Decide Once & Build in Stages Strategy in both cities at a discount rate of 3% and in Dhaka at 7%. Both strategies embody economic optimization and push some construction costs into the future. The Predict & Respond Strategy goes further, however, by allowing planners to learn about sea conditions and asset growth and then apply this continuously updated information to their sequential decisions in Years 21, 41, 61 and 81. In contrast, no learning takes place under the Decide Once & Build in Stages Strategy. As a result, the number of inundations with the Predict & Respond Strategy is much lower than with the Decide Once & Build in Stages Strategy. This finding holds for both cities and across discount rates, although in Dar-es-Salaam, at a discount rate of 7%, this decrease in the number of inundations does not yield sufficient benefits to offset the greater investment in coastal defenses.

The second real option strategy — Sense & Respond — generally performs quite well. The only exception is in Dar-es-Salaam at a 7% discount rate (where all strategies

are dominated by the Do Nothing Baseline). These results obtain despite the fact that the Sense & Respond Strategy is entirely reactive; there is neither economic optimization nor any prediction of future sea levels or asset values. In Dar-es-Salaam, it results in the highest average protection height across all strategies and prevents all inundations. In Dhaka, even though it does not generate the highest average protection height, it still prevents virtually all inundations. Of note is that these results depend heavily on the choice of the “safety margin” which triggers additional construction whenever observed sea surges come within 0.5 m of the existing height. A smaller safety margin would reduce costs but increase the risk of inundation.

When comparing all strategies at the same time, a seemingly anomalous result becomes apparent. The two strategies that entail economic optimization (i.e., the Decide Once & Build in Stages and the Predict & Respond Strategies) do not always display net benefits greater than the strategies that make no attempt to optimize. One example occurs in Dar-es-Salaam where, at a discount rate of 7%, the Do Nothing Strategy dominates all other strategies. Despite the higher benefit of doing nothing and leaving the existing defense at a height 0.75 m, the Decide Once & Build in Stages Strategy selects a target height of 2.18 m and the Predict & Respond Strategy results in an average height of 2.93 m, yielding lower net benefits for both strategies, \$257 million and $-\$2,216$ million, respectively, than the Do Nothing Baseline (\$1,123 million).

This result is attributable to the simple economic analysis we assume is conducted by the boundedly-rational coastal planner under these two strategies. Rather than operationalize the first-best approach implied by Eq. (1), planners simply apply Eq. (4) and look forward to Year 100 (or, in the case of the Predict & Respond Strategy, to a point 20 years in the future), and use point estimates of population and GDP growth to predict the value of the vulnerable asset stock (rather than estimating the benefit stream from those stocks). We also assume the planner applies the probability distribution for storm surges to these asset values to estimate expected residual damages for different protection heights. Such damages are then compared to the cost of coastal defenses of alternative heights to select the height with the lowest aggregate cost. In contrast, the ex-post cost-benefit calculus in Eq. (2) that we, as researchers, use to tally the net benefit of each strategy is appreciably more sophisticated. Based on the Monte Carlo results, it reflects stochasticity in asset and population growth, simulates ongoing asset destruction and re-investment, and values assets based on benefit streams rather than stock values. If planners used this more sophisticated economic analysis, the performance of the Decide Once & Build in Stages and the Predict & Respond Strategies would improve.

3.2. Performance of adaptation strategies: Intensified climate change scenario

As a sensitivity analysis, we evaluated the performance of the strategies under a scenario in which climate change, unbeknownst to local planners in Year 1, proves to

Table 6. Results: Intensified climate scenario. Mean present value (\$M) of net benefits* over 100 years (5000 iterations).

City/Discount rate	Result	Inflexible strategies			Real option strategies	
		Do Nothing Baseline	100-Year Event	Decide Once & Build in Stages	Predict & Respond	Sense & Respond
Dar-es-Salaam 3%	Net benefits	\$4952	\$5778	\$18,063	\$105,126	\$87,866
	Strategy rank	#5	#4	#3	#1	#2
Dar-es-Salaam 7%	Net benefits	\$1107	-\$778	\$232	-\$3,551	-\$2783
	Strategy rank	#1	#3	#2	#5	#4
Dhaka 3%	Net benefits	\$160,700	\$423,862	\$1,803,965	\$2,321,746	\$742,154
	Strategy rank	#5	#4	#2	#1	#3
Dhaka 7%	Net benefits	\$30,398	\$42,800	\$52,222	\$51,310	\$44,030
	Strategy rank	#5	#4	#1	#2	#3

*Net benefits = [Ongoing asset product – Investments in assets & coastal defenses – Value of fatalities & displaced persons + terminal asset value]

be more intense than anticipated. To do so, we adjusted the rate of global sea level rise from a normal distribution with a mean of 3 mm and a standard deviation of 2 mm to one where these parameters are, respectively, 5 and 4 mm. In addition, we applied a modified version of the extreme value distribution to generate larger and more frequent storm surges (see Table 1).

This change in the climate scenario has no effect on planning decisions made under the three inflexible strategies since those decisions are made before the intensification of climate change becomes known. Under the Predict & Respond strategy, the first (i.e., Year 1) decision is also unaffected by the intensification of climate change, but the subsequent decisions in Years 21, 41, 61 and 81 are affected. As for the change in the probability distribution for sea surges, we assume it is undetected at Year 1, but becomes known to planners by Year 21 (perhaps thanks to the work of research scientists). As for the Sense & Respond Strategy, because it responds immediately to sea conditions, the intensified climate change scenario could potentially affect planning decisions as soon as Year 2. Table 6 presents net benefits under the intensified climate scenario and Table 7 displays the impacts of each strategy on coastal defenses.

Some of the results under the intensified climate change scenario are similar to those obtained in the base climate scenario. The Do Nothing Baseline again performs quite poorly, except in Dar-es-Salaam where, at a 7% discount rate, it is again the best performing strategy. Similarly, the 100-Year Event Strategy again delivers only mid-dling performance. The relative performance of the Decide Once & Build in Stages Strategy does improve in the intensified climate change scenario, to the point where it is the most beneficial strategy in one case (i.e., Dhaka at a 7% discount rate). As discussed below, however, this relative improvement seems more attributable to the weaker performance of the Sense & Respond strategy, than to the ability of Decide

Table 7. Characteristics of coastal defenses: Intensified climate scenario. Mean value over 100 years (5000 iterations).

City - Discount rate	Do Nothing Baseline			100-Year Event Strategy			Decide Once & Build in Stages Strategy			Predict & Respond Strategy			Sense & Respond Strategy		
	# of inundations	# of height increases	Avg defense height (m)	# of inundations	# of height increases	Avg defense height (m)	# of inundations	# of height increases	Avg defense height (m)	# of inundations	# of height increases	Avg defense height (m)	# of inundations	# of height increases	Avg defense height (m)
Dar-es-Salaam — 3%	100.0	0.00	0.75	84.91	1.00	2.00	37.16	5.00	2.67	0.00	3.65	4.52	0.00	2.57	3.23
Dar-es-Salaam — 7%	100.0	0.00	0.75	84.91	1.00	2.00	52.99	5.00	2.18	0.00	3.29	4.25	0.00	2.57	3.23
Dhaka — 3%	100.0	0.00	1.50	16.98	1.00	3.00	4.61	5.00	4.76	0.01	3.35	8.30	0.30	3.50	4.02
Dhaka — 7%	100.0	0.00	1.50	16.98	1.00	3.00	4.61	5.00	4.76	0.83	3.93	7.91	0.30	3.50	4.02

Once & Build in Stages Strategy to effectively accommodate unexpected intensification of climate change. Under a scenario of intensified climate change, the Predict & Respond Strategy is the strategy with the highest net benefits at a discount rate of 3% in both cities. It achieves this result in large measure by constructing the highest coastal defenses of any strategy, thereby adapting to higher storm surges in a manner that sufficiently reduces asset and population damages over the long run to offset increased construction costs. These higher coastal defenses also have the effect of increasing the Year 100 terminal asset value, because of their ongoing contribution to protection of vulnerable assets and populations. At a 7% discount rate, however, this tradeoff between near-term construction costs and longer-term benefits becomes less favorable, and the relative performance of the Predict & Respond Strategy drops off.

While it is among the best performing strategies in the base climate scenario, the performance of the Sense & Respond Strategy weakens under the intensified climate change scenario. This result reflects the significantly lower average protection height — relative to the Predict & Respond Strategy — yielded by the Sense & Respond Strategy despite more intense climate change. While this difference does not materially affect the number of inundations during the 100-year analysis period, it does lead to a significantly more vulnerable city in Year 100. In turn, the prospect of a relatively low protection height in combination with more intense and frequent storm surges causes the terminal asset value to be appreciably lower. Especially at low discount rates, this phenomenon has a substantial impact on the overall performance of the Sense & Respond Strategy.

3.3. Value of flexibility

As shown in Table 8, it is also instructive to compute the value of flexibility by comparing the better-performing of the two inflexible strategies to the better-performing of the two real option strategies. Irrespective of the climate scenario, there is always value to flexibility at a discount rate of 3%. For Dar-es-Salaam, this flexibility ranges in value from \$87.1 billion to \$93.5 billion; in the case of Dhaka, it ranges from \$413 billion to \$518 billion. At a discount rate of 7%, however, flexibility generally does not yield increases in net benefits. (The exception is Dhaka in the base climate scenario at a discount rate of 7%.) In short, while flexibility may generate benefits, if those benefits are far enough in the future and the discount rate is high enough, the present value of the benefits may be insufficient to offset the costs of constructing coastal defenses and/or the impacts of damages caused by inundation.

3.4. Limitations of our analysis

There are some key limitations to our approach, virtually all of which originate in the simplifying assumptions made in order to render the analysis tractable. Some of these assumptions relate to the characteristics of the coastal defense. We assume that construction can be completed within a single year, that land is available for the widening

Table 8. The Value of flexibility. Mean present value (\$M) of net benefits over 100 years (5000 iterations).

Discount rate	Dar-es-salaam				Dhaka			
	Base climate change scenario		Intensified climate change scenario		Base climate change scenario		Intensified climate change scenario	
	3%	7%	3%	7%	3%	7%	3%	7%
Inflexible Strategy with Maximum Benefit	Decide Once & Stage Build	Do Nothing	Decide Once & Stage Build	Do Nothing	Decide Once & Stage Build	100-Year Event	Decide Once & Stage Build	Decide Once & Stage Build
	\$19,431	\$1,123	\$18,063	\$1,107	\$1,995,410	\$55,029	\$1,803,965	\$52,222
Real Option Strategy with Maximum Benefit	Sense & Respond	Predict & Respond	Predict & Respond	Sense & Respond	Predict & Respond	Sense & Respond	Predict & Respond	Predict & Respond
	\$112,935	-\$2,216	\$105,126	-\$2,783	\$2,408,507	\$59,630	\$2,321,746	\$51,310
Value of Flexibility	\$93,503	\$0	\$87,063	\$0	\$413,097	\$4,601	\$517,781	\$0

*Net benefits = [Ongoing asset product – Investments in assets & coastal defenses – Value of fatalities & displaced persons + Terminal asset value.]

of the base of the defense when its height is increased, and that the only pathway to inundation is from the over-topping of the defense rather than its outright failure. When it comes to development patterns, we did not simulate a behavioral link between policy decisions about coastal defense and the location decisions of firms and residents. Presumably, a stronger coastal defense system would increase the propensity to locate in lower elevations while a policy decision to minimize protection might induce some firms or residents to locate outside vulnerable areas. We also modeled climate change in a simple fashion by, for example, assuming a constant century-long trend in the annual change in global sea levels (albeit with variability around that central tendency), by assuming that local sea level change (i.e., either subsidence or uplift) is constant, by assuming that the parameters underlying the extreme value distribution for characterizing storm surges are constant, and by assuming no abrupt change in global sea levels as might be caused, for example, by a sudden collapse of the West Antarctic Ice Shelf. Finally, when it comes to the ability of coastal planners to predict future conditions, we assumed they have access to an accurate representation of the relevant extreme value distribution for sea surges, are able to extrapolate from prior sea level rise to predict future sea level rise and, in the case of intensified climate change, are able to recognize by Year 21 the shift in the extreme value distribution.

We also recognize that monetizing the value of the loss of life and displacement of populations can be a controversial topic with significant normative overtones. Rather than omit such valuations, however, we include them, both for the purposes of illustrating our methodology and to take account of the likelihood that coastal communities place a value on loss of life and displacement of populations, independent of the impact of inundation on capital assets.

4. Discussion

4.1. Implications for local planning decisions

Our analysis has several implications for local initiatives to defend a coastal city from rising sea levels. First, the performance of various adaptation strategies is heavily dependent on location-specific conditions. For example, at a 7% discount rate, making no investment in coastal defense is the optimal strategy in Dar-es-Salaam, but the worst strategy for Dhaka, irrespective of the climate scenario analyzed. Similarly, in the base climate scenario, the 100-Year Event Strategy generates about 10 times as many inundations in Dar-es-Salaam than it does in Dhaka (83 inundations vs. 8). Based on our analysis, a global conclusion about a single optimal strategy for adapting to sea level rise is not possible. Instead, location-specific analysis is required to identify the strategy with the highest expected aggregate net social benefits.

Our analysis does, however, demonstrate that real options strategies that provide flexibility have the potential to increase net social benefits, especially at lower discount rates. This advantage originates from two factors. The first is that, in contrast to an inflexible strategy where the protection height is selected at the outset of the planning

process, the flexible strategy holds out the chance that, in some cases, sea level rise or vulnerable asset growth may not be as significant as initially expected. In such cases, less robust defenses are needed and investment costs can be lower than with an inflexible strategy. Conversely, if sea levels rise faster than expected, a flexible strategy allows for fortification of the defense while an inflexible strategy may fail to prevent inundation.

The second source of a flexible strategy's advantage is the opportunity to defer investment. If planners postpone construction costs, then the present value of these costs will drop. As long as this savings is not offset by more numerous or costly inundations, then it may confer a significant cost advantage. The magnitude of this advantage, however, depends on the discount rate. It is instructive to contrast the Predict & Respond Strategy to the Decide Once & Build in Stages Strategy because both invest in coastal defenses at the same five points in time over the 100-year analysis period. In Dar-es-Salaam, irrespective of the climate scenario, the Predict & Respond Strategy out-performs the Decide Once & Build in Stages Strategy at a discount rate of 3%, but under-performs it at 7%. While the higher discount rate does reduce the present value of protection cost, it also reduces the value of the benefits. Depending on the discount rate, there are 34 to 40 fewer inundations in the base climate scenario under the Predict & Respond Strategy than under Decide Once & Build in Stages Strategy. Even though the Predict & Respond Strategy produces significant benefits over time, the higher discount rate de-values those benefits sufficiently to allow the Decide Once & Build in Stages Strategy to out-perform it. In short, not all real option strategies are superior to inflexible strategies.

Another implication of our analysis is that flexibility may come with a high price. Although our version of the Sense & Respond Strategy did not display this result, one can imagine that if a city postpones investments in coastal defense until rising seas clearly threaten its existing defenses, it may end up waiting too long to protect itself. A real options strategy must be structured so that the resolution of uncertainty occurs with sufficient time to allow the option holder to decide whether to exercise the option. If a coastal community holding a real option to strengthen its defense learns about the value of the protection only in the aftermath of a catastrophic flood, then a valuable option will have been allowed to expire without being exercised.

We also observe that the quality of the information that is being obtained over time — the source of a real option's potential to create value — has an important bearing on the option's value. The strong performance of the Predict & Respond strategy for example is due, in large measure, to the increasingly accurate prediction of sea levels over the 100-year analysis period. In Year 61, for example, local planners can use the average sea level rise over the 60 prior years to predict the rate of change for the next 20 years and adjust their coastal defense accordingly. Predictions of sea level rise do not come only from local observations, but also from the global scientific community. Groups like the IPCC can assist local planning efforts by providing information about the likely rate of sea level rise.

Especially important for local planning is not just the mean, or expected value, of potential sea level rise, but also the shape of the probability distribution from which the mean is drawn. Perhaps the largest challenge to using a real options approach for coastal defense is the need to characterize the likelihood that such defenses will be over-topped. With a probability distribution for sea level rise over time, planners can assess both the likelihood and potential extent of inundation prior to option exercise and then balance such risks against savings in protection costs. If information is available only on the central tendency, and not the probability distribution, of expected sea level rise, this balancing cannot be done accurately.

The timeframe for the required information also differs between flexible and inflexible strategies. While projections of sea level rise over the next century may be important to decisions about global climate policy, they are only relevant to local planning decisions if an inflexible, single-investment, strategy is being considered with the goal of constructing a coastal defense sufficient for a century's worth of sea level rise. If, on the other hand, local planners aspire to implement a net-benefit-maximizing real option strategy, then their information needs are markedly different from those of global policymakers. The time period for which they need projections of sea level rise would be much shorter — perhaps only 20 to 40 years. Projections over longer time frames would not be needed, since optional increases in sea level defenses can be used by planners in later years to address subsequent sea level rise should it actually occur.

Another important piece of information that would enhance coastal planning is the rate of local sea level rise. Both subsidence and increases in land elevation can have a significant impact on the local consequences of global sea level rise. The former exacerbates global sea level rise while the latter mitigates it. In conducting the background research for this study, we discovered that reliable data on local sea level rise in developing countries appear to be sparse.

4.2. Implications for policy makers

Beyond the economic merits of inflexible and real options strategies for adapting to climate change, there also exist at least two pragmatic considerations that are relevant to the choice between the two strategies. The first relates to in-country institutional capability and the second involves the practical realities of international development assistance.

4.2.1. Institutional capability to manage a real option

The process of managing a real option strategy — especially one based on ongoing benefit-cost analyses such as the Predict & Respond Strategy — is likely to be much more complex than implementing an inflexible strategy. While ongoing maintenance would be needed in either case to prevent deterioration of the coastal defense, the inflexible strategy has a “once and forget it” character absent from the real option strategy. With the real options strategy, changes in local sea conditions and in the

predictions of future sea level rise must be monitored on an ongoing basis. Changes in the value of economic assets and vulnerable populations must also be regularly assessed in order to re-calibrate the value of protection. In turn, sequential decisions must be made about whether changing circumstances warrant fortification of the coastal defense. The Sense & Respond Strategy, because it omits any economic analysis, would likely be easier to implement than the Predict & Respond Strategy. With either real option strategy, however, if a decision to improve the defense is taken, then several additional activities are needed: Project design, procurement, land acquisition (if needed), construction management and so forth.

For the real options strategy to realize its potential value, the local planning authorities must have the institutional capacity to execute all these activities successfully and to do so in a timely fashion. If such capacity is lacking, the result may be an insufficiently robust coastal defense structure. Available evidence suggests that this not just a theoretical concern. At least one study suggests that many coastal cities in Asia have large populations living in vulnerable areas that are not effectively monitored or managed when it comes to protection against flooding from sea surges (Adikari *et al.*, 2010).

4.2.2. Financial resources for future exercise of option

The use by a developing country of a real options approach for structuring its investments in adaptation to climate change may have important implications for international development assistance, such as that provided by the Global Environment Facility or the UNFCCC Adaptation Fund. Unlike a one-off project to construct a coastal defense structure, the real options approach contemplates capital investments on an ongoing basis over several decades. Both funders and recipients of development assistance would therefore need to address the question of how much funding is necessary and when it should be disbursed. The same uncertainty that makes the real options approach attractive creates a dilemma for funders and recipients: The level and timing of funding needed to exercise the option at various intervals would not be known until later in time. An inflexible strategy that entails immediate construction of a coastal defense may be more expensive than a real option strategy, but it has the advantage that it can be designed, financed, and built in a relatively short timeframe.

Most multilateral financial mechanisms are funded in tranches that extend only over a few years; it is easy to imagine that the need for funding to exercise an option could occur after funds in a particular tranche have been exhausted. A recipient country might understandably be reluctant to pursue a real options strategy if there were a chance that the funding for subsequent improvements in the coastal defense would be unavailable. One alternative might be for the funding source to put the monies in an escrow account or provide a letter of credit that could be tapped at the recipient country's discretion, thereby creating the certainty of future funding to exercise the option. An interesting codicil to this observation is that, owing to the possibility that

the option would not be exercised (if sea level rise, asset appreciation, or population growth is lower than expected), such escrowed funds might never be needed. Policies and mechanisms for handling such contingencies would need to be developed.

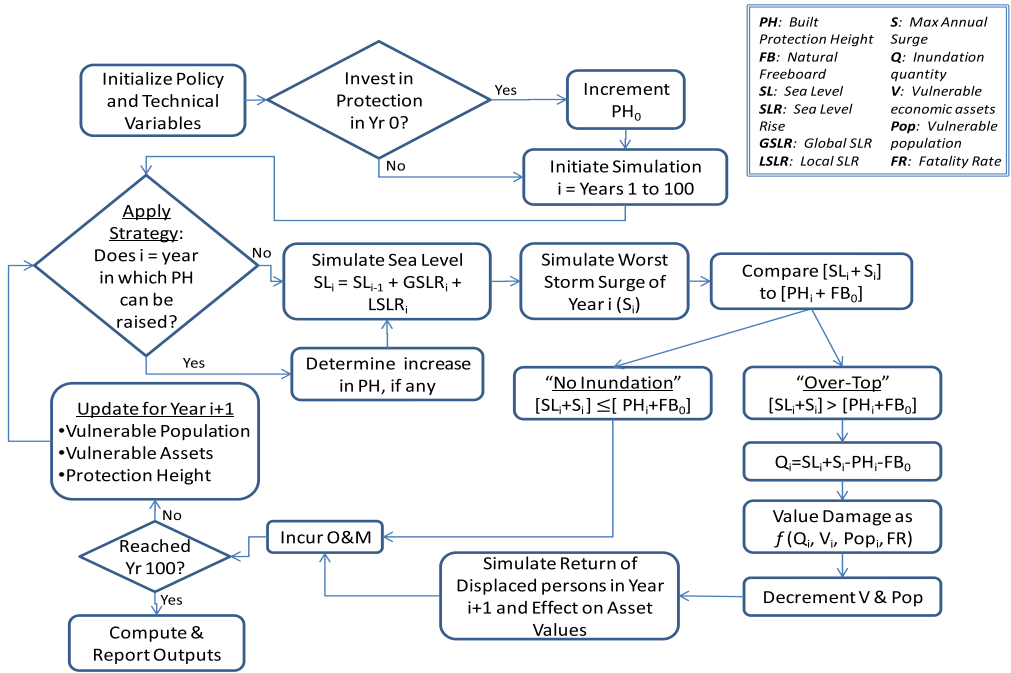
5. Future Research

The foregoing analysis suggests several possible avenues for future research. As mentioned previously, addressing the subject of risk aversion, and whether and how it should be handled in analyzing adaptation to climate change is one area for further investigation. In addition, addressing the limitations of the simulation model that were described in Sec. 3.4 would make for a more robust set of results, as would applying the model to other locations. We also anticipate using the analytic framework to better understand the key scientific, economic and policy information that is needed to improve the quality of sequential decision making about adaptation to rising sea levels. Doing so would allow us to characterize the economic value of research to improve the quality of that information. Finally, an understanding of the degree to which findings drawn from the field of sea level rise can be generalized to adaptation to other types of climate impacts would be valuable.

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Appendix. Overview of Simulation Model



References

Adikari, Y, R Osti and T Noro (2010). Flood-related disaster vulnerability: An impending crisis of megacities in Asia. *Journal of Flood Risk Management*, 3(3), 185–191.

Arrow, K and R Lind (1970). Uncertainty and the evaluation of public investment decisions. *The American Economic Review*, 60(3), 364–378.

Boardman, A, D Greenberg, A Vining, A and D Weimer (2006). *Cost Benefit Analysis: Concepts and Practices*, 3rd edn. Upper Saddle River, NJ: Pearson Prentice Hall.

Bureau of Meteorology (2011). ARI and AEP Explained. from Government of Australia. Available at www.bom.gov.au/hydro/has/ari_aep.shtml. Accessed 27 March 2011.

Cochrane, H (2010). The economics of disaster: Retrospect and prospect. In *The Economics of Natural and Unnatural Disasters* W Kern (ed.), pp. 65–85. Kalamazoo, MI: Upjohn Institute.

Copeland, T and V Antikarov (2003). *Real Options: A Practitioner’s Guide*. New York: Cengage.

Dasgupta, S, B Laplante, S Murray and D Wheeler (2009). *Sea-Level Rise and Storm Surges: A Comparative Analysis of Impacts in Developing Countries*. Environment and Energy Team, Development Research Group. Washington, DC: The World Bank.

Dobes, L (2010). *Notes on Applying “Real Options” to Climate Change Adaptation Measures, with Examples from Vietnam*. Crawford School of Economics and Government, Centre for Climate Economics & Policy. Canberra: Australian National University.

Eijgenraam, C (2007). From optimal to practical safety standards for dike-ring areas. *Water Science & Technology*, 56(4), 113–124.

Hertzer, G (2007). Adapting to climate change and managing climate risks by using real options. *Australian Journal of Agricultural Research*, 58, 985–992.

- HM Treasury (2009). *Accounting for the Effects of Climate Change: Supplementary Green Book Guidance*.
- Hoekstra, A and J De Kok (2008). Adapating to climate change: A comparison of two strategies for dike heightening. *Natural Hazards*, 47, 217–118.
- Howe, C and H Cochrane (1976). A decision model for adjusting to natural hazard events with application to urban snow storms. *Review of Economics and Statistics*, 58(1), 50–58.
- IPCC (1990). Policymakers summary prepared by Working Group 1. In *Climate Change: The IPCC Scientific Assessment*. J Houghton, G Jenkins and J Ephraums (eds.), Cambridge, UK: Cambridge University Press.
- IPCC (2007a). Summary for policy makers. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report*. M Parry, O Canaiani, J Palutkof, P V Linden and C Hanson (eds.), Cambridge, UK: Cambridge University Press.
- IPCC (2007b). Summary for policy makers. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report*. S Solomon, D Qin, M Manning, Z Chen, M Marquis, K Avery and H Miller (eds.), Cambridge, UK: Cambridge University Press.
- IPCC (2007c). Synthesis report. In *Climate Change 2007: Contribution of Working Groups I, II, and III to the Fourth Assessment Report*. R Pachauri and A Reisinger (eds.), Geneva, Switzerland: Intergovernmental Panel on Climate Change.
- IPCC (2007d). Technical summary. In *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report*. M Parry, O Canaiani, J Palutkof, P. V. Linden and C Hanson (eds.), Cambridge, UK: Cambridge University Press.
- IPCC (2010). Fifth Assessment Report., from IPCC - Activities: Available at: <http://www.ipcc.ch/activities/activities.htm>. Accessed 1 February 2011.
- Jonkman, S and J Vrijling (2008). Loss of life due to floods. *Journal of Flood Risk Management*, 1, 43–56.
- Jonkman, S, M Kok, M Van Ledden and J Vrijling (2009). Risk-based design of flood defense systems: A preliminary analysis of the optimal protection level for the New Orleans metropolitan area. *Journal of Flood Risk Management*, 2(3), 170–181.
- Kebede, A and R Nicholls (2011). *Population and Assets Exposed to Coastal Flooding in Dar-es-Salaam (Tanzania)*. University of Southampton. Global Climate Adaptation Partnership.
- Kotz, S and S Nadarajah (2000). *Extreme Value Distributions: Theory and Applications*. London: Imperial College Press.
- Kousky, C and R Cooke (2010). *Adapting to Extreme Events: Managing Fat Tails*. Washington, DC: Resources for the Future.
- Lowe, J and J Gregory (2010, April). A sea of uncertainty. *Nature Reports Climate Change*, 4, 42–43.
- Mello, M (2009). Estimates of the marginal product of capital, 1970–2000. *B.E. Journal of Macroeconomics*, 9(1), Article 16.
- Mendelsohn, R (2000). Efficient adaptation to climate change. *Climatic Change*, 45, 583–600.
- Mendelsohn, R, A Dinar and L Williams (2006). The distributional impact of climate change on rich and poor countries. *Environment and Development Economics*, 11, 159–178.
- Miller, TR (2000). Variations between countries in values of statistical life. *Journal of Transport Economics and Policy*, 34(2), 169–188.
- Milliman, J and B Haq (1996). *Sea-Level Rise and Coastal Subsidence: Casues, Consequences, and Strategies*. Boston: Kluwer Academic Publishers.

- Ministry of Transport, Government of the Netherlands. (2010). The 2011 Delta Programme: Working on the Delta.
- National Research Council (2010). *Advancing the Science of Climate Change*. Washington, DC: The National Academies Press.
- Ng, W-S and R Mendelsohn (2005). The impact of sea level rise on Singapore. *Environment and Development Economics*, 10, 201–215.
- Nicholls, R, S Hanson, C Herweijer, N Patmore, S Hallegatte, J Corfee-Morlot and R Wood (2008). Ranking port cities with high exposure and vulnerability to climate extremes: Exposure estimates. OECD Environment Working Papers. OECD Publishing.
- Pricewaterhouse Coopers. (2009). *UK Economic Outlook*.
- Rahmstorf, S (2010). A new view on sea level rise. *Nature Reports Climate Change*, 4, 44–45.
- Rosenberg Library (2003). Frequently asked questions about the 1900 Galveston Storm. Galveston and Texas History Center: Available at: <http://www.gthcenter.org/exhibits/storms/1900/victims/stormfaq.htm>. Accessed 14 March 2012.
- Russell, C (1970). Losses from natural hazards. *Land Economics*, 46(4), 383–393.
- Scandizzo, P (2010). *Adapting to Climate Changes: How to Evaluate Strategies and Projects*. Saarbrücken, Germany: VDM Verlag.
- Shockley, R (2007). *An Applied Course in Real Options Valuation*. Mason, OH: Thomson Higher Education.
- Triantis, A (2001). Real options: State of the practice. *Journal of Applied Corporate Finance*, 14(2), 8–24.
- Triantis, A (2003). Real options. In *Handbook of Modern Finance*. D Logue and J Seward (eds.), pp. D1–D32. New York: Research Institute of America.
- U.S. Council of Economic Advisors (2011). *Economic Report of the President*. Table B-7.
- U.S. Office of Management and Budget (2003). Circular A-4: Regulatory analysis.
- United Nations Secretariat (2009). World Urbanization Prospects: The 2009 Revision. Population Division, Department of Economic & Social Affairs: Available at <http://esa.un.org>. Accessed 25 July, 2011.
- Valfedis, A, G Boot, J Cox, R Maatens, L McFadden, R Nicholls and R Tol (2004). Diva database documentation. Available at: www.civil.soton.ac.uk/diva. Accessed 2 May 2011.
- Van Dantzig, D (1956). Economic decision problems for flood prevention. *Econometrica*, 24(3), 276–287.
- Vonortas, NS and CA Desai (2007). “Real options” framework to assess public research investments. *Science and Public Policy*, 34(10), 699–708.
- Weitzman, M (2009). On modeling and interpreting the economics of catastrophic climate Change. *The Review of Economics and Statistics*, 91(1), 1–19.
- Weyant, J (2008). A critique of the Stern review’s mitigation cost analyses and integrated assessment. *Review of Environmental Economics and Policy*, 2(1), 77–93.
- Woodward, M, B Gouldby, Z Kapelan, S Khu and I Townend (2011). Real options in flood risk Management Decision Making. *Journal of Flood Risk Management*, 4(4), 339–349.
- World Bank (2009). Mainstreaming adaptation to climate change in agriculture and natural resources management projects, Guidance Note 7, Annex 12. Environment Department.
- World Bank (2010). Economics of adaptation to climate change: Synthesis Report. Washington, DC.
- World Bank Databank. (2011). Available at: databank.worldbank.org. Accessed 3 May 2011.
- Yohe, G, J Neumann and P Marshall (1999). The economic damage induced by sea level rise in the United States. In *The Impact of Climate Change on the United States Economy*. R Mendelsohn and J Neumann (eds.), pp. 178–208. Cambridge, UK: Cambridge University Press.