MIT Joint Program on the Science and Policy of Global Change

Estimating the Economic Cost of Sea-Level Rise

Masahiro Sugiyama, Robert J. Nicholls and Athanasios Vafeidis

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Estimating the Economic Cost of Sea-Level Rise

Masahiro Sugiyama*, Robert J. Nicholls† and Athanasios Vafeidis‡

Abstract

To improve the estimate of economic costs of future sea-level rise associated with global climate change, this report generalizes the sea-level rise cost function originally proposed by Fankhauser, and applies it to a new database on coastal vulnerability developed as part of the Dynamic Interactive Vulnerability Assessment (DIVA) tool.

An analytic expression for the generalized sea-level rise cost function is obtained to explore the effect of various spatial distributions of capital and nonlinear sea-level rise scenarios. With its high spatial resolution, the DIVA database shows that capital is usually highly spatially concentrated along a nation's coastline, and that previous studies, which assumed linear marginal capital loss for lack of this information, probably overestimated the fraction of a nation's coastline to be protected and hence protection cost. In addition, the new function can treat a sea-level rise scenario that is nonlinear in time. As a nonlinear sea-level rise scenario causes more costs in the future than an equivalent linear sea-level rise scenario, using the new equation with a nonlinear scenario also reduces the estimated damage and protection fraction through discounting of the costs in later periods.

Numerical calculations are performed, applying the cost function to the DIVA database and socio-economic scenarios from the MIT Emissions Prediction and Policy Analysis (EPPA) model. The effect of capital concentration substantially decreases protection cost and capital loss compared with previous studies, but not wetland loss. The use of a nonlinear sea-level rise scenario further reduces the total cost because the cost is postponed into the future.

Contents

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1. INTRODUCTION

Since the seminal work of Schneider and Chen (1980), numerous researchers have tackled the problem of sea-level rise impacts, addressing a number of issues such as (1) increased risk of flooding (Nicholls *et al*. 1999; Nicholls 2004); (2) wetland loss (Nicholls 2004; Nicholls and Tol 2006); (3) damage to rice production (due to increased flooding, salinization, and/or poor drainage condition) (Hoozeman *et al*. 1993); (4) cost of protection and dryland loss (Fankhauser 1995a, hereafter F95a; Tol 2002a, 2002b; Nicholls and Tol 2006); and (5) the number of people who would be forced to emigrate (Tol 2002a, 2002b). Some looked at local and national impacts whereas others investigated global impacts.

Authoritative reviews of this body of work are provided by the Intergovernmental Panel on Climate Change (IPCC) (Warrick and Orelemans 1990; Tsyban *et al*. 1990; Warrick *et al*. 1996; Bijlsma *et al*. 1996; Church *et al*. 2001; McLean *et al*. 2001; Bindoff *et al.* 2007; Meehl *et al.* 2007; Nicholls *et al.* 2007a). In addition, there are useful works such as as Cazenave and Nerem (2004), who reviewed physical science underlying global sea-level rise, and Nicholls (2003), who summarized impact studies.

In spite of voluminous research, there remain many substantive issues. Even restricted to economic impact studies, the following five issues stand out. Two will be dealt with here:

1. *Use of a new database*. Among the past works, of particular note is the Global Vulnerability Assessment (GVA) by Hoozemans *et al.* (1993). GVA has produced vulnerability assessments for 192 coastal polygons that represent the entire global coastline, analyzing increased flooding, wetland loss, and rice production impact for each coastline polygon. It is an internally consistent global dataset, and most global analyses have relied on the dataset provided by GVA in one way or another (Nicholls *et al*. 1999; Tol 2002a, 2002b, among others). Since GVA is more than a decade old, it is desirable to revisit these studies with a new database such as the Dynamic Interactive Vulnerability Assessment (DIVA) database, which can be considered to be a successor of GVA.

2. *Improvement of the cost function of Fankhauser.* F95a formulated a minimization problem for the cost of sea-level rise, developed a simple cost function, and obtained the cost of sea-level rise for developed countries. Tol (2002a, 2002b) subsequently used this equation and calculated the global cost. However, this function is not without problems. For example, F95a found that more than 90% of the coastal segments in the UK should be protected whereas Turner *et al*.'s (1995) local-scale analysis concluded that even without acceleration of the rate of sea-level rise, 20% of the coastline in East Anglia is not worth protecting. Nicholls (2003) speculated that

the difference is due to the different scales of the two analyses, but there is a need for investigation of such a large discrepancy. Another issue concerns the assumption of deterministic sea-level rise that is linear in time. It is true that, as Nicholls (2003) points out, global-mean sea-level rise is "one of the more certain impacts of global warming." Nonetheless, a detailed review of the literature gives an unnerving picture that sea-level rise contains considerable uncertainty. One should incorporate uncertainty explicitly in the cost function. Moreover, the sea-level rise is not linear in time, but will accelerate in time, delaying the economic damage into the future.

In addition to the two above, other issues remain to be tackled:

3. *Direct cost method vs. general equilibrium*. The majority of papers to date used the direct cost method, in which the cost is defined as the quantity change (e.g., area lost due to sea-level rise) multiplied by a fixed price. In this approach, the price change due to quantity change is neglected because the price itself, not a demand/supply curve, is given. Furthermore, it does not consider how change in one market influences others, or how the impact of one country spills over to other countries through trade effect. The exceptions are Deke *et al*. (2001), Darwin and Tol (2001) and Bosello *et al*. (2007), who performed general equilibrium analyses. In particular, Darwin and Tol (2001) utilized the method of F95a, calculated optimal level of protection, and fed the optimal cost into a computable general equilibrium model by reducing the land endowment. They found that global welfare loss in the general equilibrium analysis was about 13% higher than the direct cost, although some regions incurred less sea-level rise cost by redistributing their costs through international trade. The general equilibrium estimate is still in the elementary stage, and more studies are desired.

4. *Dynamic capital effect.* In a theoretical paper, Fankhauser and Tol (2005) employed standard neoclassical growth models and explored the implication of capital loss due to climate impacts, finding that the forgone economic growth could be larger than the cost calculated neglecting the loss of capital. However, the literature on sea-level rise has largely neglected this effect.

5. *Rational vs. behavioral response (going beyond the neoclassical framework)*. It is well known that adaptation is a key determinant of the cost. For instance, F95a found a significantly lower cost than previous analyses because of his treatment of adaptation, and Yohe *et al*. (1996) and Yohe and Schlesinger (1998) reduced the estimate even further. These studies, however, assumed economically rational adaptation, whereas in some cases, adaptation clearly deviates from a rational one. For example, why did the New Orleans not take any action before Katrina, in spite of a plethora of warnings by scientists and engineers (regardless of climate change)? Another important issue is that coastal areas are under various kinds of pressure and stress, such as higher-than-national-average population growth, habitat destruction,

increased pollution and so forth (Nicholls 2003). Coastal planners will face many kinds of stresses at the same time, and they would have to solve the different problems simultaneously, sea-level rise being only one of them. Because of limited attention capacity, adaptation may not be rational in the neoclassical sense. Incorporating a behavioral aspect goes beyond the neoclassical framework, on which most of economic studies on climate change are based.

In addressing the first two points, this analysis uses a new database, the dataset from the DIVA tool, and improving the cost function of F95a. In so doing, the report provides some answers as to why F95a found such high protection levels. In addition, as a preliminary analysis, we produce some novel cost estimates, but these are based on crude calculations and care must be taken in interpreting the results.

The ultimate goal of the sea-level rise project at MIT is to include the effect in the MIT Integrated Global System Model (IGSM) framework so that we can represent the accelerated capital depreciation effect which Fankhauser and Tol (2005) pointed out is important, and the interaction between the climate system and socio-economic system. This report is a key step in that larger effort.

The rest of the report is organized as follows. Section 2 describes the general methodology used here, especially the datasets we repeatedly use—DIVA, a sea-level rise impact database, G-Econ, a geographic economic database, and EPPA model, a computable general equilibrium economic model, and the IGSM. Section 3 is the centerpiece of this paper, deriving and extending the sea-level rise cost function that was originally developed by F95a. Section 4 then applies the cost function to the models and datasets. This is followed by the results in Section 5. Section 6 concludes and explores future research directions.

2. METHODOLOGY

2.1 Overview

This report utilizes various tools: one economic model (EPPA), a set of climate model (IGSM) outputs, and two databases (DIVA and G-Econ). First, EPPA calculates economic activity and associated greenhouse and other gas emissions. IGSM simulates the behavior of the climate system and estimates the sea-level rise. The cost function calculates three kinds of costs, using sea-level rise and inputs from the DIVA and G-Econ databases.

Figure 1 outlines the overall methodology. The economic model EPPA calculates emissions of greenhouse gases such as CO_2, which the climate component of the IGSM converts into sea-level rise. The sea-level rise cost function then calculates three components of cost: (1) protection cost, (2) capital loss, and (3) wetland loss. In the future, the cost will be fed back into EPPA, but this is outside the scope of this paper.

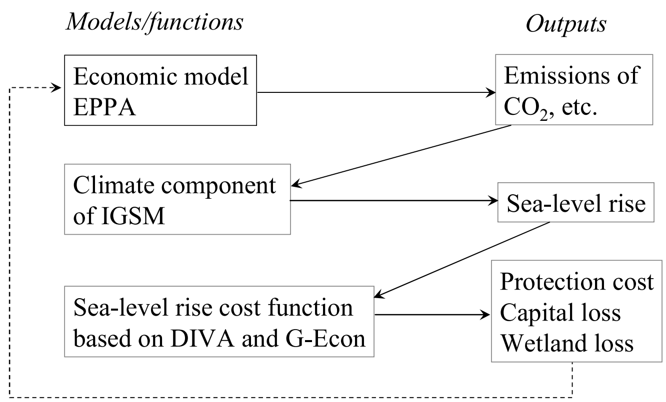

Figure 1. Schematic outlining how different models and databases are utilized. The dotted line represents the feature to be included in the future, not implemented in the current study.

2.2 Dynamic Interactive Vulnerability Assessment (DIVA)

The Dynamic Interactive Vulnerability Assessment (DIVA) tool (Hinkel 2005; Hinkel and Klein 2007; Nicholls *et al*. 2007b; Vafeidis *et al*. 2008) is a geographic information system (GIS)-based tool to assess impacts and vulnerability to sea-level rise at scales from coastal segment up to global. It comprises a database, a series of algorithms, and a graphical user interface. In this work, only the database is utilized.

The DIVA database is unique in that it is not a raster dataset (gridded or pixel-based dataset), a preferred format for various datasets, but rather its fundamental element is a coastal segment (a polygon) (Vafeidis *et al*. 2004, 2008). In the DIVA database, the world's coast is divided into 12,148 segments with an average coastal segment length of 70km. For each of the segments, DIVA provides a multitude of parameters, including population density, frequency and height of storm surges, and coastal wetland areas. These are used as inputs for the extended sea-level rise cost function as described in Section 3. DIVA also contains various data at other scales, including countries, major rivers, tidal basins, and administrative units (states, prefectures, etc.). **Table 1** summarizes DIVA's characteristics.

DIVA can be considered to be the successor of the Global Vulnerability Assessment (GVA), which was compiled by Hoozemans *et al.* (1993). GVA has only 192 coastal segments while DIVA has 12,148 segments. With two orders of magnitude more segments, DIVA provides a basis for significant improvement of impact studies.

2.3 Geographically based Economic data (G-Econ)

The Geographically based Economic data (G-Econ) (Nordhaus 2006; Nordhaus *et al*. 2006) is a geographic database of economic output for 1-by-1-degree grid cell, which the authors call *gross cell product* (GCP). The novelty of this database is that it provides economic information for each geographic cell, rather than for each country as covered by conventional economic statistics. It thus expands the number of economic observations from about 200, the number of countries, to 27,079, the number of cells in G-Econ.

Table 1. DIVA database characteristics (Vafeidis *et al.* 2008).

Geographical features used for data referencing (GIS layers)	Coastal segment, administrative unit (such as 50 states in the United States), country, river, tidal basin
Number of coastal segments	12,148
Number of parameters for each coastal segment	> 30
Sample parameters	LENGTH (length of coastal segment) UPLIFT (geological uplift/subsidence) SLOPECST (slope of the coast) TOTALWETAR (total wetland area, excluding mangrove) MANGS_KM2 (mangrove area) POPDENS (population density)
Number of countries	207
Number of parameters for each country	> 20
Sample parameters	SDIKECOST (cost of sea dike) GDPC (gross domestic product (GDP) per capita in 1995 in market exchange rate)

To arrive at gross cell product, the authors exploit a detailed geographic database on population. They calculate gross cell product as

(GCP by grid cell) = (population by grid cell) × (per capita GCP by grid cell).

They estimate per capita GCP by combining national (e.g., GDP), state (e.g., gross state product), and province/county data (e.g., regional income by industry).

Figure 2 shows a logarithmic plot of GCP for the globe. Developed economies and emerging economic countries show up in the figure. Because the scale is logarithmic, we see that the distribution is quite skewed. This is also apparent in Figure 1 of Nordhaus (2006).

2.4 MIT Emissions Prediction and Policy Analysis (EPPA) model

The MIT Emissions Prediction and Policy Analysis (EPPA) model Version 4 (Paltsev *et al.* 2005) is a computable general equilibrium model of the world economy, which calculates economic activity and associated emissions of greenhouse gas and urban gas emissions. It is recursive-dynamic and has 16 regions, and is built on the Global Trade Analysis Project (GTAP) (Hertel 1997; Dimaranan and McDougall 2002) and other datasets. It has a detailed breakdown of the energy sector.

2.5 MIT Integrated Global System Model simulations

The MIT Integrated Global System Model Version (IGSM) (Prinn *et al.*1999; Sokolov *et al.* 2005) is a model of the climate-economy system. Its components include atmosphere and ocean circulations, atmospheric and oceanic chemistry, ecosystem, and the economic model, EPPA. It is designed for efficient calculations with simplified configurations. In particular, by changing key parameters, it can reproduce the transient responses of various atmosphere-ocean general

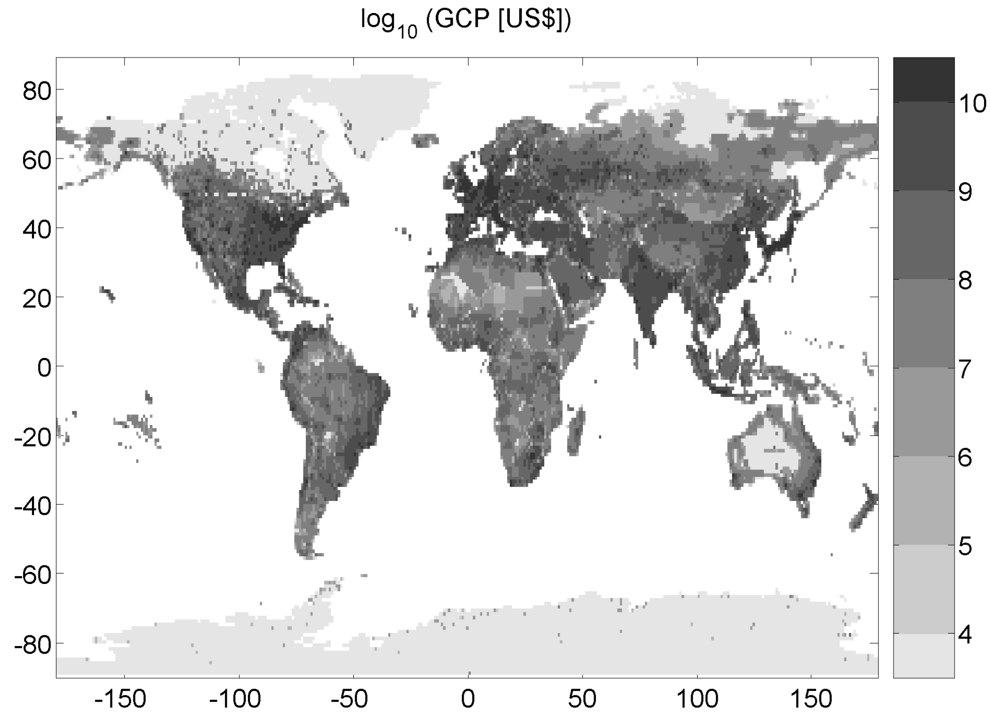

Figure 2. A graphic representation of gross cell product. Non-terrestrial cells are indicated by white. Note that some cells contain zero values, whose logarithm is undefined. They are thus also represented by white.

circulation models. Such flexibility and relative efficiency allow for numerous runs of the model and uncertainty analysis of climate change.

The MIT Joint Program on the Science and Policy of Global Change has performed 1000 runs of the IGSM version 1 (Prinn *et al.* 1999) by perturbing key socio-economic parameters and climate parameters (Webster *et al*. 2003). The stored outputs include the time series of sea-level rise (thermal expansion and glacier melting are stored separately) for every year for each run along with greenhouse gas emissions from EPPA. Note that five-year averages of the simulation outputs are used throughout the report. Although IGSM version 2 (Sokolov *et al.* 2005) is currently available, the following results are based on the IGSM version 1.

Note that the uncertainty simulations by Webster *et al.* (2003) utilized EPPA version 3.0 (Babiker *et al.* 2001) rather than version 4.0 (Paltsev *et al*. 2005). In other words, the sea-level rise scenarios depend on version 3.0 while damage calculations rely on version 4.0. On the first look, such an inconsistency appears serious. It is not, however, since in the present report there is no feedback from the sea-level rise damage on economic growth. One can interpret that the sea-level rise scenarios are simply imposed by a slightly different external model.

3. SEA-LEVEL RISE COST FUNCTION

This section derives and extends the cost function originally developed by F95a. The essential purpose of this function is to capture the trade-off between protection and retreat. While protecting a coastline avoids the loss of capital and land, it requires building a sea dike, and hence protection cost. It could also decrease the wetland area since with human intervention wetlands would be squeezed between a sea dike and the rising sea (e.g., McFadden *et al*. 2007). On the other hand, abandoning a coastline saves the cost of protection and allows wetland to migrate inland, but leads to capital loss. F95a formulated this trade-off in a fairly tractable manner, and this section builds on his work.

As pointed in Section 1, two important issues with F95a's approach have not been addressed: the discrepancy of optimal protection fraction between local-level and national-level studies, and the inclusion of nonlinear sea-level rise scenarios. In what follows, the F95a's method is extended such that it can resolve both issues.

3.1 Cost minimization problem

For a given scenario of sea-level rise $S = S(t)$, the F95a's cost minimization problem for each coastal segment is

$$\min_{L,h} Z = p^{(pv)}(L,h) + d^{(pv)}(L,S) + w^{(pv)} - g^{(pv)}(L,S)$$

$$s.t. \int_0^t h(t')\,dt' \geq S(t), \; h(t) \geq 0, \; 0 \leq L \leq 1. \tag{1}$$

With an assumption of perfect information about the future sea-level rise, the total cost to be minimized is the present value (as denoted by $^{(pv)}$) of a sum of protection cost *p*, dryland/capital loss *d*, and wetland loss *w*, less wetland *gain g*. **Figure 3** graphically illustrates the cost trade-off. The control variables are the protection fraction of a coastal segment *L* and additional sea dike height *h*=*h*(*t*). The sea dike height must be always above the level of sea, and be increasing. The protection fraction, by definition, takes a value between 0 and 1. Since the total cost is a sum of 4 components, it captures the trade-off of protection and retreat.

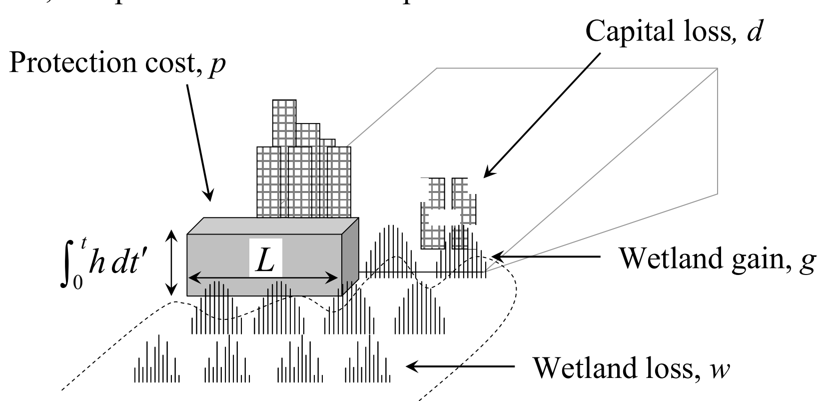

Figure 3. Schematic illustrating the cost minimization problem. The choice variables are the fraction of the coastal segment to be protected *L*, and incremental sea dike *h*. Since *h* is an additional dike height, the height of sea dike is its integral. There are four cost items: protection cost *p*, capital (dryland) loss *d*, wetland gain *g*, and wetland loss *w*. A sea dike protects capital but prevents wetland from migrating inland. A decision not to build protection allows wetland to migrate, but leads to capital loss. Regardless of the decision to protect or not, some wetland on the seaside is lost by submergence.

Some of the terms depend implicitly on the sea-level rise, $S = S(t)$. For convenience, **Table 2** gives definitions of all the symbols used throughout this section. Note that the symbols are different from those of F95a and Tol (2002a, 2002b). Because the total cost depends on the path of $h(t)$, (1) is a dynamic optimization problem. The problem is framed in terms of continuous time but it is straightforward to rewrite it in terms of discrete time periods.

Table 2. Main cost parameters in the sea-level rise cost function.

Symbol	Description
Z	Total cost
p	Protection cost (see (11) and (15))
d	Dryland loss or capital loss (see (11) and (15))
g	Wetland *gain* due to decision not to build coastal protection (see (11) and (15))
w	Wetland loss that takes place regardless of coastal protection (see (11) and (15))
π	Unit protection cost
δ	Unit capital loss (dryland value)
γ	Unit wetland loss/gain (wetland value)
$p_1(h)$	$\equiv p(h, L=1)$
$d_0(h)$	$\equiv d(h, L=0)$
$g_0(h)$	$\equiv p(h, L=0)$
P	Normalized protection cost, $P(L) = p^{(pv)}(L) / p^{(pv)}(L=1)$
D	Normalized capital loss, $D(L) = d^{(pv)}(L) / d^{(pv)}(L=0)$
G	Normalized wetland gain, $G(L) = g^{(pv)}(L) / g^{(pv)}(L=0)$
L	*Fraction* of a coastline that is to be protected
h	Additional height of sea dike (or protection in general)
S	Relative sea-level rise at the coastline
F	Sea dike height resulting from the change in design frequency
Λ	Length of a coastal segment
Ω	Length of the portion of a coastal segment with wetland
α	Wetland migration speed
ψ	Slope of the coastline
r	Discount rate
ε	Economic growth rate
t	Time
τ	The end time
$(\ )^{(pv)}$	Present value operator, $(\ )^{(pv)} \equiv \int_0^\tau (\ ) e^{-rt} dt$ or $(\ )^{(pv)} \equiv \sum_{t=0}^{\tau} (\ ) \left(\frac{1}{1+r}\right)^t$
*	Superscript denoting optimality

Equation (1) assumes that protection is only in the form of sea dikes, although there are other protection forms such as beach nourishment. Including other protection measures in the function is left to future research. Also, the constraint in (1) implies that initial dike height is zero. It is possible to include non-zero initial dike height by changing the constraint to

$$\int_0^t h(t')\,dt' + H_0 \geq S(t).$$

This report restricts itself to the case of $H_0 = 0$ for simplicity.

3.2 Separability assumption and determination of dike height

The biggest and most important assumption is separability between incremental dike height *h* and protection fraction *L*. The model assumes that *L* is determined once initially and does not change with time. This allows us to solve the model for the two decision variables, *h* and *L*, in a straightforward way.

Now let us solve for incremental dike height *h*. As F95a pointed out, if there is no economy of scale in dike construction, which we assume below, the constraint in (1) always binds. Note that no economy of scale for *h* is a reasonable assumption for projected increases in sea level. The optimal solution is therefore

$$h^*(t) = \frac{dS}{dt}(t), \tag{2}$$

where the asterisk denotes an optimal solution.

This solution actually assumes that a design frequency, which refers to the frequency of storm surges against which a coastline is protected, remains constant. However, this may not be a realistic assumption since developing countries would become wealthier and desire a safer level of coastal protection. They might tolerate 100-year storms as of today, although they might prefer to avoid flooding from storms that occur every 1000 years in the late 21st century, raising the dike height faster than sea-level rise. Indeed, Nicholls *et al*. (1999), Nicholls (2004), and Nicholls and Tol (2006) incorporated this effect in their models of inundation of population.

In the present model, it is actually easy to include the changing design frequency. The only change to make is to replace the constraint in (1) with

$$\int_0^t h(t')\,dt' \geq S(t) + F(t),$$

where $F(t)$ represents the additional sea dike height resulting from the changing design frequency. The optimal solution is then

$$h^*(t) = \frac{dS}{dt}(t) + \frac{dF}{dt}(t).$$

Nonetheless, there is an issue of how to decompose the total cost into the change in preference and the damage of sea-level rise. For simplicity, we neglect this effect in the calculations below.

It is straightforward to incorporate the effect of economies of scale of protection construction or the nonlinear cost of sea dikes (doubling the height of protection costs more than double) for *h*. Such a case can be expressed as a dynamic optimization problem.[1]

3.3 Determination of coastline fraction to protect

The next question is how to determine the optimal protection fraction *L*. Because determining *h* is a separate problem and $w^{(pv)}$ is independent of *L*, we can drop these two from the optimization problem (1). It then becomes

$$\min_L \tilde{Z} = p^{(pv)}(L) + d^{(pv)}(L) - g^{(pv)}(L). \tag{3}$$

It is useful to rewrite this problem in terms of normalized costs as

$$\min_L \tilde{Z} = p_1^{(pv)} \cdot P(L) + d_0^{(pv)} \cdot D(L) - g_0^{(pv)} \cdot G(L) \tag{4}$$

where $p_1(h) = p(h, L = 1)$ and $P(L) = p^{(pv)}(L) / p^{(pv)}(L = 1)$, and so forth. Here $P(L)$, $D(L)$, and $G(L)$ are normalized cost functions since $P(L) = p^{(pv)}(L) / p^{(pv)}(L = 1)$, etc. Their derivatives $\partial P/\partial L$, $\partial D/\partial L$, and $\partial G/\partial L$, represent marginal costs and gain. They thus represent normalized cumulative cost distribution functions. It follows that

$$0 \le P(L), D(L), G(L) \le 1,$$

$$P(0) = 0,\ P(1) = 1,\ D(0) = 1,\ D(1) = 0,\ G(0) = 1,\ G(1) = 0,$$

$$\partial P / \partial L \ge 0,\ \partial D / \partial L \le 0, \text{ and } \partial G / \partial L \le 0. \tag{5}$$

So far we have not specified the functional forms of $P(L)$, $D(L)$, and $G(L)$. Since $P(L)$ is determined by engineering considerations, it would be reasonable to approximate $P(L)$ with a linear function if the variation within a coastal segment is negligible. It may be difficult to get a handle on $G(L)$ because of variations of ecological factors, and we adopt a simple assumption of a linear function. Our choice is thus $P(L) = L$ and $G(L) = 1–L$. The form of *D* is discussed below.

It is useful to notice that *P*, *G*, and *D* can be defined at multiple scales. For instance, it is possible to define *D* for a country like the entire United States, or for a region like Greater Boston. What F95a had in mind was *D* at the national level. Later in the report, we address the difference between the *D* at the country scale and that at the scale of each coastal segment in the DIVA database.

For the interior solution, the first-order condition for optimization of (4) is

$$\partial\tilde{Z} / \partial L(L = L^*) = 0 = p_1^{(pv)} + d_0^{(pv)} D'(L^*) + g_0^{(pv)}.$$

By defining

$$C \equiv \frac{p_1^{(pv)} + g_0^{(pv)}}{d_0^{(pv)}} \tag{6}$$

[1] See Sugiyama (2007) for details.

Table 3. Solutions for some forms of *D*. *C* is given by (6).

$D(L) = 1 - L$	$L^* = \begin{cases} 0 & C > 1 \\ 1 & C < 1 \end{cases}$
$D(L) = (1-L)^\beta \qquad (\beta > 1)$	$L^* = \max\left[1 - \left(\frac{C}{\beta}\right)^{\frac{1}{\beta-1}},\ 0\right]$
$D(L) = \frac{e^{-\lambda L} - e^{-\lambda}}{1 - e^{-\lambda}} \qquad (\lambda > 0)$	$L^* = \max\{0, \min(1, \tilde{L})\}$ where $\tilde{L} = \frac{1}{\lambda} \ln\left[\frac{\lambda}{1 - e^{-\lambda}}\left(\frac{1}{C}\right)\right]$

we can concisely write the optimal solution as

$$L^* = (D')^{-1}(-C), \tag{7}$$

where the asterisk indicates optimality. The case of corner solutions depends on the choice of *D* and should be treated appropriately. L^* in (7) represents the protection fraction that equates marginal benefit from wetland gain with marginal costs from protection and dryland loss. Equation (7) shows that we can obtain the closed form of the optimal value of *L* as long as the derivative of *D* is invertible. **Table 3** lists solutions for some analytic forms of *D*. F95a chose $D(L) = (1-L)^\beta$ with $\beta = 2$ since he assumed that the marginal dryland loss is linear: $\partial D/\partial L = -2(1-L)$ for $\beta = 2$.

Interestingly, the optimal level of protection is determined only by the functional form of *D* and the ratio *C*, which is a ratio of capital loss in the case of no protection to a sum of full protection cost and maximum possible wetland gain. For the same level of wetland gain, (7) implies that a higher protection cost leads to less protection, and the larger potential capital loss means more protection, an intuitive result.

How sensitive are the total cost and optimal protection fraction to the choice of the capital loss distribution function $D(L)$? Especially, how do these variables change with the degree of capital concentration? A simple choice of $D(L) = (1 - L)^\beta$ helps to illustrate the sensitivity. Since *D* represents the normalized cumulative capital loss, the higher β, the more concentrated is capital. **Figure 4** depicts $D(L) = (1 - L)^\beta$ for $\beta = 2$, 5, and 15. If β is higher and capital is more concentrated, a lower protection fraction *L* is required to avoid the same level of capital loss.

Interestingly Figure 4 hints at an alternative interpretation of *D*: a Lorenz curve for spatial distribution of capital along the coastline, with the horizontal axis reversed. The Lorenz curve is often utilized to describe income inequality, but Nicholls and Small (2002) created Lorenz curves for coastal population and Asadoorian (2005) constructed such curves for geographic distribution of population. These works inspired this alternative interpretation of *D*.

To gain insight into the sensitivity to the degree of capital distribution, it is helpful to rearrange the cost equation in (4):

$$\tilde{Z} = \left(p_1^{(pv)} + g_0^{(pv)}\right)L^* + d_0^{(pv)}(1 - L^*)^\beta - g_0^{(pv)}.$$

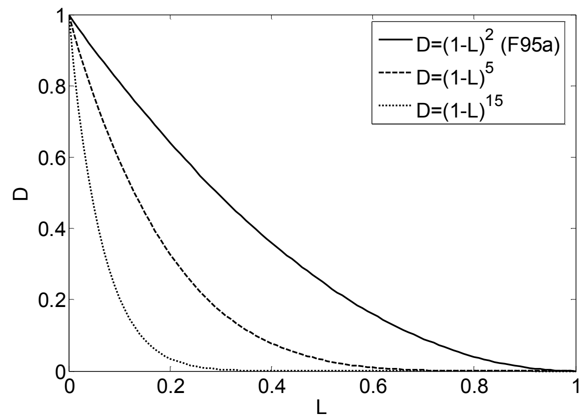

Figure 4. $D = (1 - L)^{\beta}$ for β = 2, 5, and 15. Note that F95a chose β = 2.

Moving $g_0^{(pv)}$ to the left-hand side and dividing through $d_0^{(pv)}$, we arrive at

$$\frac{\tilde{Z} + g_0^{(pv)}}{d_0^{(pv)}} = \frac{p_0^{(pv)} + g_0^{(pv)}}{d_0^{(pv)}} L^* + (1 - L^*)^{\beta}.$$

With the definition of C in (6), this becomes

$$\zeta(\beta) \equiv \frac{\tilde{Z} + g_0^{(pv)}}{d_0^{(pv)}} = CL^* + (1 - L^*)^{\beta}. \tag{8}$$

ζ is the total cost plus the wetland gain normalized by the present value of capital loss, and can be considered as a measure of the total cost.

Figure 5 describes two variables, the optimal protection fraction $L^*(\beta)$ and a measure of normalized total cost $\zeta(\beta)$ for three different values of C: C = 0.01, 0.1, and 1. $L^*(\beta)$ is given in Table 3 and $\zeta(\beta)$ in (8). The top three panels indicate that for all cases considered here, the optimal protection fraction decreases with β. The more concentrated the capital is, the smaller the optimal protection fraction. Similarly, the bottom 3 panels display that the measure of the total cost ζ declines with β. For example, the bottom left panel shows that changing β from 2 to 10 reduces ζ by about half.

In general, whether the optimal protection fraction L^* and the total cost (as measured by ζ) decrease or not with β depends on C, because for interior solutions,

$$\frac{\partial L^*}{\partial \beta} = \left\{ \frac{1}{\beta - 1} \ln\left(\frac{C}{\beta}\right) + \frac{1}{\beta} \right\} \frac{1}{\beta - 1} \left(\frac{C}{\beta}\right)^{1/(\beta-1)},$$

$$\frac{\partial \zeta}{\partial \beta} = \frac{1}{\beta - 1} \ln\left(\frac{C}{\beta}\right) \cdot \left(\frac{C}{\beta}\right)^{\beta/(\beta-1)}. \tag{9}$$

Here the envelope theorem facilitates the calculation of $\partial\zeta/\partial\beta$. From the results in Table 3, the interior solution implies $C/\beta < 1$, and hence $\partial\zeta/\partial\beta < 0$ as $\ln(C/\beta) < 0$ in (9). The sign of $\partial L^*/\partial\beta$ cannot be determined algebraically.

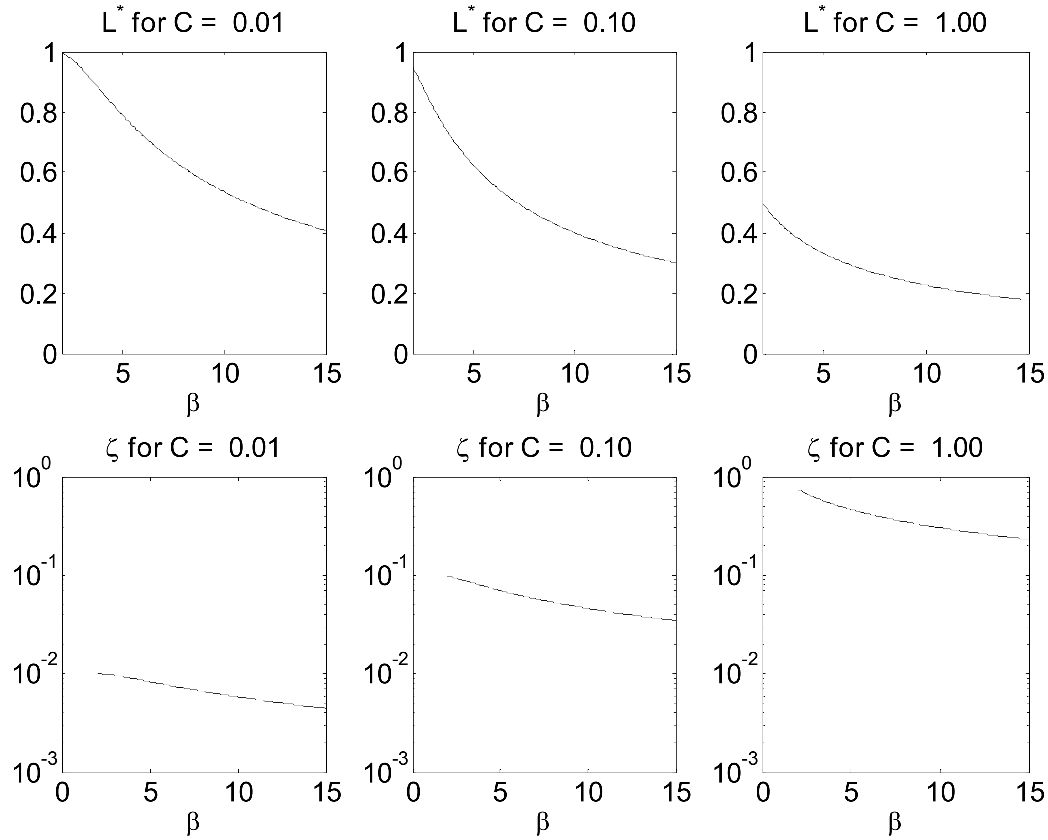

Figure 5. (Top 3 panels) Optimal protection fraction L^* as a function of β for (left) C = 0.01, (middle) C = 0.1, and (right) C = 1. (Bottom 3 panels) A measure of the total cost ζ as a function of β for (left) C = 0.01, (middle) C = 0.1, and (right) C = 1. In lower panels, the vertical axis is in logarithm.

Figure 6 describes $\partial L^*/\partial\beta$ and $\partial\zeta/\partial\beta$ as given in (9). The right panel shows $\partial\zeta/\partial\beta$, which is always negative as shown above. On the other hand, $\partial L^*/\partial\beta$, which is shown in the left panel, can be positive. An intuitive result holds for ζ but not L^*; more concentrated capital leads to a smaller total cost (as measured by ζ), but not necessarily a smaller protection fraction L^*.

What is a realistic functional form of $D(L)$? As discussed above, Nicholls and Small (2002) calculated how population is distributed along the coastline for the entire globe. Such an estimate is illuminating but ideally we would like to know the capital distribution *within a country* since F95a used GVA-type data, where each country is represented by about one polygon. Here the new database, DIVA, is useful. DIVA has two orders of magnitude more coastal segments than its predecessor GVA, and it can give us some insight into the nature of the distribution.

To estimate the distribution function D, population is chosen as a surrogate for the dryland value. Let Λ_j be the length of the j-th coastal segment and q_j be the population density per length. Λ_j is indexed such that q_j decreases monotonically (more precisely, $q_{j+1} \le q_j$). The discrete form of the function D can be defined as

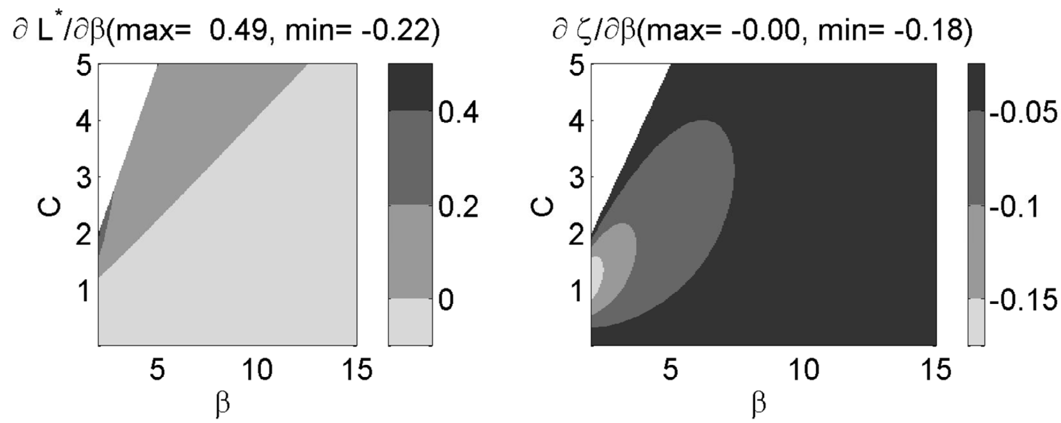

Figure 6. (left) $\partial L^*/\partial\beta$ and (right) $\partial\zeta/\partial\beta$ as a function of β and C, as given in (9). The maximum and minimum values are also shown in the parentheses. Corner solutions are indicated by white.

$$D(L_i) = 1 - \frac{\sum_{j=1}^{i} q_j \Lambda_j}{\sum_{j=1}^{N} q_j \Lambda_j} \quad \text{where } L_i = \frac{\sum_{j=1}^{i} \Lambda_j}{\sum_{j=1}^{N} \Lambda_j}. \tag{10}$$

Figure 7 conceptualizes how to formulate this function.

Figure 8 presents D functions calculated from DIVA for 3 countries, using (10). Along with D, the figure shows $(1–L)^2$, the choice of F95a, and nonlinear fits of the equations in Table 3. The nonlinear fit was performed by using the nlinfit function of the software package MATLAB®. The distribution of population in the DIVA data is highly concentrated, and the exponent for $(1–L)^\beta$ should be much higher than $\beta = 2$, the value F95a used. In the bottom right panel, Figure 8 also presents different methods to create the D function: population and economic output from DIVA. The two methods produce similar results, confirming that a high concentration of population characterizes the basic feature.

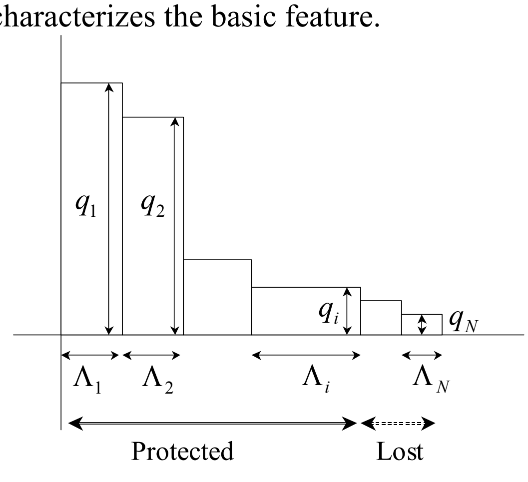

Figure 7. Schematic explaining how to calculate (10). Λ_j is the length of the j-th coastal segment, and q_j is the population density per length.

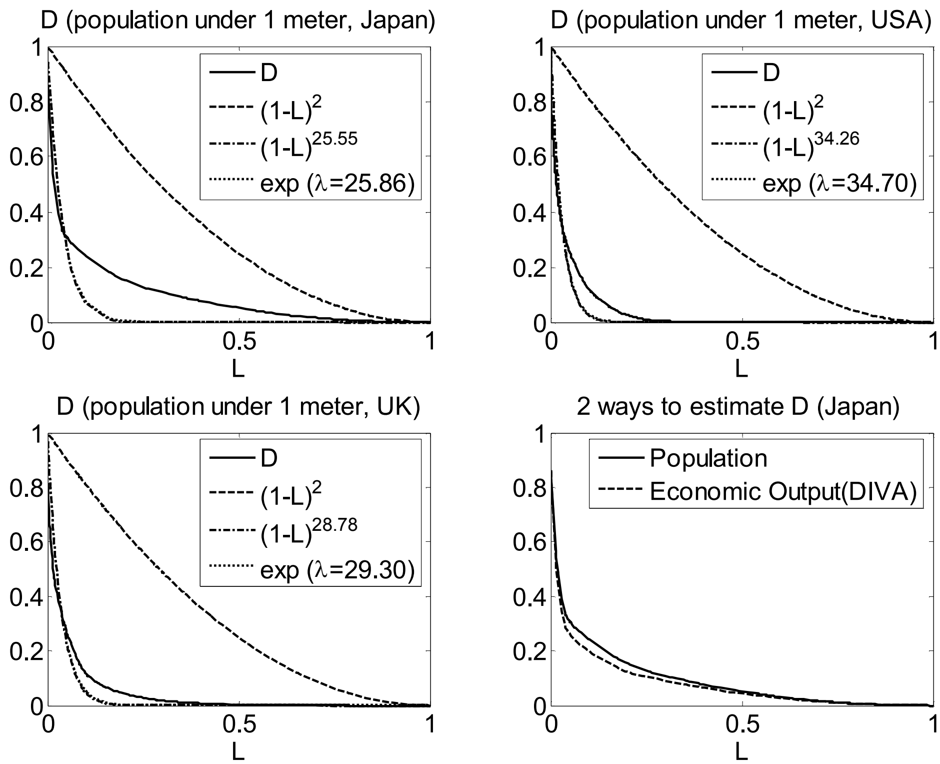

Figure 8. (Top left, top right, and bottom left panels) *D* from DIVA as estimated from (10), using the population under the 1-meter altitude divided by the coastline length as q_j. (Bottom right panel) *D*'s estimated using two different measures: population under the 1-meter altitude and economic output under the 1-meter altitude as provided by DIVA.

As noted in the beginning of Section 1, F95a and Turner *et al*. (1995) found quite different optimal protection fractions. Presumably one reason is that F95a's choice of exponent was too small.

It is important to recognize that Figure 8 presents *D*'s at the *country scale*. As Turner *et al*. (1995) found, capital is concentrated at the *local scale* as well. It is thus possible to create a *D* function at the *local* level. We discuss this in more detail when applying the cost function to DIVA.

3.4 Calculation of the present value of each cost item

The following derives analytic expressions for the present values of each cost item. A constant slope assumption simplifies the procedure greatly, and the following calculation makes use of it. The cost is obtained by simply multiplying a unit value (per area or per length per height) by an area or length times height. From the definitions in Table 2, it follows that

$$p_1^{(pv)} = \left[\pi \cdot \frac{dS}{dt}(t) \cdot \Lambda \right]^{(pv)},$$

$$d_0^{(pv)} = \left[\delta(t) \cdot \frac{S(t)}{\tan\psi} \cdot \Lambda \right]^{(pv)} ,$$

$$g_0^{(pv)} = \left(\gamma \cdot \alpha \, t \cdot \Omega\right)^{(pv)},$$

$$w^{(pv)} = \left[\gamma \cdot \frac{S(t)}{\tan\psi} \cdot \Omega \right]^{(pv)}, \tag{11}$$

where $p_1(t) = \pi \cdot dS/dt(t) \cdot \Lambda$ and so forth. F95a took the unit protection cost π as a function of the sea-level rise at the final time $S(\tau)$, but this paper neglects it for simplicity.

It is possible to further simplify the equations by Taylor-expansion of sea-level rise. Writing

$$S(t) = \sum_{n=0}^{\infty} \frac{\sigma^{(n)}}{n!} t^n \tag{12}$$

allows us to write

$$p_1^{(pv)} = \pi \cdot \Lambda \cdot \sum_{n=1}^{\infty} \frac{\sigma^{(n)}}{(n-1)!} \left(t^{n-1}\right)^{(pv)},$$

$$d_0^{(pv)} = \frac{\Lambda}{\tan\psi} \cdot \sum_{n=0}^{\infty} \frac{\sigma^{(n)}}{n!} \left[\delta(t) \cdot t^n\right]^{(pv)} ,$$

$$w^{(pv)} = \frac{\gamma\Omega}{\tan\psi} \sum_{n=0}^{\infty} \frac{\sigma^{(n)}}{n!} \left(t^n\right)^{(pv)}. \tag{13}$$

Although F95a restricted himself to a linear sea-level rise, (13) demonstrates that it is possible to obtain analytic expressions of present values for any well-behaved sea-level rise scenarios $S(t)$. **Table 4** presents the detailed results for linear and quadratic cases. For illustrative purposes, the present value operator here is taken to be

$$(\;)^{(pv)} = \sum_{t=0}^{\infty} (\;) \cdot \left(\frac{1}{1+r}\right)^t \text{ and } \delta(t) = \delta_0 (1+\varepsilon)^t .$$

3.5 Linear versus quadratic sea-level rise scenarios

Much of the past literature on impact assessment has been concerned with a linear sea-level rise. In actuality, we would expect that the rate of sea-level rise would accelerate in the future, and that a quadratic function or an exponential function might be a better choice. Recent papers have used realistic sea-level rise scenarios such as those based on SRES. However, some of the recent literature still continues to rely on a linear sea-level rise, at least partially. For example, Nicholls and Tol (2006), while using SRES-based sea-level rise scenarios, assumed a linear sea-level rise for the purpose of calculating the optimal protection fraction. This is because they used the model of Tol (2004), which in turn depends on the model of F95a, who assumed a linear sea-level rise scenario. It is thus important to analyze the effect of using a linear sea-level rise.

Figure 9 illustrates equivalent linear and quadratic sea-level rises. Such difference between them could actually change the cost estimate since, as is clear in Figure 9, a quadratic sea-level rise will postpone the bulk of cost, which would be substantially discounted in the present value. The key point here is that even though the sea levels in 2100 are the same for both scenarios, the costs could be substantially different between them.

Table 4. Analytic expressions of the cost components. The linear case corresponds to the equations of F95a. Tol (2002b) uses formulations almost identical to what is shown here. Subscripts in the sea-level rise function *l* and *q* denote linear and quadratic forms, respectively.

Linear $S=\sigma_l^{(1)}\cdot t$	$p_1^{(pv)}=\pi\sigma_l^{(1)}\Lambda\frac{1+r}{r}$,	$d_0^{(pv)}=\frac{\delta_0}{\tan\psi}\sigma_l^{(1)}\Lambda\frac{(1+\varepsilon)(1+r)}{(r-\varepsilon)^2}$
	$g_0^{(pv)}=\gamma\alpha\Omega\frac{1+r}{r^2}$,	$w^{(pv)}=\gamma\frac{1}{\tan\psi}\sigma_l^{(1)}\Omega\frac{1+r}{r^2}$
Quadratic $S=\sigma_q^{(1)}t+\frac{\sigma_q^{(2)}t^2}{2}$	$p_1^{(pv)}=\pi\Lambda\left(\sigma_q^{(1)}\frac{1+r}{r}+\sigma_q^{(2)}\frac{1+r}{r^2}\right)$,	
	$d_0^{(pv)}=\frac{\delta_0\Lambda}{\tan\psi}\left\{\sigma_q^{(1)}\frac{(1+\varepsilon)(1+r)}{(r-\varepsilon)^2}+\frac{1}{2}\sigma_q^{(2)}\left(\frac{(1+\varepsilon)(1+r)}{(r-\varepsilon)^2}+\frac{2(1+\varepsilon)^2(1+r)}{(r-\varepsilon)^3}\right)\right\}$	
	$g_0^{(pv)}=\gamma\alpha\Omega\frac{1+r}{r^2}$	
	$w^{(pv)}=\frac{\gamma\Omega}{\tan\psi}\left\{\sigma_q^{(1)}\frac{1+r}{r^2}+\frac{1}{2}\sigma_q^{(2)}\left(\frac{1+r}{r^2}+\frac{2(1+r)}{r^3}\right)\right\}$	

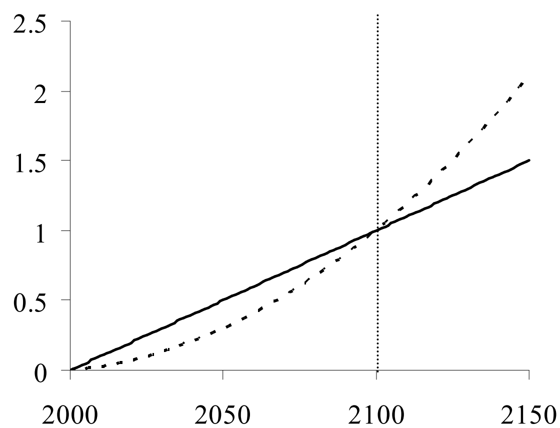

Figure 9. Illustration of equivalent linear and quadratic sea-level rises. The horizontal axis is the year whereas the vertical axis denotes the change of sea level in meters. The solid line represents a linear sea-level rise of 1 meter per century while the dotted line implies an equivalent quadratic sea-level rise. Both start from the same sea level in 2000 and reach 1 meter in 2100, but the quadratic one starts slowly and accelerates, exceeding the linear sea-level rise after 2100.

To address how different the cost would be between equivalent linear and quadratic sea-level rises, we compare the total costs for linear (Z_l) and quadratic (Z_q) sea-level rises. Recall that Z is defined as

$$Z = L^* p_1^{(pv)} + (1-L^*)^\beta d_0^{(pv)} - (1-L^*) g_0^{(pv)} + w^{(pv)} \ .$$

The next equation defines equivalent linear and quadratic sea-level rises, assuming that the total sea-level rise is equal in 100 years from now:

$$S(t=100) = \sigma_l^{(1)} \cdot 100 = \sigma_q^{(1)} \cdot 100 + \frac{1}{2}\sigma_q^{(2)} \cdot 100^2 \ . \tag{14}$$

This neglects subsidence and uplift for simplicity.

The following calculation uses the parameters below:

$\delta_0 = \$3\text{million/km}^2$, $\pi = \$1\text{million/km/m}$, $\gamma = \$5\text{million/km}^2$, $\Omega/\Lambda = 0.2$,
$\psi = 1^\circ$, $\alpha = 50\text{cm/year}$, $\rho = 1\%$, $\varepsilon = 2\%$, $r = \varepsilon + \rho$, $\beta = 2$.

The values of δ_0, π, Ω/Λ, and ψ approximately correspond to averages for the United States, taken from DIVA. The values of γ and α are provided by F95a. The time rate of preference and the economic growth rate were arbitrarily set to the given numbers.

Using DIVA, we have already demonstrated that β should be much larger than 2. But we here choose $\beta = 2$ for the following reason. Because of the wetland gain term g, it is possible that the total cost Z can be zero or negative. This, however, leads to trouble since we are attempting to calculate the ratio Z_q/Z_l and must avoid division by zero. The choice of $\beta = 2$ does not cause this problem, and thus we use it for illustrative purposes. We discuss the issue of negative cost in detail when implementing F95a's approach in EPPA in the next section.

To gain more insight, one can obtain an approximate equation for the ratio of total costs Z_q/Z_l. As F95a and other analyses have shown, the cost of wetland loss tends to dominate the total cost of sea-level rise. We would therefore expect

$$\frac{Z_q}{Z_l} \approx \frac{w_q}{w_l} = \frac{\frac{\gamma\Omega}{\tan\psi}\left\{\sigma_q^{(1)}(t)^{(pv)} + \frac{1}{2}\sigma_q^{(2)}(t^2)^{(pv)}\right\}}{\frac{\gamma\Omega}{\tan\psi}\sigma_l^{(1)}(t)^{(pv)}} = \frac{\sigma_q^{(1)}}{\sigma_l^{(1)}} + \frac{1}{100}\left(1 - \frac{\sigma_q^{(1)}}{\sigma_l^{(1)}}\right)\left(1 + \frac{2}{r}\right)$$

where (14) has been used. This indicates that Z_q/Z_l depends only on r and is insensitive to any other parameter listed above, as long as the wetland loss is the dominant component of the total cost.

Figure 10 shows the ratio of the total costs for equivalent linear and quadratic sea-level rises, Z_q/Z_l, for $\tau = 100$ and $\tau = \infty$. It also shows the ratio of wetland loss, w_q/w_l. Comparing top and bottom panels indicates that w_q/w_l generally explains Z_q/Z_l since wetland is a dominant component. However, a closer inspection of the top and bottom left panels reveals a difference between w_q/w_l and Z_q/Z_l, especially for small $\sigma_q^{(1)}$. For instance, comparison of the two right panels ($\tau = 100$) shows that for $\sigma_q^{(1)}$ = 1[mm/year], $S(t{=}100) \sim 0.2$, Z_q/Z_l is 0.6 whereas w_q/w_l is about 0.7.

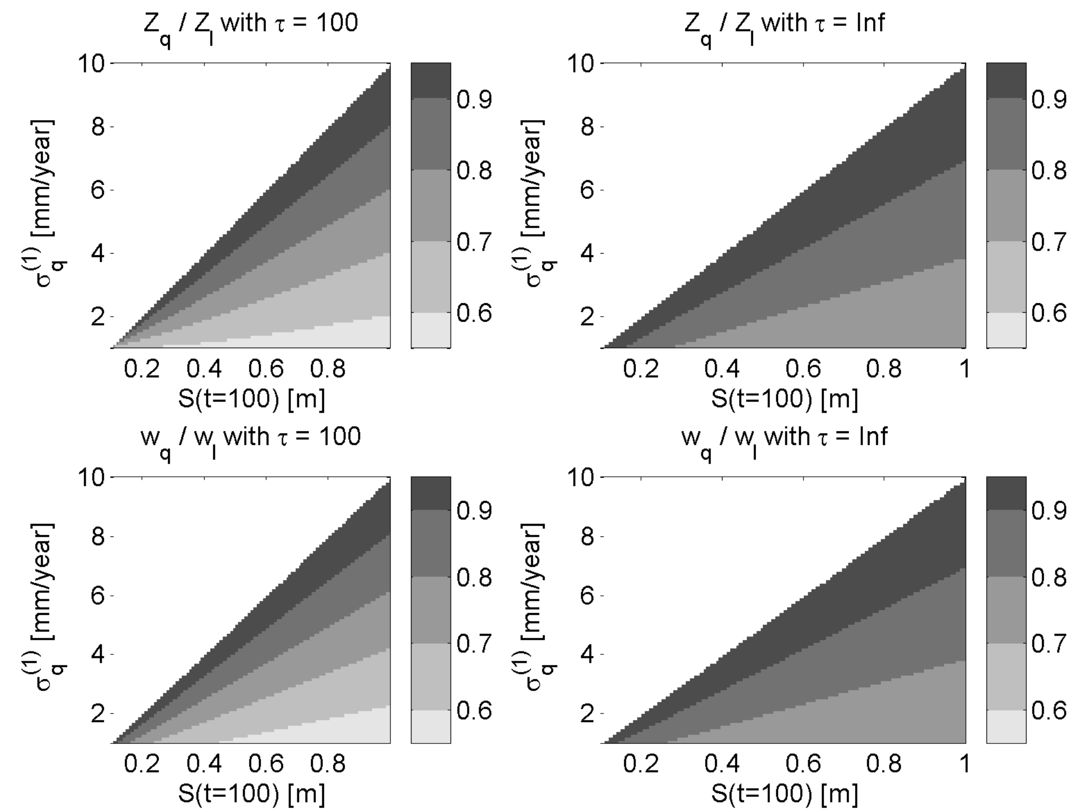

Figure 10. The total cost ratio between equivalent linear and quadratic sea-level rises (top left) for 100 years and (top right) an infinite time horizon. (Bottom) as in the top panels but for the wetland loss ratios. The horizontal axis is the sea-level rise in the final year, $S(t=100)$ whereas the vertical axis represents the rate of a quadratic sea-level rise at the initial period, $\sigma_q^{(1)}$.

All the panels in Figure 10 show values less than 1, indicating that quadratic sea-level rise scenarios lead to reduction of the total cost, as expected. For $\tau = 100$, the lowest value of Z_q/Z_l is about 0.6 (top, left panel), implying that the total cost for a quadratic sea-level rise could be up to 40% lower than that of a linear sea-level rise. The right panels exhibit that even for an infinite time horizon ($\tau = \infty$), Z_q/Z_l can go down to 0.7, which means that there is a substantial cost difference. All this shows that the past literature that relied on a linear sea-level rise has probably overestimated the present value of the cost of sea-level rise in this regard.

Having shown that a linear sea-level rise tends to overestimate the cost, the next question is, can we quantify whether the future sea-level rise is more likely to be quadratic or linear? Here the IGSM 1000 simulations can assist us in addressing the question. **Figure 11** exhibits sea-level rise for randomly selected IGSM runs together with linear and quadratic fits. For all the cases presented here, the quadratic fit and model result are indistinguishable whereas the linear fit clearly deviates from the model result.

To quantify how much improvement quadratic fits can provide (a quadratic fit is always "better" since it has one more regression coefficient), **Figure 12** displays (single and multiple) regression coefficients for linear and quadratic fits. It is clear that quadratic fitting equations are much better than linear fits, making a stronger case that a quadratic sea-level rise better represents realistic sea-level rise scenarios. It is actually possible to perform a statistical test to assess whether a quadratic equation is superior or not, but that is left to future research.

Presumably the reason why a quadratic fit performs very well is because the time scale of the ocean adjustment is long. Without stabilization of the atmospheric greenhouse gas concentration, the sea level continues to rise and can be approximated by an exponential function. Since its adjustment time scale is thousands of years, the first hundred years can be represented well by a quadratic equation.

4. APPLYING THE COST FUNCTION

This section describes how the sea-level rise cost function derived above is applied to DIVA and EPPA. The basic idea is to apply the sea-level rise cost function to each of DIVA's 12,198 segments. Tol (2002a, 2002b) used GVA, which provides 192 polygons, to estimate the cost of sea-level rise. The increase in spatial resolution from GVA to DIVA is substantial. However, we still use $D(L) = (1 - L)^{\beta}$ to incorporate the capital concentration effect since even within a coastal segment, capital is concentrated. In other words, *D* in this section is defined at the regional or coastline scale and different from those presented in Figure 8, which presents *D*'s at a

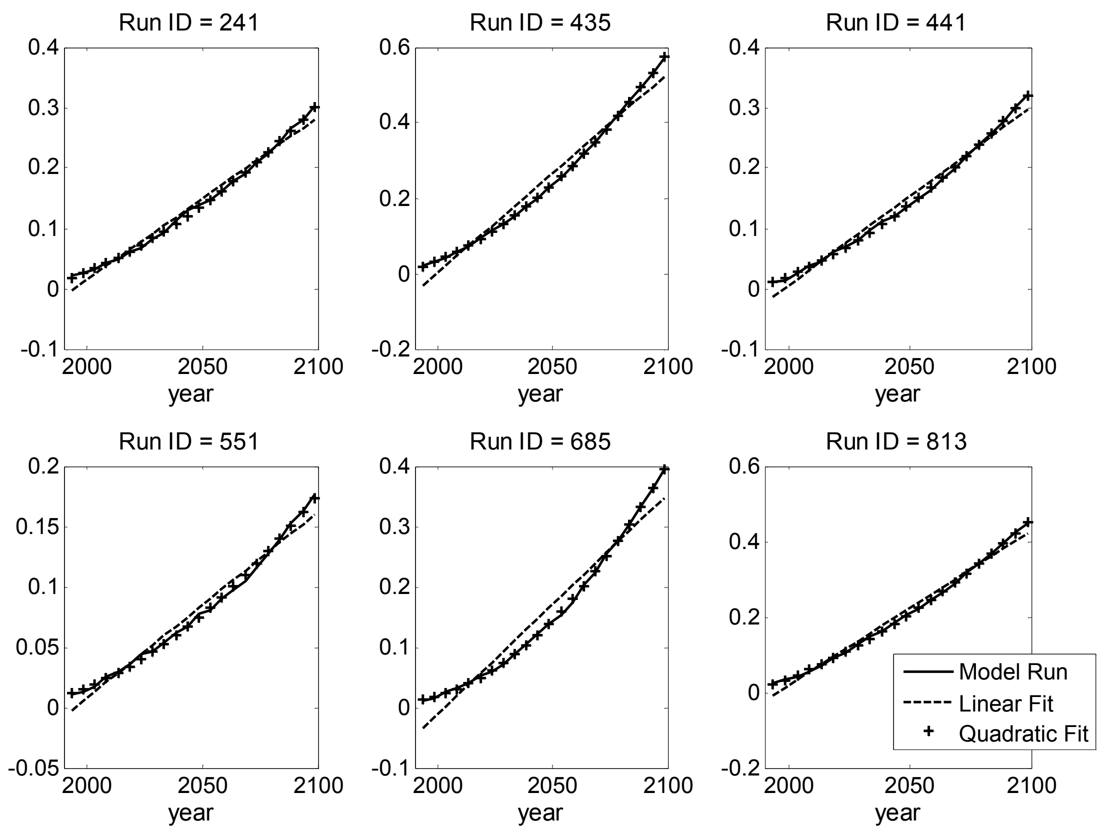

Figure 11. Sea-level rises (vertical axis) from randomly selected IGSM simulations. Each panel corresponds to different runs, showing the model result (solid), a linear fit (dashed), and a quadratic fit (pluses).

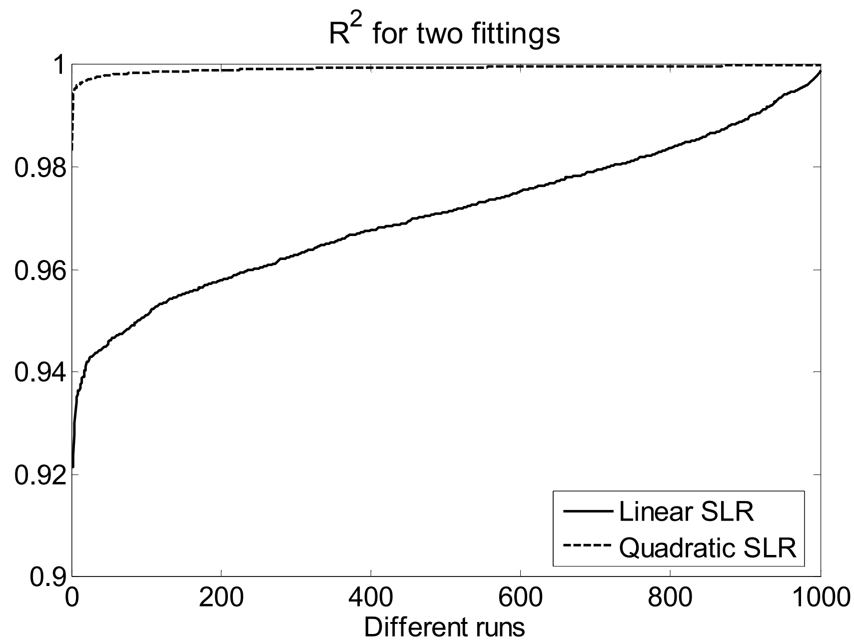

Figure 12. Regression coefficients R^2 for linear fits (solid) and quadratic fits (dashed). The result for each fit is sorted such that R^2 increases toward the right. Note that the order of runs is different between the linear and quadratic fits.

country scale. Indeed, Turner *et al*. (1995) found that some portion of East Anglia was not worth protecting, supporting capital concentration even at the regional scale. On the other hand, the degree of concentration would not be as high at the regional scale as at the national scale. The standard value is thus taken to be $\beta = 2$, and sensitivity tests are performed.

The calculation proceeds in the following way. First, the global sea-level rise is taken either from the IGSM simulations or assumed to follow a predetermined path, which is converted into relative sea-level rise by adding geologic subsidence. Second, the cost function produces the cost items p_1, d_0, g_0, and w at each time step. Third, present values are obtained, using discount rates consistent with the economic model EPPA. Fourth, the cost function determines the optimal protection fraction and optimal cost. In the discussion below each step is described.

Relative sea-level rise

In each time step of EPPA, the global sea-level rise is taken either from the IGSM 1000 simulations or assumed to follow a predetermined path, such as a linear one meter rise per century. DIVA gives the rate of geological uplift or subsidence for each coastal segment (parameter UPLIFT), and the relative sea-level rise is calculated as a sum of the global sea-level rise and the local geologic component.

Cost at each time step

For given relative sea-level rise, the costs are calculated as

$$p_1(t) = \pi \cdot \frac{dS}{dt}(t) \cdot \Lambda \cdot \Theta(S(t)),$$

Table 5. Correspondence between DIVA variables and symbols. See Table 1 for definitions of DIVA variables. Due to the error in the version of DIVA database used for this report, the dike cost here reflects that of IPCC CZMS (1990) rather than that of GVA.

Symbol	DIVA variable	Units in DIVA
π	SDIKECOST	U.S. $m per m per km
Λ	LENGTHY	km
ψ	SLOPECST	Degrees
Ω	min((TOTALWETAR/100+MANGS_KM2)/1, LENGTHY)	TOTALWETAR in ha, LENGTHY in km, so that Ω in km

Table 6. Other parameters and sources.

Symbol	Descriptions	Source
α	50 cm per year	F95a
γ	$5\,\text{million USD} \times \left[\frac{\text{(GDP per capita)/\$20000}}{1+\text{(GDP per capita)/\$20000}}\right] \Big/ \left[\frac{\text{(GDP per capita)}_{\text{US}}\text{/\$20000}}{1+\text{(GDP per capita)}_{\text{US}}\text{/\$20000}}\right]$	F95a, Tol (2002a)

$$d_0(t) = \delta(t) \cdot \frac{S(t)}{\tan\psi} \cdot \Lambda \cdot \Theta(S(t))$$

$$g_0(t) = \gamma \cdot \min\left(\alpha t, \frac{S(t)}{\tan\psi}\right) \cdot \Omega \cdot \Theta(S(t)),$$

$$w(t) = \gamma \cdot \frac{S(t)}{\tan\psi} \cdot \Omega \cdot \Theta(S(t)), \qquad (15)$$

where Θ is the Heaviside step function. The step function is introduced to prevent negative costs. Now that *S* represents the relative sea-level rise, it can be negative since geologic uplift may exceed global sea-level rise. We assume that the cost is incurred only after *S* becomes positive (due to the acceleration of sea-level rise). Also note that the wetland gain g_0 now contains a minimum operator so that wetland gain does not exceed the wetland loss *w*; contrast (15) with (11). Although under some circumstances there can be *net* wetland gain (as a sum of *gross* wetland gain and wetland loss), it is difficult to figure out whether net wetland gain occurs or not for each coastal segment. The present report simply ignores such a possibility.

DIVA provides data on each parameter utilized in (15), which is summarized in **Table 5**. Some coastal segments have $\psi = 0$, and no cost is calculated for such segment. Other required parameters are given in **Table 6**. Note that *S* here represents *relative* sea-level rise for each coastal segment, rather than global sea-level rise. Note also that the value of wetland is not adjusted for inflation. In fact, the uncertainty in the value of wetland dwarfs adjustment due to inflation, and we perform a sensitivity test on the wetland value in Section 5.

For wetlands, DIVA provides the areas, not the length, Ω. To convert the areas into lengths, we assume that wetlands extend inland on average about 1 km, following F95a. In reality, the inland extent scales with the area, although its functional form is not known.

We have yet to specify the time evolution of capital loss. A simple choice is

$$\delta(t) = \delta(t=0) \cdot \frac{Y(t)}{Y(t=0)}$$

where Y is economic output. There are two possible ways to specify $\delta(t=0)$:

$$\delta(t=0) = (\text{capital-output ratio}) \cdot (\text{economic output of segment per area}),$$

$$\delta(t=0) = (\text{economic output of segment per area}).$$

What is at stake is not the capital but return on the capital, and thus the second specification appears more appropriate. Nevertheless, the next section conducts sensitivity tests. Also note that the formulation adopted here assumes that the geographical population distribution in a country does not change over time.

To use the economic growth rate from EPPA, we associate each segment in DIVA with one of the 16 regions in EPPA. Since each of the coastline segments in DIVA belongs to a country, this task is to define a correspondence table between countries in DIVA and regions in EPPA. Appendix B of Sugiyama (2007) gives such a correspondence table.

There is a technical issue with the difference in the reference years between EPPA and DIVA. While EPPA uses 1997 as the reference year, DIVA utilizes 1995. A crude but simple approach to combine DIVA and EPPA is to multiply the economic output of DIVA by the growth rate of each region for 1995–1997. We attempted to obtain growth rates for each region by comparing the regional outputs from DIVA and EPPA, but they turned out to be very different, calling into question the validity of this method of estimating growth rates. Here we simply ignore the difference in the reference year, allowing for errors of up to 20% (for economically dynamic areas) in the unit capital loss. This should not, however, lead to substantial errors in the cost estimate since, in most cases, the cost is dominated by wetland loss and precious land is already protected. In any event, this problem must be remedied in the future.

DIVA provides economic output of each segment but G-Econ contains more detailed data. We therefore test the data from the two datasets. However, there are some issues with combining DIVA and G-Econ data. First, as in the case with DIVA and EPPA, the reference year is different (1995 for DIVA and 1990 for G-Econ), although both datasets adopt 1995 U.S. dollars as currency units. Second, DIVA and G-Econ are not provided on the same spatial grid.

The difference in the reference years can easily be accommodated by using the data from G-Econ for spatial scaling only. For the purpose of spatial scaling, we define the local economic multiplier as

$$(\text{local economic output multiplier}) = \frac{(\text{local economic output per capita})}{(\text{GDP per capita})}. \quad (16)$$

DIVA provides this parameter as "GDP per capita multiplier." This parameter can also be readily calculated from G-Econ (since local economic output is gross cell product in G-Econ). Therefore, the economic output of each segment is calculated by multiplying GDP per capita from DIVA with the multiplier either from DIVA or G-Econ.

Next, it is necessary to assign each of the DIVA coastal segments to one of the G-Econ grid cells. G-Econ grid cells and DIVA segments are matched by calculating the "distance":

$$(\text{distance}) = \sqrt{\left(\text{lat}_{\text{DIVA}} - \text{lat}_{\text{GEcon}}\right)^2 + \left(\text{lon}_{\text{DIVA}} - \text{lon}_{\text{GEcon}}\right)^2} . \tag{17}$$

For a particular DIVA segment, the G-Econ grid cell that has minimum distance and that belongs to the same country as the DIVA segment is chosen. This chosen G-Econ grid cell gives per-capita economic output for the DIVA segment in question. We obtain economic output for this segment by multiplying the G-Econ per-capita output by population density of this DIVA segment. If (17) gives a "distance" larger than 2, G-Econ data is not utilized for that particular DIVA segment.

Admittedly this is a crude way to match DIVA and G-Econ. An ideal way is to utilize a GIS system to combine both datasets, which is left for future research. For instance, future updates of the DIVA database could derive relevant economic parameters from G-Econ, making the dataset internally consistent.

Figure 13 shows the local economic output multipliers from DIVA and G-Econ for three countries. Comparison of dashed lines (DIVA) and solid lines (G-Econ) reveals that using G-Econ increases the maximum value of multiplier and decreases its minimum value. For the U.S., G-Econ implies that some grid cells have per-capita income more than 20 times larger than the U.S. average. Overall, G-Econ shows more spatial concentration of per-capita economic output than DIVA, probably reflecting its higher spatial resolution.

Present value calculation

The discount rate is assumed to be the economic growth rate plus the pure rate of time preference. The actual calculation is prompted by the relations

$$\frac{1}{1+\varepsilon(t)+\rho} \approx \frac{1}{1+\varepsilon(t)}\frac{1}{1+\rho}, \quad \prod_{t=0}^{\tau} \frac{1}{1+\varepsilon(t)} = \frac{Y(t=0)}{Y(t=\tau)}, \text{ and}$$

$$\prod_{t=0}^{\tau} \frac{1}{1+\varepsilon(t)+\rho} \approx \frac{Y(t=0)}{Y(t=\tau)}\frac{1}{(1+\rho)^{\tau}},$$

where Y is the gross domestic product and ρ is the pure rate of time preference, which is taken to be 1%. In sum,

$$(\ )^{(pv)} = \sum_{t=0}^{\tau} (\ )\frac{Y(0)}{Y(t)}\frac{1}{(1+\rho)^{t}} . \tag{18}$$

The base year is taken to be 2000 (that is, $t = 0$ refers to 2000).

What do the discount rates based on Equation (18) look like? It is useful to define an equivalent discount rate as

$$\tilde{r}(t) \equiv \left(\frac{Y(t)}{Y(0)}\right)^{\frac{1}{t}}(1+\rho) - 1 \text{ so that } \frac{1}{\left\{1+\tilde{r}(t)\right\}^{t}} = \frac{Y(0)}{Y(t)}\frac{1}{(1+\rho)^{t}} . \tag{19}$$

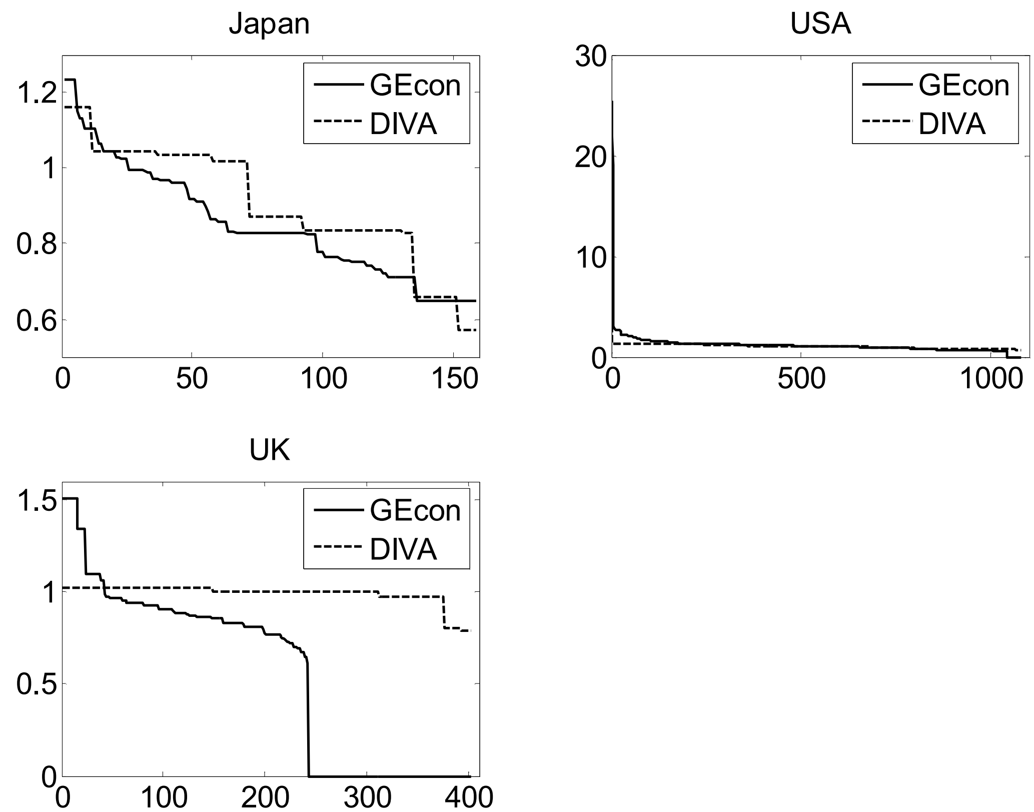

Figure 13. Local economic output multipliers for 3 countries. Solid lines correspond to estimates from G-Econ whereas dashed lines are from DIVA. The horizontal axes indicate different segments. Segments are sorted in the order of decreasing multiplier.

Table 7 displays the equivalent discount rate calculated for the United States, based on the EPPA reference economic scenario. It is about 4% initially and gradually decreases to about 3%, as the economic growth slows down. **Table 8** shows the same parameter for all the EPPA regions for selected years. The equivalent discount rate is 3 – 4% on average.

Table 7. Equivalent discount rate $\tilde{r}$ as defined in Equation (19) for the United States, estimated from the EPPA reference case economic scenario and a pure rate of time preference of 1%. Units are in percent.

Year	$\tilde{r}$	**Year**	$\tilde{r}$	**Year**	$\tilde{r}$	**Year**	$\tilde{r}$
2005	3.50	2030	4.10	2055	3.79	2080	3.41
2010	4.02	2035	4.06	2060	3.71	2085	3.34
2015	4.17	2040	4.01	2065	3.63	2090	3.28
2020	4.18	2045	3.94	2070	3.55	2095	3.23
2025	4.14	2050	3.87	2075	3.48	2100	3.18

Table 8. As in Table 7 but for all the EPPA regions and selected periods.

	2005	**2010**	**2020**	**2040**	**2060**	**2080**	**2100**
United States	3.50	4.02	4.18	4.01	3.71	3.41	3.18
Canada	3.85	4.26	4.34	4.09	3.76	3.46	3.21
Mexico	3.07	3.69	3.89	3.77	3.51	3.35	3.23
Japan	2.07	3.16	3.72	3.92	3.72	3.45	3.21
Australia & New Zealand	4.42	4.64	4.60	4.33	4.00	3.67	3.40
European Union	2.79	3.50	3.80	3.76	3.57	3.34	3.13
Eastern Europe	4.30	4.37	4.36	4.27	4.13	3.93	3.75
Former Soviet Union	5.55	5.23	5.14	4.89	4.45	4.09	3.83
Higher Income East Asia	4.47	4.49	4.51	4.35	4.16	3.91	3.71
China	7.14	6.52	6.02	5.46	5.02	4.58	4.24
India	6.15	5.76	5.34	4.66	4.28	4.05	3.86
Indonesia	3.41	3.93	4.25	4.36	4.14	3.92	3.73
Africa	4.61	4.87	4.80	4.10	3.87	3.70	3.55
Middle East	4.05	4.46	4.45	3.96	3.72	3.49	3.32
Central & South America	2.74	3.57	4.11	4.44	4.33	4.07	3.82
Rest of World	4.46	4.39	4.18	3.63	3.53	3.48	3.44

Optimal protection fraction

Given the present values of each cost item, it is now possible to determine the optimal protection fraction. Recalling Equation (1), it is imperative to notice that the nature of the problem is forward-looking. What is being calculated is the trade-off between future economic growth and current cost of building a sea dike. Such a trade-off cannot be appropriately dealt within a dynamic-recursive model like the standard version of EPPA. Nevertheless, we apply F95a's method to the DIVA and EPPA, with a caution that this method should be improved in the future.

With F95a's approach, we can take the sea-level rise scenario from the "reference" case and calculate the present value. We further assume $D(L) = (1 - L)^{\beta}$ and choose $\beta = 2$. There is no information about capital distribution within each of the coastal segments in DIVA and it is impossible to justify $\beta = 2$, which motivates sensitivity tests on β. By combining the present values of each cost item and the cumulative distribution function D, Equation (7) gives the optimal protection fraction L^*.

Optimal cost

Given the optimal protection fraction L^*, it simply follows that the optimal costs are

$$p^*(t) = L^* p_1(t),\ d^*(t) = (1-L^*)^{\beta} d_0(t),\ g^*(t) = (1-L^*) g_0(t). \qquad (20)$$

The total cost in each time period is thus

$$L^* p_1(t) + (1-L^*)^{\beta} d_0(t) + w(t) - (1-L^*) g_0(t),$$

where all terms are defined in (15). Note that there is no optimal (gross) wetland loss since wetland loss does not involve the choice variable L. (Recall that the *net* wetland loss is the sum of (gross) wetland loss w and wetland gain g).

5. RESULTS

5.1 Socio-economic and sea-level rise scenarios

This section presents the results of numerical cost calculations. Socio-economic scenarios are taken from the reference run of the EPPA. The following results ignore the effect of capital loss on economic welfare. As noted in Section 4, ideally, we should utilize a forward-looking model to capture the trade-off between protection cost and loss of future economic welfare due to reduced capital. And yet we do not take this approach, using the cost function derived in Sections 3 and 4. Also, the present results are based on partial equilibrium calculations, rather than general equilibrium calculations, which is another limitation of the present report.

Several scenarios of sea-level rise are examined to illustrate the sensitivity:

1. A one-meter-over-century linear sea-level rise for comparison with F95a;
2. An average of IGSM 1000 simulations; and
3. Linear equivalent sea-level rise scenario.

All the results presented below are in 1995 U.S. dollars, although EPPA's reference year is 1997. This is because the costs presented below are based on DIVA, which takes 1995 as the reference year.

5.2 One-meter-per-century linear sea-level rise

The use of a linear sea-level rise of 1 meter over a century facilitates comparison with F95a. **Tables 9 and 10** display the results in market exchange rate (MER) and purchasing power parity (PPP) terms, respectively. The conversion between MER and PPP is performed using the conversion rates described by Paltsev *et al*. (2005), who in turn relied on the Penn World Tables (Heston *et al*. 2002). The results are later compared with those of F95a.

The review of cost items is in order. In each period, there are four kinds of cost incurred: (1) protection cost $p(t)$, (2) dryland/capital loss $d(t)$, (3) wetland loss $w(t)$, and (4) wetland gain $g(t)$. Protection cost $p(t)$ represents the cost of building an *additional* dike at each period. Maintenance cost is neglected here. Capital loss $d(t)$ in each period is the loss of capital because of inundation in that period. Net wetland loss $w(t) - g(t)$ is wetland loss w minus wetland gain g. Subsection 3.1 describes the detailed definitions of each cost item. Note that all the tables in this section show present values: $[\, p(t)\,]^{(pv)}$, $[\, d(t)\,]^{(pv)}$, $[\, w(t) - g(t)\,]^{(pv)}$, where $(\ )^{(pv)}$ is the present value operator defined in (18).

The global estimate shows the relative importance of cost items. Table 9 shows that wetland loss is on the order of \$1000 billion, while protection cost is \$100 billion and capital loss is \$30 billion in MER. For PPP, Table 10 indicates larger cost estimates, but the relative magnitude of

Table 9. Results from the reference case socio-economic scenario and linear one-meter-over-century sea-level rise in 1995 U.S. billion dollars in MER. A simple sum based on MER is given as the global cost, without taking PPP conversion into account.

	Present values of cost and loss					Protection
EPPA regions	**Total**	**Protection**	**Capital**	**Net wetland**	**% of wetland**	**fraction [%]**
Global	1182.21	126.35	37.94	1017.93	86.10	29.86
United States	317.72	10.31	3.32	304.09	95.71	40.14
Canada	123.04	5.78	3.29	113.98	92.63	6.66
Mexico	29.01	3.46	1.64	23.91	82.42	47.83
Japan	14.56	9.52	0.15	4.88	33.54	97.88
Australia & New Zealand	145.64	4.77	5.11	135.76	93.21	40.57
European Union	147.20	28.23	4.48	114.48	77.78	34.64
Eastern Europe	1.01	0.56	0.03	0.42	41.44	92.10
Former Soviet Union	7.96	3.73	2.79	1.44	18.05	6.35
Higher Income East Asia	33.11	9.81	0.68	22.62	68.31	79.83
China	6.45	5.55	0.21	0.69	10.74	93.19
India	5.92	3.64	0.12	2.16	36.48	80.92
Indonesia	36.87	3.89	1.64	31.34	85.02	51.37
Africa	21.45	5.57	3.20	12.68	59.10	30.49
Middle East	20.39	1.96	0.58	17.85	87.53	51.36
Central & South America	249.74	19.89	7.44	222.41	89.06	40.52
Rest of World	22.15	9.67	3.25	9.22	41.65	45.66

each cost remains the same. Wetland loss constitutes a dominant component, as in previous studies (F95a, etc.), and each cost item differs by an order of magnitude.

Several countries make up the majority of wetland loss: the United States, Canada, Australia & New Zealand, the European Union, and Central & South America (and Indonesia, if PPP is used). Nicholls *et al*. (1999) list regions with vulnerable wetlands: the Atlantic coast of North and Central America, the Mediterranean, and the Baltic. The present results show that more regions are vulnerable than Nicholls *et al*. suggested. The reason is two-fold. First, the wetland damage function here is much cruder than that of Nicholls *et al*.; a better wetland model would be a major improvement. Second, Nicholls *et al*.'s database had many countries missing.

For MER, regions with highest protection cost are European Union, Central & South America, and the United States, whereas the highest capital loss is incurred by Central & South America, Australia & New Zealand, and European Union. This order changes for PPP. Regions with highest protection cost are Central & South America, the Rest of World, and the European Union; those with highest capital loss are Central & South America, Rest of World, and Africa. In light of their low GDP, it is noteworthy that Africa and Rest of World incur high protection cost and capital loss under PPP, implying that poorer countries tend to suffer more.

Table 10. As in Table 9 but for PPP based on conversion described by Paltsev *et al*. (2005).

EPPA regions	Present values of cost and loss				% of wetland	Protection fraction [%]
	Total	Protection	Capital	Net wetland		
Global	1991.24	285.75	87.66	1617.78	86.10	29.86
United States	317.72	10.31	3.32	304.09	95.71	40.14
Canada	148.88	6.99	3.98	137.92	92.63	6.66
Mexico	43.81	5.22	2.48	36.10	82.42	47.83
Japan	10.05	6.57	0.10	3.37	33.54	97.88
Australia & New Zealand	184.96	6.06	6.49	172.42	93.21	40.57
European Union	176.64	33.88	5.38	137.38	77.78	34.64
Eastern Europe	2.85	1.58	0.08	1.18	41.44	92.10
Former Soviet Union	34.31	16.08	12.02	6.21	18.05	6.35
Higher Income East Asia	97.01	28.74	1.99	66.28	68.31	79.83
China	28.77	24.75	0.94	3.08	10.74	93.19
India	31.79	19.55	0.64	11.60	36.48	80.92
Indonesia	147.11	15.52	6.54	125.05	85.02	51.37
Africa	82.58	21.44	12.32	48.82	59.10	30.49
Middle East	50.98	4.90	1.45	44.63	87.53	51.36
Central & South America	539.44	42.96	16.07	480.41	89.06	40.52
Rest of World	94.36	41.19	13.85	39.28	41.65	45.66

The optimal protection fraction shows interesting behavior. It is highest for Japan, followed by China and Eastern Europe, all of which have protection levels exceeding 90%. Japan's high protection level is consistent with the finding of F95a. F95a also found high protection levels for the United States and Europe, but the results here show moderate protection fractions (about 40% and 30%, respectively) for these regions. Why do Japan, the United States, and Europe show different behaviors in terms of protection fraction?

Figure 8 gives some hints for this difference. Comparing the upper two panels reveals that Japan has a long tail of modest D while D falls sharply for the United States. In other words, Japan's D doesn't reach 0 until $L = \sim 0.8$ whereas that of the United States becomes indistinguishable from 0 at $L = \sim 0.4$. Presumably such a difference in the D would explain differing protection levels.

Table 11 compares the results here with those of F95a for selected countries. Note that the present values are now in 1990 U.S. dollars rather than 1995 dollars, unlike other tables in this section. One prediction of the cost function derived in Section 3 is that using DIVA should result in smaller protection fractions. In fact, Table 11 shows exactly this, except that Japan's protection fraction decreases only little, which we just discussed. It is noteworthy that the protection cost of $9.13 billion for the United States is even lower than $36.1 billion estimated by Yohe *et al*. (1996).

Table 11. Comparison of the results of this report and F95a and Fankhauser (1995b). The protection fraction for F95a is taken to be an average of protection levels for open coasts, beaches (see his Figure 2), cities, and harbors (100%) weighted by coastline lengths as presented in Fankhauser (1995b). Because open coasts account for the majority of a country's coastline, protection fractions from F95a closely follow those of open coasts. Units are in 1990 U.S. dollars. For conversion between 1990 and 1995 dollars, a GDP deflator of 1.129 is used, which was taken from the GDP price implicit deflator in the National Income and Product Accounts Tables (Table 1.1.9 of http://bea.gov/bea/dn/nipaweb/SelectTable.asp?Selected=Y).

		Total	Protection	Capital loss	Net Wetland loss	% of net wetland loss	Protection fraction [%]
United States	This report	281.42	9.13	2.94	269.34	95.71	40.14
	Fankhauser	425.16	62.59	15.96	346.61	81.52	81
Japan	This report	12.90	8.43	0.13	4.32	33.54	97.88
	Fankhauser	141.47	6.83	0.03	134.55	95.11	99
Canada	This report	108.98	5.12	2.91	100.96	92.63	6.66
	Fankhauser	6.92	3.73	3.12	N/A	N/A	28
Australia	This report	129.00	4.22	4.53	120.25	93.21	40.57
& New Zealand	Fankhauser	50.76	44.58	5.94	N/A	N/A	76
European Union	This report	130.38	25.00	3.97	101.40	77.78	34.64
	Fankhauser	300.66	55.24	1.90	243.52	81.00	95

However, it is likely that the difference in protection fraction is not entirely due to the effect of capital concentration. The average value of the dryland could be different between the two calculations. Unfortunately, such comparison is not easy since F95a calculated the cost for different types of coastal areas (e.g., cities, harbors, open coasts), while the present report does not distinguish them. Most likely we are seeing the combined effect of capital concentration and differing values of dryland.

In spite of lower protection fractions, the new cost estimates are not necessarily lower than F95a's. Wetland loss, which tends to be dominant, can account for most of the differences. The wetland loss for the United States is 24 % lower than that of F95a, and the total cost is 35% lower but still comparable. F95a did not provide wetland loss for Canada and Australia & New Zealand; adding this substantially increases the total cost for these countries. Why the results here based on DIVA show lower wetland loss for Japan and European Union is not clear.

It is instructive to see the sensitivity of the present results to parameters of interest. The following lists parameters and motivation for sensitivity calculations:

1. *Wetland price*. Titus *et al*. (1991) show a wide range of wetland price, from ~$1.5 million to ~$7.4 million per km^2. Moreover, wetland loss tends to dominate the total cost;
2. *Protection cost*. Although the present study considers only sea dike construction as protection measure, different coastal types require different options. For example, beaches require beach nourishment which, according to F95a, is more costly than dikes;

3. *The exponent of cumulative capital distribution function*, *β*. Section 3 estimated *β* at the *country scale*, but the value at the *coastline scale* is unknown;

4. *Discount rate*. Impact assessment is generally susceptible to the choice of discount rate, as was confirmed for sea-level rise by F95a. How sensitive are our results to the discount rate?;

5. *Capital-output ratio*. Ideally, one should evaluate the return on capital rather than capital itself in calculating the cost. Although DIVA and G-Econ provide local economic output, this may not be directly related to return on capital. Therefore a sensitivity test is performed on the capital-output ratio to explore how to treat this; and

6. *Use of DIVA-based economic output*. As Section 4 showed, using G-Econ renders the geographic distribution of economic output even more skewed. How does it affect the cost of sea-level rise damage?

Table 12 lists the sensitivity calculations, focusing on the United States. Halving the wetland price reduces wetland loss and the total cost approximately by half, since the wetland loss is the dominant term in the total cost. Doubling the unit protection cost increases protection cost to about twice the reference-case cost, but the total cost does not change appreciably since it is dominated by wetland loss. Using the DIVA-based economic output rather than the G-Econ dataset does not alter the cost estimates significantly. Reducing *β* from 2 to 1 increases both protection cost and capital loss. This is because the capital is assumed to be uniform at the coastline scale. Increasing *β* to 5 leads to less protection cost but slightly more capital loss. For both values of *β*, the total cost does not change because of the predominance of wetland loss. Setting the capital-output ratio to 1 reduces both protection cost and capital loss as expected, but

Table 12. Sensitivity tests of the costs for the United States for a one-meter-over-century linear sea-level rise.

	Total	Protection	Capital loss	Net wetland loss	% of net wetland loss	Protection fraction [%]
Reference	317.72	10.31	3.32	304.09	95.71	40.14
Half wetland price	165.58	10.43	2.93	152.23	91.93	40.59
Double protection cost	327.51	18.83	4.79	303.89	92.79	36.99
DIVA-based economic output	317.47	10.18	3.32	303.97	95.75	39.72
$\beta = 1$	318.50	10.68	3.43	304.39	95.57	41.50
$\beta = 5$	312.14	8.14	3.38	300.62	96.31	31.67
Capital-output ratio = 1	314.71	8.84	2.82	303.04	96.29	34.89
Discount rate = 1%	1180.82	27.01	10.81	1143.00	96.80	44.58
Discount rate = 3%	423.10	12.71	4.27	406.12	95.99	40.69
Discount rate = 5%	201.35	7.71	2.25	191.39	95.06	37.68

the total cost does not differ much.

Table 12 also shows the sensitivity of the cost to the discount rate. For the last 3 rows of Table 12, a fixed discount rate is used for the entire periods. As expected, a lower discount rate gives a higher present value of the costs. The reference case falls between discount rates of 3 – 5%, which is confirmed by Table 7 that shows equivalent discount rates for all the periods.

The results here are only for the United States, and the total costs of other countries behave differently since, for example, Japan has small wetland loss and changing the protection cost does affect the total cost. Nevertheless, the results for other countries are as straightforward as for the United States.

5.3 Average of IGSM 1000 simulations

Although a linear sea-level rise of 1 meter is important for comparison purposes, it is higher than IPCC projections of 18–59 cm in 2100 (Meehl *et al.* 2007). In what follows, we discuss the effect of a more realistic sea-level rise scenario, using an average of 1000 sea-level rise scenarios produced by the MIT IGSM. It also compares linear and quadratic sea-level rises. **Figure 14** depicts the quadratic fit to the IGSM sea-level rise scenario and the equivalent linear scenario.

The calculation utilizes the quadratic fit to the average of IGSM simulations across different runs. Since the multiple regression coefficient is extremely high ($R^2 > 0.9999$), the error should be negligible from the use of a quadratic fit. The sea-level rise in 2100 is about 0.44 m. In conjunction with the quadratic effect, the cost here is anticipated to decrease substantially.

Table 13 lists the cost estimates for the United States in the same format as Table 12. The reference case exhibits much lower costs than presented in Tables 9 and 10. The last row describes the cost associated with the equivalent linear sea-level rise. As expected, the equivalent linear sea-level rise leads to about 60% higher cost. The results of other sensitivity tests are easy to understand as in the previous subsection.

5.4 Summary

This section has produced new estimates of the cost of sea-level rise. Results presented here affirm some classical results and provide new insight:

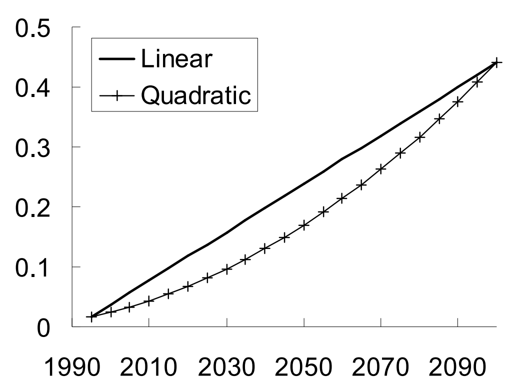

Figure 14. A quadratic fit to the average of the IGSM 1000 sea-level rise scenarios. Also shown is an equivalent linear sea-level rise scenario.

Table 13. Sensitivity tests of the costs for the United States for the mean of 1000 sea-level rise scenarios.

	Total	Protection	Capital loss	Net wetland loss	% of net wetland loss	Protection fraction [%]
Reference	75.72	2.42	1.71	71.58	94.54	40.22
Half wetland price	39.76	2.47	1.17	36.13	90.86	41.06
Double protection cost	77.98	4.28	2.20	71.50	91.69	36.97
DIVA-based economic output	75.59	2.40	1.70	71.49	94.57	40.05
β = 1	76.56	2.52	1.24	72.80	95.09	41.99
β = 5	71.88	1.91	1.80	68.18	94.85	31.46
Capital-output ratio = 1	73.76	1.94	2.24	69.57	94.33	33.71
Linear equivalent sea-level rise	125.75	3.80	1.99	119.96	95.40	39.95

1. Replacing GVA with the new vulnerability database DIVA leads to lower optimal protection fractions, generally reducing the protection cost;
2. Wetland loss continues to be the dominant cost item. Nevertheless, capital loss and protection cost may not be negligible for developing countries, in light of their small GDP;
3. Different sea-level rises yield different cost estimates. What matters is not the final sea-level rise but the *path* of sea-level rise, which reaffirms the finding of Section 3 about the difference between linear and quadratic sea-level rises; and
4. The role of D (cumulative capital distribution function) at the *country level* is subtle for some countries because a simple equation may not approximate the capital distribution derived from DIVA because of a long tail.

The next section addresses what can be done to further improve the cost estimates.

6. CONCLUSIONS AND DISCUSSIONS

6.1 Conclusions

As part of an effort to incorporate the sea-level rise damage effect in EPPA, this report generalized the sea-level rise cost function originally developed by F95a, and made an initial attempt to calculate the cost of global sea-level rise, using EPPA.

F95a's cost function has been generalized in two ways. First, we have shown that the capital distribution is not restricted to a quadratic function but can take any form; as long as its derivative is invertible, it is possible to obtain a closed form solution for the optimal protection fraction. Using DIVA, we demonstrated that capital is quite concentrated, much more than F95a's choice of a quadratic function. Second, we have clarified that F95a's methodology can take nonlinear sea-level rise, and calculated some closed-form solutions. We also showed that because a nonlinear sea-level rise causes more damage in later periods, the cost and protection fraction for nonlinear sea-level rise is usually lower than that of an equivalent linear one. These two effects combine to indicate that the cost estimate from F95a's method and the GVA could be an overestimate.

Having extended F95a's methodology, we used an economic scenario from EPPA and utilized DIVA and G-Econ, producing novel estimates of the cost of global sea-level rise. Wetland loss continues to be the dominant cost item for most countries, and there is no drastic change in the total cost for a linear one-meter-over-century sea-level rise for regions where the wetland loss remains about the same. Realistic nonlinear sea-level rises yield appreciably lower costs. The role of *D* (capital distribution function) at the country level is subtle because a simple equation may not appropriately represent the capital distribution based on DIVA because of a long tail.

6.2 Discussion

Further extension of the generalized F95a's approach

Despite progress made in this work, a number of issues need to be addressed. Indeed, there are potential improvements to be made within F95a's framework. Examples include:

1. *Protection cost other than sea dikes, such as beach nourishment*. In this report, we assumed that the protection cost arises in the form of dike protection, and yet a better model should include other protection measures such as beach nourishment;
2. *Representation of wetland loss that takes accretion into account*. Wetlands are treated as passive in the present model, but they are active agents. They accumulate sediment (accrete) and may be able to keep up with relative sea-level rise, at least to some extent. Moreover, the current formulation assumes instantaneous gain and loss of wetlands although there is a finite response time for such changes. Ecology of wetland is extremely complex, but some simple models do exist (e.g., Nicholls 2004; McFadden *et al*. 2007), and can be included in F95a's framework;
3. *Forced emigration cost*. Sea-level rise will not only lose useful land but also displace people living there. Some argue that the cost associated with emigration could be substantial. Tol (2002a, 2002b) provides such estimates as an additional cost component, determined outside of the cost minimization problem, but it should be possible to include this as another item in the generalized F95a's approach; and
4. *Dynamic optimal protection fraction*. One of the key assumptions of F95a is that the optimal protection fraction does not change with time, which greatly simplifies the model solution strategy. For example, the model does not allow a situation where a coastline may be protected until 2050 and then abandoned. A simple dynamic optimization problem will certainly give a solution, but the question is how tractable that model would be. Creating a detailed but still tractable model is an interesting research topic.

Other improvements

In addition to the improvement of the cost functions, there are possible options for better cost estimates. One issue is the changing distribution of population. Currently the coastal areas are experiencing faster rates of population growth than national averages. Some studies took this trend into account by assuming that the present trends will continue (e.g., Nicholls *et al*. 1999). The future study may take advantage of the work of Asadoorian (2005), who derived empirical relations that can be used to forecast future population distributions.

Another issue concerns with the use of economic output from DIVA. It would be ideal to use the DIVA for spatial scaling only (to calculate the economic output of a coastal segment for a given GDP) since DIVA's economic data may not be compatible with the GTAP database that underlies EPPA. One can follow the way G-Econ is utilized in this report as described in Section 4.

It is also possible to relax the constant slope assumption since DIVA contains the areas at different elevations. In the current calculation, no cost is estimated for coastal segments with a zero slope, which might have led to an underestimate of the costs. Making use of the area data can overcome this problem.

Beyond Fankhauser

Those presented above are presumably straightforward problems. But we are confronted with more challenging questions.

F95a's optimization problem is a dynamic one, exposing the forward-looking nature of adaptation to sea-level rise. This means that in including sea-level rise damage in an economic model, ideally one should be using a forward-looking model. Currently the standard version of EPPA is recursive-dynamic, and it is inconsistent to use F95a's approach in an ad hoc manner. One could, however, develop a rule of thumb to mimic the forward-looking calculation by exploiting a fact that the cost of the damage is quite small relative to economic output. A starting point is a neoclassical growth model with a decision variable on coastal protection. There is no guarantee that this approach leads to a reasonable methodology, but if successful, the result would be helpful since a forward-looking model is usually expensive to run.

The most challenging issue is about imperfect information and storm surge. F95a's model requires perfect information about the future sea-level rise up to 2100. And yet, such information simply does not exist in the literature of future sea-level rise projections. Another relevant point is that what matters is not gradual sea-level rise itself, but storm surges that would be exacerbated by it.

Admittedly the future projection is full of uncertainty, but it is steadily taking place. Nevertheless, we do not see coastal planners deciding which coastal segments to protect. It might be that people would feel the effect of sea-level rise only when there occurred an extreme event. Modeling such human behavior in a simple manner and teasing out the *portion* of the extreme event damage due to sea-level rise is, indeed, challenging.

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