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from Sea Level Rise with the
Coastal Impact and Adaptation
Model (CIAM)**

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Summary

The costs of coastal sector impacts from sea level rise (SLR) are an important component of the total projected economic damages of climate change, a major input to decision-making and design of climate policy. Moreover, the ultimate costs to coastal resources will depend strongly on adaptation, society's response to cope with the impacts. This paper presents a new model to assess coastal impacts from SLR, combining global scope with high spatial resolution to fill a gap between very detailed local studies and aggregate global estimates. The Coastal Impact and Adaptation Model (CIAM) determines the optimal strategy for adaptation at the local level, evaluating over 12,000 coastal segments, as described in the DIVA database (Vafeidis et al, 2006), based on their socioeconomic characteristics and the potential impacts of relative sea level rise and uncertain storm surge. An application of CIAM is then presented to demonstrate the model's ability to assess local impacts and direct costs, choose the least-cost adaptation, and estimate global net damages for several probabilistic SLR scenarios (Kopp et al, 2014). CIAM finds that there is large potential for coastal adaptation to reduce the expected impacts of SLR compared to the alternative of no adaptation, lowering global net present costs by a factor of 10 to less than \$1.5 trillion over the next two centuries, although this does not include initial transition costs to overcome an under-adapted current state. In addition to producing aggregate estimates, CIAM results can also be interpreted at the local level, where we find that retreat (e.g., relocate inland) is often a more cost-effective adaptation strategy than protect (e.g., construct physical defenses).

Keywords: Adaptation, Coastal Impacts, Climate Change, Sea Level Rise, Storm Surge, Flooding

JEL Classification: C61, Q25, Q51, Q54

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Estimating Global Damages from Sea Level Rise with the Coastal Impact and Adaptation Model (CIAM)

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Abstract

The costs of coastal sector impacts from sea level rise (SLR) are an important component of the total projected economic damages of climate change, a major input to decision-making and design of climate policy. Moreover, the ultimate costs to coastal resources will depend strongly on adaptation, society's response to cope with the impacts. This paper presents a new model to assess coastal impacts from SLR, combining global scope with high spatial resolution to fill a gap between very detailed local studies and aggregate global estimates. The Coastal Impact and Adaptation Model (CIAM) determines the optimal strategy for adaptation at the local level, evaluating over 12,000 coastal segments, as described in the DIVA database (Vafeidis et al, 2006), based on their socioeconomic characteristics and the potential impacts of relative sea level rise and uncertain storm surge. An application of CIAM is then presented to demonstrate the model's ability to assess local impacts and direct costs, choose the least-cost adaptation, and estimate global net damages for several probabilistic SLR scenarios (Kopp et al, 2014). CIAM finds that there is large potential for coastal adaptation to reduce the expected impacts of SLR compared to the alternative of no adaptation, lowering global net present costs by a factor of 10 to less than \$1.5 trillion over the next two centuries, although this does not include initial transition costs to overcome an under-adapted current state. In addition to producing aggregate estimates, CIAM results can also be interpreted at the local level, where we find that retreat (e.g., relocate inland) is often a more cost-effective adaptation strategy than protect (e.g., construct physical defenses).

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1 Introduction

Coastal zones are one of several key impact sectors that are threatened by potential impacts to the earth system from climate change. Rising sea levels will affect tens of millions of people who live in low-lying coastal areas, as well as infrastructure and capital assets, vulnerable ecosystems, cultural heritage, major port cities, and island nations (IPCC, 2014; Melillo et al, 2014). The potential damages to coasts from sea level rise (SLR) and storm surge include accelerated erosion of beaches and cliffs, permanent inundation of low-lying zones, increased flooding, saltwater intrusion into aquifers and surface water resources, and degradation of coastal wetlands that are rich in habitat and biological diversity and provide important services such as flood protection (Dasgupta et al, 2007; Nicholls et al, 2007; Nicholls, 2011; Hinkel et al, 2013b).

The ultimate economic cost of climate change on coastal resources will depend closely on adaptation to cope with the impacts of SLR. Coastal adaptation serves to reduce vulnerability through various strategies that are broadly characterized as protect, accommodate, and retreat (Dronkers et al, 1990; Nicholls, 2011).¹ Protection prevents inundation of low-lying, high economic value areas through physical armoring measures like seawalls, dikes, and bulkheads. Accommodation allows rising waters to encroach, but minimizes damages by flood-proofing or raising structures. Retreat moves humans and capital assets out of harm's way. Regardless of the adaptation strategy pursued, certain regions are likely to suffer disproportionately from SLR, such as small island nations and delta areas like Bangladesh, which have particularly vulnerable populations.

Adaptation decisions must consider the long-term nature of the threat as well as the potential for extreme events. Regarding the former, global mean thermosteric SLR will unfold gradually over several centuries due to thermal inertia in oceanic processes such as mixing and circulation (Church and Clark, 2013).² Global mean SLR is also driven by loss of land ice from glaciers as well as the polar ice sheets of Greenland and Antarctica, which store approximately 65m of SLR combined; despite incomplete understanding of the links between atmospheric and ocean warming and the rate of loss, the time frame for ice sheet disintegration is believed to be on the order of multiple centuries to millennia (National Research Council, 2013; Applegate et al, 2014). While this is fast on a geological timescale, the incremental signal of global SLR is manageable for human response, offering time to prepare.

In contrast to gradual rise, storm surge extremes will continue to happen without warning

¹Nicholls (2011) further differentiates three modes of adaptation: autonomous, which occurs automatically with negligible net cost (e.g., property appreciation or wetland migration); reactive, which responds to realized impacts (e.g., relocation or beach nourishment); and anticipatory, which occurs with foresight (e.g., seawall construction or storm sewer upgrades).

²The very same inertia that moderates the rate of SLR also ensures that SLR will not be easily reversed even with aggressive greenhouse gas mitigation, a feature known as *commitment* to SLR (Meehl et al, 2007). The limited efficacy of mitigation to avoid coastal impacts means that adaptation planning will be an essential part of society's response to SLR.

and cause local flooding. SLR has an additive effect on the current frequency of extreme water heights, shifting the probability distribution by the amount of rise, which will shorten return periods and expand current floodplain boundaries (Tebaldi et al, 2012).³ Finally, relative SLR includes local change in the sea surface height relative to the land, due to factors such as daily tides, seasonal weather patterns, mass redistribution effects, subsidence, isostasy, and tectonics (Church and White, 2011; Kopp et al, 2014). Effective coastal adaptation planning is an exercise in managing all of these risks: global incremental rise, storm surge extremes (and potential nonstationarity), and other local change.

1.1 Literature on global coastal impact estimates

Because coastal zones are some of the most densely populated and economically productive in the world, the threat of rising seas from climate change has been studied for several decades. Most coastal impact studies fit into two categories: (1) aggregate global exposure surveys that quantify the land, people, and capital at risk of inundation, often ignoring adaptation or applying generalized rules that overlook its local determinants; and (2) high-resolution local studies that evaluate targeted adaptation projects, which are critical for local planning but are site-specific so cannot be extrapolated or applied more broadly to inform global estimates of coastal impacts.

Before presenting the current model, designed to bridge the gap between these two extremes, we first review prominent global direct cost estimates of coastal impacts along key dimensions (summarized in Figure 1) and then describe how these studies relate to the present work.

Dimensions	increasing complexity or coverage						Present study			
Scope	local	→	national	→	regional	→	global	global		
Resolution	region	→	nation	→	county	→	city	→	property	segment*
Temporal	static					→			dynamic	dynamic
<u>Other factors:</u>										
Adaptation	none (exposure)	→	fixed rule	→	cost-benefit rule	→	optimal			optimal
SLR impact	global mean SLR					→			local SLR	local SLR
Flood impact	none	→			average surge	→			surge PDF	surge PDF

Figure 1: Characteristics of coastal impact studies for key dimensions or factors, increasing in complexity from left to right. Most aggregate global studies have limited complexity in dimensions other than scope. The present study seeks to improve coverage along many dimensions, as described in the far right column of the diagram. *segment refers to a variable spatial unit between county and property, depending on the extent of roughly homogenous divisions.

³It is not fully understood whether the tail of the surge distribution will be further influenced by climate change (Grinsted et al, 2013) or other factors such as SLR, bathymetry, water depth, or wetland effects (Menéndez and Woodworth, 2010; Cayan et al, 2008; Smith et al, 2010).

The first rigorous assessment of SLR was a static vulnerability study of the continental US that quantified the land, population, income, and capital that would be exposed for 4.6 m and 7.6 m SLR scenario (Schneider and Chen, 1980). Such vulnerability assessments have been updated over time with advances in the underlying geophysical and socioeconomic data (see Yohe, 1990; Hoozemans et al, 1993). The next generation of direct cost studies accounted for likely adaptation measures by using a ‘fixed rule’ (e.g., protect all coastal zones above a threshold population density) to estimate the total costs of protection measures, coastal retreat, and land inundation. A national study of the US estimated total cost would be between \$270 and \$475 billion (\$1985) for 1 m of SLR in 2100 (Titus et al, 1991), while a similar global assessment estimated \$488 billion to protect the world’s developed coastlines (Dronkers et al, 1990). A more sophisticated fixed rule approach accounts for societal risk attitudes by linking protection standards to income levels (Yohe and Tol, 2002); this has been applied to estimate population exposure by Nicholls (2004) and protection costs by Hinkel et al (2014). The main limitation of the fixed rule approach is that it neglects optimal adaptation decisions based on the relative cost of protection versus retreat.

Work by Fankhauser (1995) and Yohe et al (1995) delivered the next advance in coastal impact estimates, formulating cost-benefit models to determine the economically optimal level of protection based on the relative cost of protection and retreat, building off earlier work by van Danzig (1956). Fankhauser’s global study of 1 m SLR in 2100 estimated direct costs to developed countries of \$932 billion, including protection-induced wetland loss. He also derived a reduced-form equation to approximate the optimal fraction of protection for a given coastline based on the present value cost ratio of protection to inundation.⁴ While such cost-benefit rules are more credible than fixed rules, one limitation of the approach is that by simplifying the optimal result to a closed-form equation it cannot interact dynamically with changing climate impacts, and the approximation is often further exacerbated by the low spatial resolution and limited temporal structure common to many global and regional analyses.

Progress in some of these other dimensions was afforded by the Dynamic Interactive Vulnerability Assessment (DIVA), which uses geospatial analysis to divide world’s coastlines into 12,148 distinct coastal segments of similar physical characteristics (Vafeidis and Nicholls, 2008).⁵ Several regional and global studies of coastal impacts have been published with DIVA (see Hinkel et al, 2012, 2013a,b, 2014); these studies account for additional damage factors related to local SLR, storm surge flooding, and wetlands, but stop short of assessing optimal adaptation. The most

⁴Fankhauser’s reduced-form cost-benefit rule has been formalized in the FUND model (Tol, 1996), which has been used for numerous analyses of the economic impacts of SLR (see Darwin and Tol, 2001; Nicholls and Tol, 2006; Bosello et al, 2007; Nicholls et al, 2008; Tol, 2007; Anthoff et al, 2010). Similarly, Yohe’s result has been integrated in the Global Impact Model (Mendelsohn et al, 2000).

⁵Prior to DIVA, the original coastal dataset with global scope was the Global Vulnerability Analysis (GVA), consisting of 192 coastal segments, roughly one per country (Hoozemans et al., 1993). Despite the pioneering effort involved with developing the GVA, country-level resolution is not sufficient to inform adaptation decisions that are inherently local. Advances in computing technology and remote sensing have enabled more detailed and accurate coastal datasets.

recent global study with DIVA applies fixed rule adaptation strategies to a range of socioeconomic scenarios, digital elevation models, and SLR projections to estimate that annual costs in 2100 will range between \$12-71 billion for coastal protection, with flood costs between \$11-95 billion (Hinkel et al, 2014).

Sugiyama et al (2008) take advantage of the increased spatial resolution of DIVA to reprise the Fankhauser (1995) reduced-form approach. They derive a new analytical model of optimal coastal adaptation, adding capital stock as a measure of value, adjusting the vertical distribution of population, and allowing for nonlinear SLR scenarios.⁶ This analytical work yields a more detailed and credible reduced-form cost-benefit rule that is then applied at the high spatial resolution of DIVA’s coastal segments. However, the study omits the dimensions of local SLR and flood damage from storm surge, and does not produce global cost estimates.

A final dimension in the coastal impact literature is the distinction between direct cost estimates and welfare effects of SLR across various sectors of the economy (e.g., agriculture, energy, land). Early studies by Darwin and Tol (2001) and Deke et al (2001) used computable general equilibrium (CGE) models (FARM and DART, respectively) in order to estimate the economy-wide effects of coastal impacts and adaptation. More recent work by Bosello et al (2007, 2012) confirms the importance of CGE approach and finds that direct costs may underestimate the actual welfare loss to society.

1.2 Present work

This paper presents a new model for coastal impact studies that reconciles the need for global scope combined with high spatial resolution, the Coastal Impact and Adaptation Model (CIAM). CIAM improves upon previous global direct cost estimates by determining the least-cost adaptation strategy of over 12,000 coastal segments in the DIVA database. In addition to being the first coastal assessment that specifically optimizes the adaptation strategy for the local segment, it includes several key damage factors including relative SLR, wetland losses, and uncertain storm surge damages that have not been fully accounted for in prior studies.

CIAM provides new estimates of the direct economic costs of SLR that can be flexibly aggregated at the city, country, regional, and global level. The motivation for this global assessment is to understand the magnitude and sensitivity of potential coastal impacts, which therefore informs the stringency of the global mitigation effort. The remainder of the paper is organized as follows. Section 2 summarizes the model formulation. Section 3 introduces a set of SLR scenarios and presents the results of applying CIAM to evaluate adaptation and estimate costs, both at the global and local level. Section 4 summarizes these findings and provides a general discussion of the

⁶Capital stock and other socioeconomic parameters are drawn from the Yale G-Econ geospatial gridded economic characteristics (Nordhaus, 2006).

work, its limitations, and recommendations for future research.

2 Coastal Impact and Adaptation Model (CIAM)

The Coastal Impact and Adaptation Model (CIAM) is a high spatial resolution optimization model with global scope that disaggregates the least-cost adaptation decision to the local level, evaluating over 12,000 distinct coastal segments. Each coastal segment has an independent planner who chooses a public adaptation strategy based on the local socioeconomic characteristics and the potential impacts of relative SLR and uncertain storm surge extremes.

Coastal adaptation in CIAM is pursued incrementally and modularly, and adaptation decisions are updated over time following an iterative process depicted in Figure 2. Despite significant uncertainty regarding long-term projections of global mean SLR,⁷ CIAM makes the simplifying assumption that the near-term extent (e.g., 40-year outlook) of SLR is known with perfect foresight for a given climate scenario.⁸

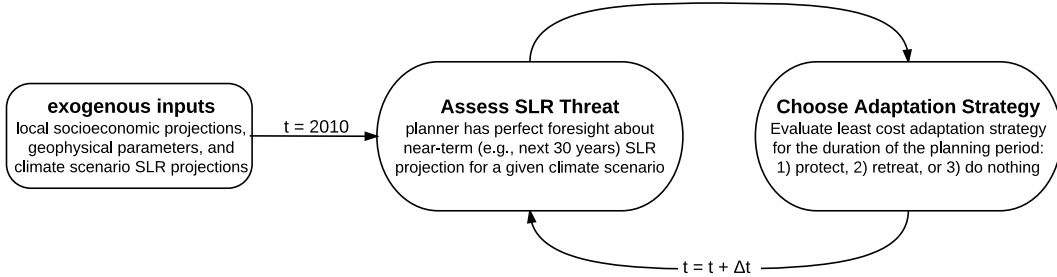


Figure 2: Iterative decision-making process in CIAM. The planner for a given segment is assumed to have perfect foresight about the near-term projection for relative SLR, and then chooses the least-cost adaptation strategy for that 40-year planning period. This process repeats over the model time horizon from 2010 to 2200.

For each coastal segment, the local planner evaluates the adaptation strategies for the cost minimization problem

$$\min_s \sum_{t \in \Delta t} \left(\frac{1}{(1+r)^t} (\text{ProtectionCost}_{s,t} + \text{RetreatCost}_{s,t} + \text{InundationCost}_{s,t} + \text{WetlandCost}_{s,t} + \mathbb{E}[\text{FloodCost}_{s,t}]) \right) \quad (1)$$

⁷For example, the latest Intergovernmental Panel on Climate Change report gives a likely rise in 2100 that ranges from 0.28-0.98 m (Church and Clark, 2013) while some semi-empirical estimates are as high as 1.9 m (Vermeer and Rahmstorf, 2009)

⁸The relatively smooth, incremental rise due to oceanic inertia and lags allows this simplified construction of SLR ‘learning’, whereas other climate changes are likely to be more difficult to detect (e.g., thermohaline circulation as in Keller et al (2008)).

where Δt is the decision-making planning period of annual time-steps t , r is the discount rate of 4%, and s is the adaptation strategy (i.e., protect, retreat, or do nothing and the extent, since extra adaptation can be pursued to minimize the expected cost of flood impacts).⁹ The objective of each coastal segment, as expressed in Equation 1, is to minimize the sum of adaptation costs (either protection or retreat) plus residual damages due to land inundation, wetland loss, and expected flood costs.¹⁰

These strategies can be summarized diagrammatically. Figure 3a shows the counterfactual baseline case of no SLR, against which all climate scenarios will be compared. Figures 3b-d shows the cases corresponding to the three adaptation strategies: no adaptation, retreat, and protect. In the application presented in Section 3, CIAM will evaluate these adaptation strategies for several exogenous SLR scenarios.

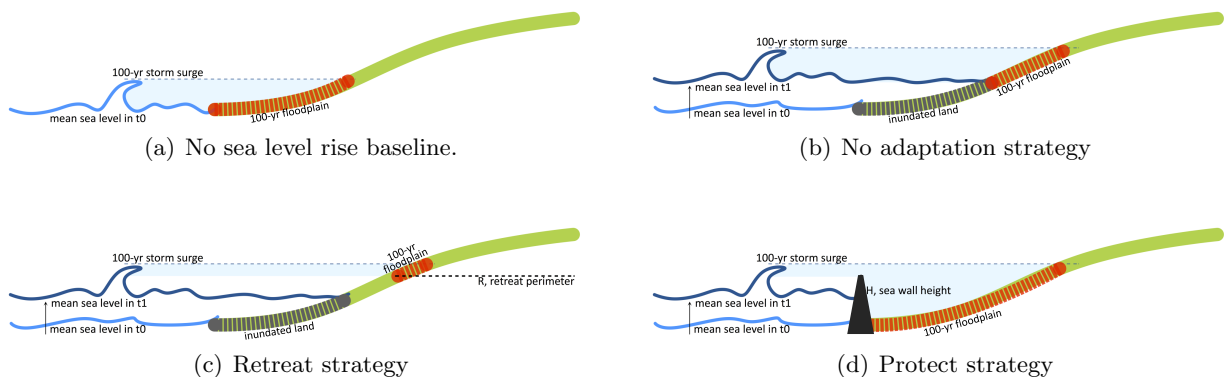


Figure 3: Diagrams of adaptation strategies. (a) No sea level rise. Baseline floodplain for an illustrative 100-year surge height is marked by the red hatched line; there may be some initial level of floodplain adaptation prior to SLR. (b) No adaptation. SLR causes incremental loss of inundated coastal land marked by the gray hatched line and incurs the cost of reactive retreat. The new 100-year floodplain is marked by the red hatched line, exposing more or less area than the baseline depending on the coastal topography. This may be the least-cost strategy in some undeveloped areas. (c) Retreat. SLR causes the loss of inundated coastal land and planned relocation costs are incurred for everything below the retreat perimeter R . Storm damages in the exposed floodplain is limited to surge cases that penetrate the retreat perimeter (e.g., surge $s \geq R$). (d) Protect. Land is protected from SLR damages by the sea wall with height H . In addition to protection costs, surge cases that overtop the sea wall (e.g., surge $s \geq H$) incur an expected flood cost. For simplicity, the impact of SLR to wetlands and associated loss is not depicted in the diagram.

⁹The decision-making planning period (Δt) is assumed to be 40 years. This interval helps avoid premature or unnecessary adaptation investments (Hallegatte, 2009; Felgenhauer and Webster, 2013); however, we conduct a sensitivity analysis of 100 years to investigate the case that major coastal defense structures may be planned for a much longer duration.

¹⁰CIAM models public adaptation and assumes the entire coastal segment acts in unison (as if it was enforced by policy), rather than account for heterogeneity in adaptation strategy (e.g., sorting behavior). Furthermore, the decision of one segment is assumed to have no bearing on neighboring segments.

2.1 CIAM parameters

Here we describe the geophysical and socioeconomic parameters that determine the potential magnitude of coastal impacts and adaptation costs. The unit of analysis in CIAM is the individual coastal segment, as described by the DIVA database, which divides the world’s coasts into 12,148 distinct segments of similar physical characteristics, with a median length of 18 km.¹¹ The DIVA parameters that are used in CIAM are the inundation zone areas, coastline length, storm surge frequencies, exposed wetlands, and initial population density for each segment. With the exception of initial population density, the DIVA database does not provide the socioeconomic characteristics that are needed to evaluate adaptation costs and residual damages in CIAM. We integrate a variety of additional data sources described below.¹²

Inundation zones CIAM computes inundation area as the piece-wise linear interpolation between 1 m increments of vertical elevation. DIVA provides land surface area based on the Global Land One-kilometer Base Elevation (GLOBE) gridded Digital Elevation Model.

Storm surge extremes DIVA reports the 1, 10, 100, and 1000-year and maximum surge height, calculated from tidal level data, barometric pressure, wind speeds, and sea bed slopes. CIAM assumes a generalized extreme value (GEV) distribution to represent uncertain surge events (as in Lempert et al, 2012) and calibrates a probability density function to the current frequency. The present study assumes stationarity in the distribution of sea level extremes (i.e., the current surge distribution persists despite climate change), such that the effect of SLR is linear and additive.¹³

Coastal wetlands DIVA reports total wetland area within a coastal segment, given by the combined extent of wetlands, based on a global survey of 4,315 wetland sites (Hoozemans, 1993), and mangroves, based on the World Mangrove Atlas (Spalding, 1997).

Relative sea level rise The background rate of relative, or local, SLR is based on Kopp et al (2014), which includes oceanographic effects and static-equilibrium effects of land ice mass loss in addition to uplift and subsidence.

¹¹Descriptions of the database and the integrated model can be found in Hinkel and Klein (2009); Vafeidis and Nicholls (2008). The CIAM framework presented here has been independently developed based on the publicly-released DIVA database v1.5.5 (DINAS-COAST Consortium, 2006).

¹²Segments are assumed to be uniform in density of socioeconomic characteristics.

¹³In contrast to this simplification, Grinsted et al (2013) present a nonstationary distribution and estimate how the frequency of extreme surges could change with warming. This topic remains for future CIAM studies.

Population, income, and capital CIAM projects socioeconomic growth over time. National population growth rate projections to 2100 are based on the United Nations World Population Prospects (2012), with linear growth thereafter, and applied to the segment-level initial population density as reported in DIVA. National income levels are based on Penn World Table (2011) with IMF World Economic Outlook (2011) projections to 2100, with exponential growth of 1% per year thereafter.¹⁴ Local capital stocks are estimated using a capital-output ratio of 3 to overcome the lack of geospatial data on capital, reflecting the fact that capital stocks will grow over time based on the potential investment available.¹⁵

Land values The value of the coastal land endowment lost to inundation corresponds to the value of interior land, as argued in Yohe (1989). Interior national land value is derived from average rents for agricultural land from Global Trade Analysis Project (GTAP) (Baldos and Hertel, 2012).¹⁶ Land values are assumed to appreciate over time, depending on demand and willingness to pay, following Yohe et al (1999). Wetland value is based on annual willingness to pay for ecosystem services, increasing in income and population density per the wetland service valuation meta-analysis of Brander et al (2006).

2.2 CIAM cost functions

Adaptation cost: Protection Protection construction costs are assumed to be linear in coast-line length and quadratic in sea wall height, the latter reflecting the fact that higher protection requires proportionally more structural foundation:

$$\text{ConstructionCost}_t = l \cdot pc \cdot (H_t^2 + mcH_t) \quad (2)$$

where pc is the country-specific protection construction cost after endogenous technological change and mc is the annual maintenance cost based on the size of the defense.

In addition to the cost of constructing the protection, there is an opportunity cost to the land occupied by the dike given by the land value lv . CIAM assumes a 60° slope on each side of the dike, which implies that the dike width is 1.7 times the height. Thus, the total costs of protection are

$$\text{ProtectionCost}_t = \text{ConstructionCost}_t + l \cdot lv \cdot 1.7H_t \quad (3)$$

¹⁴The current analysis does not consider alternative socioeconomic projections, although Hinkel et al (2014) have shown such drivers can have a bearing on coastal impacts over time.

¹⁵Although capital formation and production functions may change in a warming world, and these shifts would have significant implications for impact assessments, this is beyond the scope of this analysis.

¹⁶The GTAP database includes 129 regions, which map to most of the coastal countries in CIAM on a one-to-one basis.

CIAM makes the simplifying assumption that all protection is constructed to be 100% reliable. In addition to omitting potential damages resulting from this residual vulnerability, protection may have negative externalities such as inhibiting public shore access and increased erosion (Kriesel and Friedman, 2003; Nicholls, 2011); these costs are not accounted for in the current model.

Adaptation cost: Retreat There are two costs incurred with the decision to retreat incrementally to a perimeter R_t from R_{t-1} . One is the damage cost from inundation, the permanent loss of land and immobile capital; these costs will be discussed in the next heading. The other is the adaptation cost associated with redeveloping and relocating the affected people and infrastructure further inland. These costs are based on observed domestic migration costs. The adaptation cost of retreat is a function of the affected mobile capital K and population L :

$$\text{RetreatCost}_t = \theta_L^{\text{retreat}} L(\text{area}(R_t - R_{t-1})) + \theta_K^{\text{retreat}} K(\text{area}(R_t - R_{t-1})) + dc \quad (4)$$

where $\theta_K^{\text{retreat}}$ and $\theta_L^{\text{retreat}}$ are the cost coefficients of retreat per unit of mobile capital and population, respectively, and the quantity of affected K and L depend on the density of each and the incremental area of retreat. Additionally, there is a demolition cost for immobile capital that must be abandoned. In the case of a do nothing strategy reactive retreat is assumed to be five times as costly due to the lack of advance planning.

CIAM treats each coastal segment as a single low-lying zone. When people or capital relocate, they do so to the outer extent of the development and are assumed to be out of harm's way with full productivity. Although a detailed treatment of capital is essential to any local assessment of coastal impacts, the requisite geospatial capital stock data are not available on a global basis. Thus, capital dynamics are beyond the scope of this model.

Damage cost: Inundation Unprotected land will be incrementally inundated by rising seas. These damage costs are based on the extent of land endowment lost and national land values. Moreover, immobile capital (e.g., infrastructure and transportation networks, assumed to be 75% of the total capital stock) will be abandoned upon inundation. Sufficient foresight about inundation can avoid real capital losses, so these damages depend on the type of adaptation. If retreat is planned in advance, true economic depreciation is the efficient market response: affected fixed capital assets will be fully depreciated by the time of retreat (see Yohe et al, 1995). Accordingly, CIAM assumes that with advance notice of SLR and the decision to make a planned retreat, coastal structures will be depreciated over the IRS structure lifetime of 30 years such that at the point that land is lost, the capital has no value. In contrast, the No Adaptation strategy assumes no advance notice of SLR, so the entire asset value is lost in a reactive retreat.

Damage costs from inundation are incurred when SLR exceeds the height of protection H :

$$\text{InundationCost}_t = lv_t \cdot \text{area}(\cdot) + (1 - \delta) K(\text{area}(\cdot)) \quad (5)$$

$$\text{where } \text{area}(\cdot) = \begin{cases} \text{area}(slr_t) - \text{area}(slr_{t-1}) & \text{if } H_t < slr_t \text{ and } H_{t-1} < slr_{t-1} \\ \text{area}(slr_t) - \text{area}(R_{t-1}) & \text{if } H_t < slr_t \text{ and } H_{t-1} \geq slr_{t-1} \\ 0 & \text{if } H_t \geq slr_t \end{cases}$$

and where lv is the interior land value, K is the affected capital stock, and δ can be 1 or 0, denoting full or no advance depreciation, respectively.

Damage cost: Wetland loss CIAM assumes that wetlands have the ability to migrate naturally inland on unprotected land. However, the potential for vertical wetland accretion is limited by the rate of SLR, and wetlands cannot tolerate a rate above 10 mm per year (Kirwan and Guntenspergen, 2010). Moreover, while a coastal segment pursues a protection strategy wetland services are lost due to coastal squeeze (McFadden et al, 2007). Annual wetland costs are given

$$\text{WetlandCost}_t = \begin{cases} wv_t \cdot \text{area}(\cdot) \left(\frac{\frac{dSLR}{dt}}{0.01} \right)^5 & \text{if Retreat or No Adaptation and } \frac{dSLR}{dt} < 0.01 \\ wv_t \cdot \text{area}(\cdot) & \text{if Protect or } \frac{dSLR}{dt} \geq 0.01 \end{cases} \quad (6)$$

$$\text{where } \text{area}(\cdot) = \min \{ \text{area}(slr_t), \text{wetland extent} \}$$

and where wv_t is the annual value of wetland services and $\frac{dSLR}{dt}$ is the rate of SLR in m per year.

Damage cost: Flooding The expected damage of coastal floods can be thought of as the actuarially fair cost of insurance. Recall from the parameter descriptions that uncertain storm surge heights are represented as a random variable s . The expected cost of flooding is computed as the integral over all storm surge heights s that exceed the current adaptation level, multiplying the probability $f(s)$ of a given surge height (given earlier in Equation ??), times the resulting damage:

$$\mathbb{E}[\text{FloodCost}] = \int_A^{s_{max}} f(s) \text{Damage}(s) ds \quad (7)$$

Flood damage for surge height s is given

$$\text{Damage}(s) = \text{Exposure}(s) \cdot (\sigma_K + VSS\sigma_L) \cdot \phi(s, slr) \cdot \rho(\text{ypc}) \quad (8)$$

where $\text{Exposure}(s)$ is a measure of the total area flooded (see Equation 9), and is multiplied by the population σ_L and capital density σ_K to determine the number of exposed people and amount of capital affected. The flood depth-damage function $\phi(s, slr)$ is a logistic function increasing in

both surge height and current SLR, to reflect the power of the flood, and follows from Hinkel et al (2014). The resilience term ρ is decreasing in national per capita income ypc , to reflect resilience from safety measures and building codes.

The total area exposed to a given surge height exceeding the current level of adaptation and depends on the type of adaptation chosen: a protect strategy floods the entire area trapped behind the sea wall, while a retreat strategy exposes much less settled land to the surge.

$$\text{Exposure}(s) = \begin{cases} \text{area}(s + slr_t) & \text{if Protect} \\ \text{area}(s + slr_t - R_t) & \text{if Retreat} \\ \text{area}(s) & \text{if No Adaptation} \end{cases} \quad (9)$$

Not included in the model Coastal impacts in CIAM do not include all known damages from SLR. Some of these omitted impacts include the cost of migration, erosion, salt water intrusion on water resources, and interactions with coastal agricultural production. The treatment of uncertain extreme surge and the resulting damages could benefit from exploring different attitudes towards risk, as well sensitivity analysis around the increasing likelihood of coastal floods due to climate change.

3 Current study

While the development of CIAM is the core contribution of this work, the remainder of this paper presents an application of the CIAM framework to evaluate the adaptive response to a set of climate scenarios and estimate the coastal impacts. This demonstration is directly based on the publicly-available probabilistic global mean SLR projections published in Kopp et al (2014), which are used as an exogenous input to CIAM.¹⁷ The three specific scenarios evaluated by CIAM are shown in Table 1, referred to here as SLR2.6, SLR4.5, and SLR8.5, which respectively correspond to representative concentration pathway (RCP) 2.6, 4.5, and 8.5, the standardized climate scenarios for the Coupled Model Intercomparison Project Phase 5 (Meinshausen et al, 2011).¹⁸

¹⁷These projections are specified as SLR since 2000, which does not include the 0.15 m of SLR since 1900 (Church and Clark, 2013). Because CIAM assesses coastal impacts relative to a baseline from 2000-2200, the extent to which floodplains have expanded due to SLR prior to 2000 and that the initial state is therefore under-adapted is not captured.

¹⁸It is worth noting that although the RCPs may imply different (though unspecified) socioeconomic pathways, this study does not adjust the socioeconomic pathways, instead evaluating each scenario with the socioeconomic assumptions described in the previous section.

Table 1: Projections of global mean SLR since 2000 in m by climate scenario, showing the median and 5-95th percentile range as determined in Kopp et al (2014). Table adapted from Kopp et al (2014).

(m of SLR)	SLR2.6		SLR4.5		SLR8.5	
	median	5-95th	median	5-95th	median	5-95th
2050	0.25	0.18-0.33	0.26	0.18-0.35	0.29	0.21-0.38
2100	0.50	0.29-0.82	0.59	0.36-0.93	0.79	0.52-1.21
2150	0.73	0.34-1.50	0.93	0.42-1.73	1.34	0.78-2.31
2200	0.97	0.28-2.38	1.27	0.40-2.72	1.96	0.99-3.73

Kopp et al (2014) develop full probability distributions for each RCP using 10,000 Latin hypercube samples from time-dependent probability distributions of cumulative contributions from thermal expansion, glaciers, ice sheets, and land water storage based on process model projections and expert assessments. All three scenarios project similar amounts of SLR to 2050, at which point the highest climate change scenario (SLR8.5) begins to deviate more sharply.

The remainder of this section presents findings from CIAM, first in terms of global aggregate cost estimates and then country-level impacts. Next, local adaptation choices are geographically with maps. Finally, we demonstrate the robustness of CIAM results with a sensitivity analysis to bound the worst case scenario.

3.1 CIAM results: global cost estimates

Figure 4 depicts the estimated global costs in terms of annual expenditures over time. For each scenario we evaluate two policies for comparison. No Adaptation is a benchmark policy that assumes that all coastal segments follow a strategy of no adaptation, in which the planner does nothing until forced by nature: inundated land and capital stocks are permanently lost, and populations must migrate inland without advance planning. The Least-Cost policy allows each coastal segment to select the single least-cost adaptation strategy of protect or retreat and the extent over the time horizon.

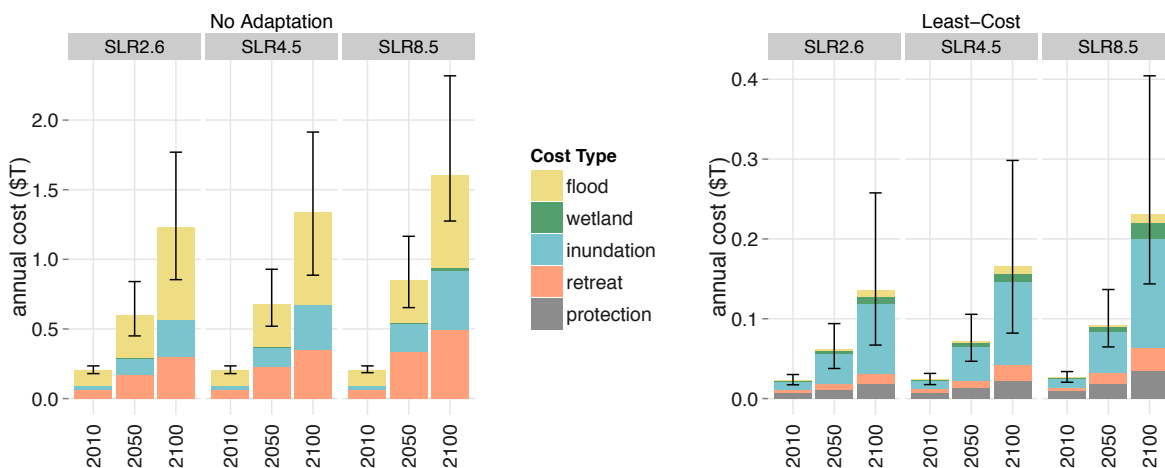


Figure 4: Annual damage and adaptation costs for years 2010, 2050, and 2100 under the No Adaptation (left) and the Least-Cost policies (right, note y-axis scale change) for the three RCP scenarios (column). Error bars show the 5th-95th percentile range for global SLR scenario.

The left panel of Figure 4 shows the breakdown of costs incurred by the No Adaptation policy. Retreat, at the bottom of each stacked bar, takes the form of reactive adaptation, having not been planned in advance. Next, inundation costs include the loss of undepreciated capital assets as well as lost land rents as sea levels rise. The expected value of flood damage, shown at the top, increases over time as SLR adds to storm surge extremes, expanding current floodplain boundaries. Finally, in response to the faster pace of SLR in the SLR8.5 scenario there is also modest loss of wetland services (though this could be offset by wetland expansion that is not modeled in CIAM).

The Least-Cost policy (right panel) result shows that a targeted investment in adaptation, whether planned retreat or protection measures, delivers a significant reduction in the realized impacts of SLR. Across all scenarios, annual costs are roughly an order of magnitude lower than for No Adaptation, reflecting a substantial role for adaptation to reduce potential impacts in the coastal sector. Within each policy, net costs consistently increase with the SLR scenario, following the intuition that higher SLR leads to higher global costs. However, Figure 4 shows that the adaptation policy has a much stronger effect on the overall magnitude of cost to society. This

suggests that how adaptation occurs is a more important factor than the extent of the SLR threat.

3.2 CIAM results: national costs

Although these annual net damages exceed several hundred billion dollars, it is worth noting that these annual costs comprise a small fraction of global GDP. For example, \$1 trillion is 0.67% of the \$147.6 trillion global GDP projection. Moreover, on a per-country basis the median cost of adaptation in 2050 is estimated to be 0.066% of national GDP, although certain countries will be impacted disproportionately – the three countries found to face the largest burden are the Marshall Islands, Dominica, and the Maldives. Table 2 below shows the ten most impacted countries, ranked by annual cost in 2050 as a percentage of national GDP and by net present value (NPV) of impacts from 2010 to 2200.

Table 2: National adaptation cost estimates for the ten most impacted countries by annual percentage of national GDP (left) and total NPV (right).

ranked by percentage country	% GDP	NPV (\$B)	ranked by NPV country	NPV (\$B)	% GDP
Marshall Islands	6.5%	\$1.2	United States	\$425	0.08%
Dominica	6.4%	\$1.4	Australia	\$107	0.30%
Maldives	4.7%	\$7.4	China	\$100	0.03%
Tuvalu	4.2%	\$0.2	Brazil	\$88	0.12%
Tonga	3.4%	\$1.0	Indonesia	\$58	0.20%
Kiribati	2.7%	\$0.4	Japan	\$50	0.04%
Antigua and Barbuda	2.7%	\$1.5	United Kingdom	\$47	0.05%
Netherlands Antilles	2.0%	\$3.3	India	\$45	0.03%
French Polynesia	1.9%	\$11.0	Germany	\$39	0.04%
Palau	1.8%	\$0.3	Mexico	\$37	0.08%
median country	0.066%		median country	\$0.95	

3.3 CIAM results: local coastal adaptation maps

The global cost estimates shown in Figure 4 are aggregated over 12,148 distinct coastline segments, each of which followed an adaptation strategy determined by local characteristics. This key dimension of spatial resolution is seen in Figure 5 with maps showing the adaptation strategy selected by CIAM for each coastal segment in 2050.

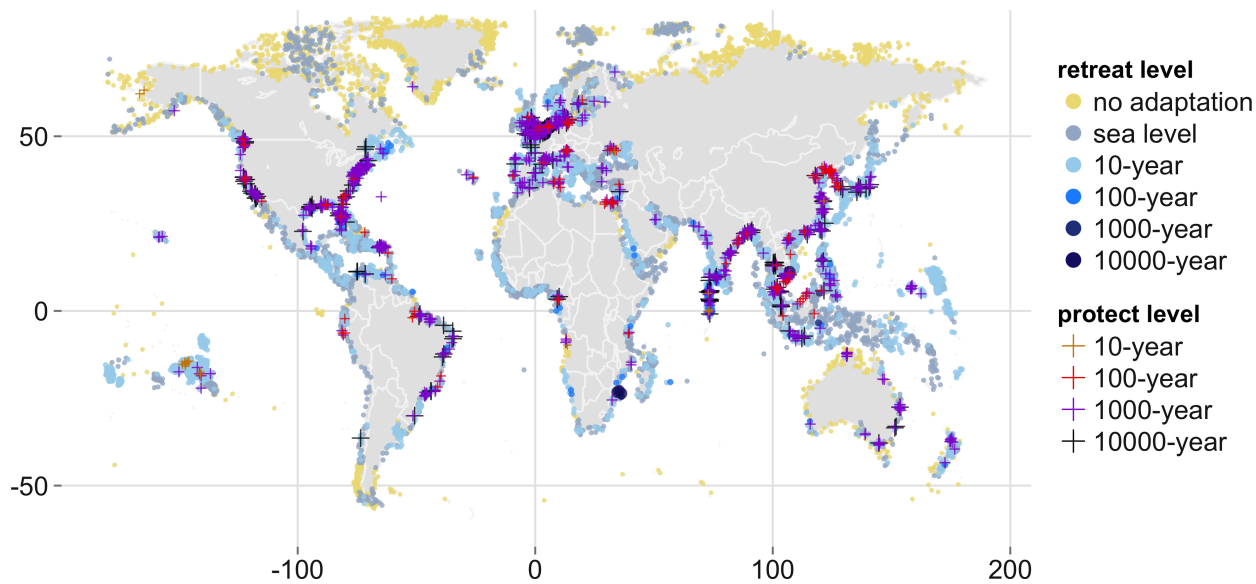


Figure 5: Map of optimal adaptation strategy decisions at the local segment for the SLR8.5 scenario in 2050. Yellow dots indicate no adaptation, blue dots indicate retreat, crosses indicate protect, and darker colors indicate higher adaptation levels.

This figure illustrates that retreat is cost-effective for the majority of the world’s coastlines, while protection is pursued selectively in areas that are very dense in people and capital and have large areas exposed to both inundation and flooding. For both protect and retreat it is often optimal for coastal segments to pursue additional adaptation above what is required by rising seas to lessen the impact of uncertain flooding on an annual basis. These geographical results highlight a defining feature of CIAM, the fact that adaptation decisions and costs are evaluated at the local level, where it will ultimately take place.

3.4 CIAM results: sensitivity analysis

To demonstrate that these results are robust to a wide range of assumptions, we perform one-at-a-time sensitivity analysis on the discount rate, the length of the adaptation planning horizon, the efficient capital depreciation assumption, and cost parameters for protection and land value. Figure 6 depicts the sensitivity of the NPV of global coastal costs under the high climate scenario

SLR8.5 to these alternative assumptions.

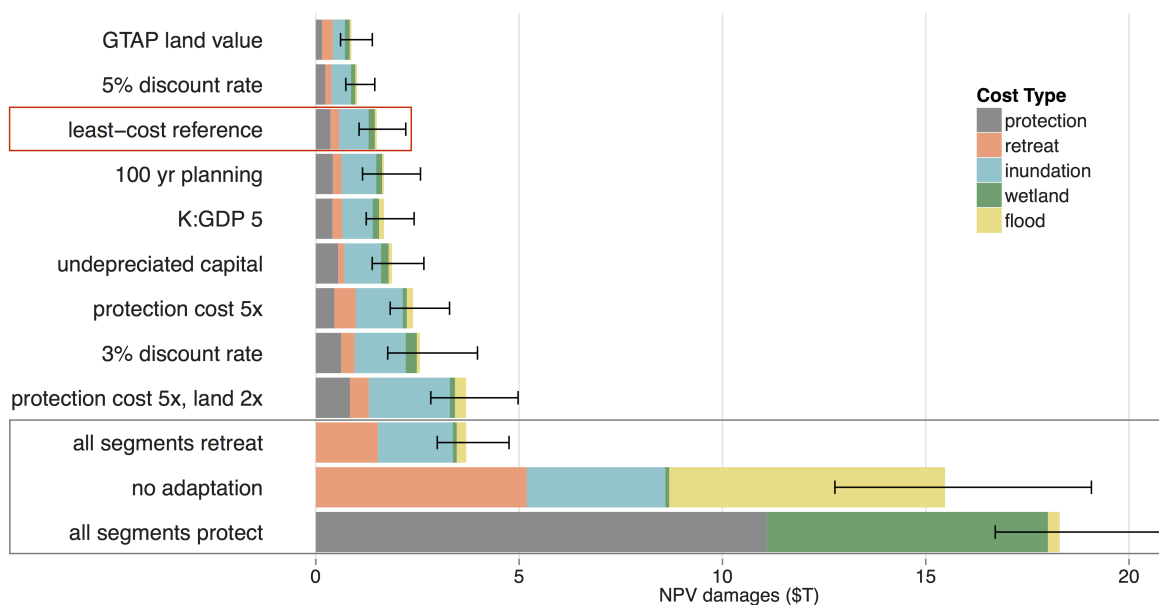


Figure 6: NPV of damage and adaptation costs for sensitivity cases, ordered from lowest to highest. Error bars show the 5th-95th percentile range for global SLR scenario.

The upper portion of the figure illustrates the fact that these sensitivity cases bound the net present costs by a factor of 2 relative to the Least-Cost reference case. This result is helpful in establishing an upper bound on coastal impact estimates. The lower portion of the figure compares the Least-Cost policy results with suboptimal adaptation policy extremes, in which all segments are forced to Retreat, to do No Adaptation, or to Protect. These three policy extremes have a much stronger influence on aggregate cost than the sensitivity cases. This result reinforces the earlier conclusion that adaptation strategy is a key factor underlying coastal impact estimates, and therefore efforts to advance the representation of adaptation trade-offs will serve to improve the credibility of coastal impact assessments.

4 Discussion

4.1 Summary and policy implications

These CIAM results build on previous coastal impact assessments, incorporating improvements in multiple dimensions (Figure 1) with a bottom-up approach afforded by the highly-resolved DIVA database. By disaggregating the optimal adaptation decision to the segment level, the model can evaluate the relative cost-effectiveness of adaptation strategies based on key, intrinsically local de-

terminants such as coastal geography, population and income density, and land value. Additionally, CIAM accounts for the impacts of storm surge, wetland loss, and relative SLR, three factors which have been omitted in previous estimates.

The CIAM application presented in this paper illustrates the large potential for coastal adaptation to reduce the worst expected impacts of SLR on coastal resources, reducing global net present costs substantially by a factor of 10 to less than \$1.5 trillion over the next two centuries. Study results (Figures 4 and 6) show that the choice of adaptation is far more important than the ultimate magnitude of the SLR threat in determining the overall cost of coastal impacts. Moreover, the optimal adaptation strategies at the segment level tend to be insensitive to the SLR scenario. These findings support proactive coastal planning and also suggest that adaptation policy need not be entangled in climate discussions – mitigation and adaptation can proceed independently.

CIAM results can also be interpreted at the local level, with a qualitative conclusion that retreat is often a more cost-effective adaptation strategy than protect. This finding is particularly true for higher SLR scenarios: protection costs necessarily continue to increase as higher seawalls are required, while the relocation costs of retreat begin to slow with coastal slopes that tend to steepen inland. For lower SLR scenarios with slower rates of change, retreat is an effective strategy for avoiding wetland losses. Moreover, retreat has the added benefit of reducing flood exposure, which adds to the robustness of the policy choice. This general result suggests a shift from how coastal adaptation is generally conceived: “protect at all costs” may not be prudent for the majority of coastlines. This conclusion supports the need for thoughtful policies for coastal land management to limit development in anticipation of a planned retreat.

Although these CIAM results reflect the potential to minimize costs to society, there are institutional and informational reasons why suboptimal outcomes may ensue. Private agents acting in their own interest (e.g., unwilling to depreciate capital stock early, or lacking perfect information on expected SLR) may decide to protect their own coastline even when this policy is worse overall for society. There is already evidence that society is under-adapted, which suggests even current flood events are not well accounted for by private agents and federal insurance programs (Bakkensen, 2013). This research raises awareness about the role of adaptation, and how advance planning, governance, research, and education can affect the realized impacts of climate change.

4.2 Limitations and future work

While CIAM’s disaggregated approach helps to achieve greater coverage improving the credibility of aggregate damage estimates, there are also inherent limitations in performing optimization analysis over such an extensive scope, related to accounting for special cases. CIAM is designed for the general case, solving the same optimization problem over 12,148 segments, even though certain

areas are known to have distinct features that warrant special treatment. Small island nations and barrier islands are important cases that should be evaluated as a group, rather than independent segments, to determine whether local retreat is feasible given land availability or if migration to a mainland is required, which introduces additional costs and issues related to climate migration.¹⁹ In this way, CIAM is not designed to replace highly detailed site-specific studies of targeted adaptation scenarios, which will always be essential for public planning. However, those site-specific studies cannot be extrapolated or applied more broadly to inform global estimates of coastal impacts, which is the motivation behind CIAM. While CIAM will not get every segment exactly right, in aggregate it informs a more rigorous estimate of global impacts and constitutes an improvement over previous aggregate estimates.

Finally, there are a host of dimensions to explore in future work. To begin with, key issues that have been omitted from this analysis include the special treatment of vulnerable areas such as low-lying islands and ports. In addition, this type of disaggregated coastal impact model could be extended to account for localized impacts like erosion, salt water intrusion on water resources, coastal tourism and recreation, and interactions with agricultural production. The treatment of uncertain extreme surge and the resulting damages could benefit from exploring different attitudes towards risk, as well sensitivity analysis around the potential for nonstationarity in the storm surge distribution, should warming increase the likelihood of sea level extremes as in Grinsted et al (2013). Furthermore, CIAM considers storm surge in isolation, however natural disasters often combine flooding with wind damage (e.g., Superstorm Sandy in 2012). This work has begun to examine the potential for suboptimal outcomes, however there are deeper dimensions related to insurance markets and maladaptation that merit treatment. Lastly, future studies could extend the direct cost estimates presented here, integrating the high resolution of CIAM’s adaptation decisions with a CGE framework to determine the economy-wide welfare effects of sea level rise.

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¹⁹A less dramatic example is Miami, Florida, where CIAM finds that the most cost-effective adaptation strategy is to build protection because of the high population and income density and a very shallow coastal slope, while in reality the area’s porous limestone foundation makes most protection measures ineffective. The current version of CIAM has not adjusted parameters to handle such special cases in any way, but could in the future.

References

- Anthoff D, Nicholls RJ, Tol RSJ (2010) The economic impact of substantial sea-level rise. *Mitigation and Adaptation Strategies for Global Change* pp 321–335
- Applegate PJ, Parizek BR, Nicholas RE, Alley RB, Keller K (2014) Increasing temperature forcing reduces the Greenland Ice Sheets response time scale. *Climate Dynamics* 2100
- Bakkensen LA (2013) Adaptation and natural disasters: evidence from global tropical cyclone damages and fatalities. In: EAERE 2013 annual conference, Toulouse
- Baldos U, Hertel T (2012) Development of the GTAP Version 8 Land Use Data Base for Years 2004 and 2007
- Bosello F, Roson R, Tol RSJ (2007) Economy-wide Estimates of the Implications of Climate Change: Sea Level Rise. *Environmental and Resource Economics* 37(3):549–571
- Bosello F, Nicholls RJ, Richards J, Roson R, Tol RSJ (2012) Economic impacts of climate change in Europe: Sea-level rise. *Climatic Change* 112(1):63–81
- Brander LM, Florax RJGM, Vermaat JE (2006) The Empirics of Wetland Valuation: A Comprehensive Summary and a Meta-Analysis of the Literature. *Environmental & Resource Economics* 33(2):223–250
- Cayan DR, Bromirski PD, Hayhoe K, Tyree M, Dettinger MD, Flick RE (2008) Climate change projections of sea level extremes along the California coast. *Climatic Change* 87(S1):57–73
- Church JA, Clark PU (2013) Sea Level Change. In: Stocker, TF, D Qin, G-K Plattner, M Tignor, SK Allen, J Boschung, A Nauels, Y Xia VB, Midgley P (eds) *Climate Change 2013: The Physical Science Basis*, Cambridge University Press, chap 13
- Church JA, White NJ (2011) Sea-Level Rise from the Late 19th to the Early 21st Century. *Surveys in Geophysics* 32(4-5):585–602
- van Danzig D (1956) Economic Decision Problems for Flood Prevention. *Econometrica* 24(3):276–287
- Darwin R, Tol RSJ (2001) Estimates of the economic effects of sea level rise. *Environmental and Resource Economics* pp 113–129
- Dasgupta S, Laplante B, Meisner C, Wheeler D, Yan J (2007) The impact of sea level rise on developing countries: a comparative analysis, vol 4136. World Bank Publications
- Deke O, Hooss KG, Kasten C, Klepper G, Springer K (2001) Economic impact of climate change: Simulations with a regionalized climate-economy model. Tech. rep., Kiel Working Papers
- Dronkers J, Gilbert JTE, Butler LW, Carey JJ, Campbell J, James E, Mckenzie C, Misdorp R, Quin N, Ries KL, Schroder PC, Spradley JR, Titus JG, Vallianos L, Dadelszen JV (1990) Strategies for Adaption to Sea Level Rise. Tech. rep., Coastal Zone Management Subgroup, International Panel on Climate Change
- Fankhauser S (1995) Protection versus retreat: the economic costs of sea-level rise. *Environment and Planning A* 27(2):299–319
- Felgenhauer T, Webster M (2013) Multiple adaptation types with mitigation: A framework for policy analysis. *Global Environmental Change* 23(6):1556–1565

- Grinsted A, Moore JC, Jevrejeva S (2013) Projected Atlantic hurricane surge threat from rising temperatures. *Proceedings of the National Academy of Sciences of the United States of America* pp 1–5
- Hallegatte S (2009) Strategies to adapt to an uncertain climate change. *Global Environmental Change* 19(2):240–247
- Hinkel J, Klein R (2009) Integrating knowledge to assess coastal vulnerability to sea-level rise: The development of the DIVA tool. *Global Environmental Change* 19:384–395
- Hinkel J, Brown S, Exner L (2012) Sea-level rise impacts on Africa and the effects of mitigation and adaptation: an application of DIVA. *Regional Environmental Change* pp 207–224
- Hinkel J, Nicholls RJ, Tol RSJ, Wang ZB, Hamilton JM, Boot G, Vafeidis AT, McFadden L, Ganopolski A, Klein RJ (2013a) A global analysis of erosion of sandy beaches and sea-level rise: An application of DIVA. *Global and Planetary Change* 111:150–158
- Hinkel J, van Vuuren D, Nicholls RJ, Klein R (2013b) The effects of adaptation and mitigation on coastal flood impacts during the 21st century. An application of the DIVA and IMAGE models. *Climatic Change* pp 783–794
- Hinkel J, Lincke D, Vafeidis AT, Perrette M, Nicholls RJ, Tol RSJ, Marzeion B, Fettweis X, Ionescu C, Levermann A (2014) Coastal flood damage and adaptation costs under 21st century sea-level rise. *Proceedings of the National Academy of Sciences of the United States of America*
- Hoozemans F, Marchand M, Pennekamp H (1993) A global vulnerability analysis: vulnerability assessment for population, coastal wetlands and rice production on a global scale
- IPCC (2014) *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.* Cambridge University Press
- Keller K, McInerney D, Bradford DF (2008) Carbon dioxide sequestration: how much and when? *Climatic Change* 88(3-4):267–291
- Kirwan M, Guntenspergen G (2010) Limits on the adaptability of coastal marshes to rising sea level. *Geophysical Research ...* 37(September):1–5
- Kopp RE, Horton R, Little C, Mitrovica JX, Oppenheimer M, Rasmussen DJ, Strauss BH, Tebald, C (2014) Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. *Earth's Future* pp 383–406
- Kriesel W, Friedman R (2003) *Coping with Coastal Erosion: Evidence for Community-Wide Impacts.pdf*
- Lempert R, Sriver R, Keller K, RAND (2012) *Characterizing Uncertain Sea Level Rise Projections to Support Investment Decisions.* Tech. rep., California Energy Commission
- McFadden L, Spencer T, Nicholls RJ (2007) Broad-scale modelling of coastal wetlands: what is required? *Hydrobiologia* pp 5–15
- Meehl G, Stocker T, Collins W, Friedlingstein P, Gaye A, Gregory J, A Kitoh R, Knutti J, Murphy A, Noda S, Raper I, Watterson AW, Zhao ZC (2007) *Global Climate Projections.* In: Solomon, S, D Qin, M Manning, Z Chen, M Marquis, KB Averyt MT, Miller H (eds) *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change,* Cambridge University Press

- Meinshausen M, Smith SJ, Calvin K, Daniel JS, Kainuma MLT, Lamarque JF, Matsumoto K, Montzka SA, Raper SCB, Riahi K, Others (2011) The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. *Climatic Change* 109(1-2):213–241
- Melillo JM, Richmond T, Yohe GW (2014) *Climate Change Impacts in the United States: The Third National Climate Assessment*. Tech. rep., U.S. Global Change Research Program
- Mendelsohn R, Morrison W, Schlesinger M, Andronova N (2000) Country-specific market impacts of climate change. *Climatic change* pp 553–569
- Menéndez M, Woodworth PL (2010) Changes in extreme high water levels based on a quasi-global tide-gauge data set. *Journal of Geophysical Research* 115(C10):C10,011
- National Research Council (2013) *Abrupt Impacts of Climate Change: Anticipating Surprises*. The National Academies Press, Washington, D.C.
- Nicholls RJ (2004) Coastal flooding and wetland loss in the 21st century: Changes under the SRES climate and socio-economic scenarios. *Global Environmental Change* 14:69–86
- Nicholls RJ (2011) Planning for the impacts of sea level rise. *Oceanography-Oceanography Society* 24(2):144–157
- Nicholls RJ, Tol RSJ (2006) Impacts and responses to sea-level rise: a global analysis of the SRES scenarios over the twenty-first century. *Philosophical transactions Series A, Mathematical, physical, and engineering sciences* 364(1841):1073–95
- Nicholls RJ, Wong PP, Burket VR, Codignotto J, Hay JE, McLean RF, Ragoonaden S, Woodroffe CD (2007) Coastal systems and low-lying areas
- Nicholls RJ, Tol RSJ, Vafeidis AT (2008) Global estimates of the impact of a collapse of the West Antarctic ice sheet: an application of FUND. *Climatic Change* 91(1-2):171–191
- Nordhaus WD (2006) Geography and macroeconomics: new data and new findings. *Proceedings of the National Academy of Sciences of the United States of America* 103(10):3510–7
- Schneider SH, Chen RS (1980) Physical Factors and Climatic Impact. *Annual Review of Energy*
- Smith J, Cialone M, Wamsley T, McAlpin T (2010) Potential impact of sea level rise on coastal surges in southeast Louisiana. *Ocean Engineering* 37(1):37–47
- Sugiyama M, Nicholls RJ, Vafeidis A (2008) Estimating the Economic Cost of Sea-Level Rise
- Tebaldi C, Strauss B, Zervas C (2012) Modelling sea level rise impacts on storm surges along US coasts. *Environmental Research Letters* 014032
- Titus JG, Park RA, Leatherman SP, Weggel JR, Greene MS, Mausel PW, Brown S, Gaunt C, Trehan M, Yohe G (1991) Greenhouse effect and sea level rise: the cost of holding back the sea. *Coastal Management* 19(2):171–204
- Tol RSJ (1996) The damage costs of climate change towards a dynamic representation. *Ecological Economics* 19(1):67–90
- Tol RSJ (2007) The double trade-off between adaptation and mitigation for sea level rise: an application of FUND. *Mitigation and Adaptation Strategies for Global Change* pp 741–753
- Vafeidis A, Boot G, Cox J, Maatens R, McFadden L, Nicholls RJ, Spencer T, Tol RSJ (2006) The DIVA database documentation. DINAS-COAST Consortium

- Vafeidis AT, Nicholls RJ (2008) A new global coastal database for impact and vulnerability analysis to sea-level rise. *Journal of Coastal Research* pp 917–925
- Vermeer M, Rahmstorf S (2009) Global sea level linked to global temperature. *Proceedings of the National Academy of Sciences of the United States of America* 106(51):21,527–32
- Yohe G (1990) The cost of not holding back the sea: Toward a national sample of economic vulnerability. *Coastal Management* 18(4):403–431
- Yohe G, Tol R (2002) Indicators for Social and Economic Coping Capacity - Moving Toward a Working Definition of Adaptive Capacity. *Global Environmental Change* 2002(12):25–40
- Yohe G, Neumann JE, Marshall P (1999) The economic damage induced by sea level rise in the United States. Cambridge University Press, Cambridge, UK
- Yohe GW (1989) The Potential Effects of Global Climate Change on the United States, Appendix B: Sea Level Rise, Part 4: The Cost Of Not Holding Back The Sea - Phase 1 Economic Vulnerability. Tech. Rep. December, U.S. EPA Office of Policy, Planning, and Evaluation
- Yohe GW, Neumann JE, Ameden H (1995) Assessing the Economic Cost of Greenhouse-Induced Sea Level Rise Methods and Application in Support of a National Survey. *Journal of Environmental Economics and Management* 29:S78–S97

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