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An Integrated Climate Science-Economic Model for Evaluating Adaptations to Sea Level Rise: A Prototype Model for Monterey, California

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1. INTRODUCTION

Society's response to climate change focuses on two issues: mitigation and adaptation. Mitigation most frequently refers to efforts to reduce the pace and extent of climate change, primarily through reductions in the greenhouse gas (GHG) emissions at the root of the problem. Adaptation refers to actions taken to reduce the consequences of climate change. Both mitigation and adaptation pose a variety of thorny economic issues from the estimation of the social cost of carbon to the problem of the optimal share current and future consumption and investment that should be devoted to mitigation. As the reality of climate change has become more and more apparent, attention is being devoted to the problems of choosing which adaptive strategies should be employed given that the extent to which mitigation efforts can actually reduce the extent of climate change is not known.

One of the significant features of climate change is that mitigation- reducing the possible extent of change- is a problem best addressed at the national level since, as a global problem, climate changes requires coordinated national actions. Adaptation, however, is a problem which must be addressed locally since the interaction between changing natural systems and socioeconomic assets varies tremendously with location. This is seen clearly with respect to one of the most serious consequences of climate change: sea level rise.

The world's shorelines are complex socio-ecological systems that vary enormously in shape, elevation, and composition along with the types and extents of human uses of the shores, from undisturbed natural parks to the hearts of the major cities. Each location faces a different adaptation challenge and will require a different response. Defining and implementing those responses is a central economic challenge created by climate change regardless of the level of mitigation. But it is also one of the most difficult economic problems. While there is little controversy of the benefits of replacing fossil fuels with renewable sources, it is not at all clear what the most efficient responses to sea level rise will be in terms of cost and effectiveness nor when is the optimal time to deploy them even.

This is because of the "deep uncertainty" surrounding the problem of climate change adaptation. There are at least three major sources of this deep uncertainty (Heal and Millner 2014):

1. Climate uncertainties

Though much progress has been made in both the theory and empirical measurement of climate change, the sheer scale of the interaction between

anthropogenic and natural climate systems across the entire planet means that the critical information can only be embedded in complex computer models. These models are constantly improving but still contain sufficient problems of specification, observation and residual error that outputs remain more statements of probabilities than point forecasts, though they are often portrayed as such.

Three features of computational models contribute to uncertainty. The first is the sheer number of variables that must be managed. This paper focuses on sea level rise, which is driven by multiple variables. The effects of sea level rise are amplified by weather events whose frequency and intensity may change, not always in the same direction. The second is that, for adaptation purposes, the projections of global climate models must be “downscaled” to localities to reflect the variances in climate around the world. Finally, time frames of 80 or more years are needed to evaluate projects and their possible effects, well beyond the more generally accepted forecasting windows for even the most long-lived projects.

2. Technological Uncertainties

In contrast to technologies such as carbon capture and storage, about which there is much uncertainty about effectiveness and cost for the formulation of mitigation strategies, the technologies involved in adaptation to sea level rise are relatively straight forward. There are three basic strategies: alter structures (e.g. elevating buildings); interposing barriers between assets and the sea (e.g. sea walls, sand for beaches), and retreat (moving inland/upland). Most of these are not associated with significant technological uncertainties; in one form or another they have been used for centuries. But there are still issues. Seawalls have limited lives before even normal erosion diminishes their effectiveness. The rates at which seawalls or “natural infrastructure” such as nourished beaches will degrade with sea level rise is likely to be unknown with precision in most cases.

3. Socioeconomic Uncertainties

The responses of socioeconomic systems to the challenges of climate change is another source of uncertainty. Perhaps the most significant are uncertainties about what policies with respect to both mitigation and adaptation will be chosen. The principal differences among the standard scenarios of the Intergovernmental Panel on Climate Change (Intergovernmental Panel on Climate Change 2014) rests on the assumptions about the extent and effectiveness of global efforts at GHG reduction. But these are not the only socioeconomic systems creating uncertainty. Responses to increased flooding will be shaped by insurance systems, along with myriad public and private choices about investments to reduce damages before, during, and after hazard events such as storms, and

the demand for housing in vulnerable areas is likely to change as these hazards become known.

The cumulative impact of these uncertainties is to make planning in any traditional sense almost impossible. Effective planning requires focus on a specific set of issues of concern and holding all else constant. But with climate change, *ceterus* can no longer be *paribus*; all factors, even the very existence of the land on which we live, can no longer be assumed.

The weight of these uncertainties could make it very easy to avoid planning or taking any action. The direction of change may be known and there may be a general understanding of an increase in risks to socioeconomic systems and assets, but without detailed information on the pace of change and the extent of change, it is argued, taking action may result in wasting resources defending against a threat that might never be as serious as currently perceived.

This is not an unreasonable position, but it must be evaluated against its mirror image: what are the potential wasted resources from failing to act or failing to act in time? Responding to climate change is ultimately a problem in risk management: evaluating the costs and benefits of taking action or not and of acting too soon or too late. Climate change does present some unique challenges, leading many to conclude that the tools economists have used to assess choice problems are inappropriate or inadequate. (For a review of the debate about the economics of adaptation, see Colgan 2016).

But decisions must still be made. The large stock of public and private capital that already sits in existing and newly vulnerable locations must still be maintained to offset depreciation. Expanded investments in that capital stock are needed or in some places desired. Moreover, many communities have fully recognized the dangers posed by climate change and sea level rise and wish to actively respond as soon as a reasonable assessment suggests.

It is imperative therefore that there be some way to confront the uncertainty that cannot be avoided and evaluate the options available for each locality. Doing this requires changing how we perceive the problem of adaptation. If we see adaptation as only the sum of the uncertainties, the problem is analogous to a game of roulette with an unknown number of slots on the wheel and only the vaguest knowledge of when the ball will be released. Some effort must be made to turn this game into one where the numbers of slots and timing of the release are known with at least moderate confidence. This ultimately means using some version of cost-benefit analysis together with probabilities to estimate expected present values (EPV) which combine information about both

This paper reports the development of a Monte Carlo-based integrated climate change/cost-benefit model that can be used to evaluate the economic viability of selected strategies to deal with sea level rise at specific locations. The model is of the type of “end to end” model capable of dealing with uncertainties in both climate science and socioeconomic/technological uncertainties that have been suggested as one way of addressing climate adaptation. (Heal and Millner 2014) It is also suitable for applications of robust decision making (RDM) that have been used for project evaluation incorporating sea level rise. (Lempert, Sriver, and Keller 2012).

The model described is a prototype that is designed to illustrate how such integrated models can be designed and parameterized. The prototype is implemented using an example of sea level rise adaptation planning from Monterey, California, a small city a variety of shoreline types that are ideal for testing different adaptation strategies.

2. OVERVIEW OF THE MODEL

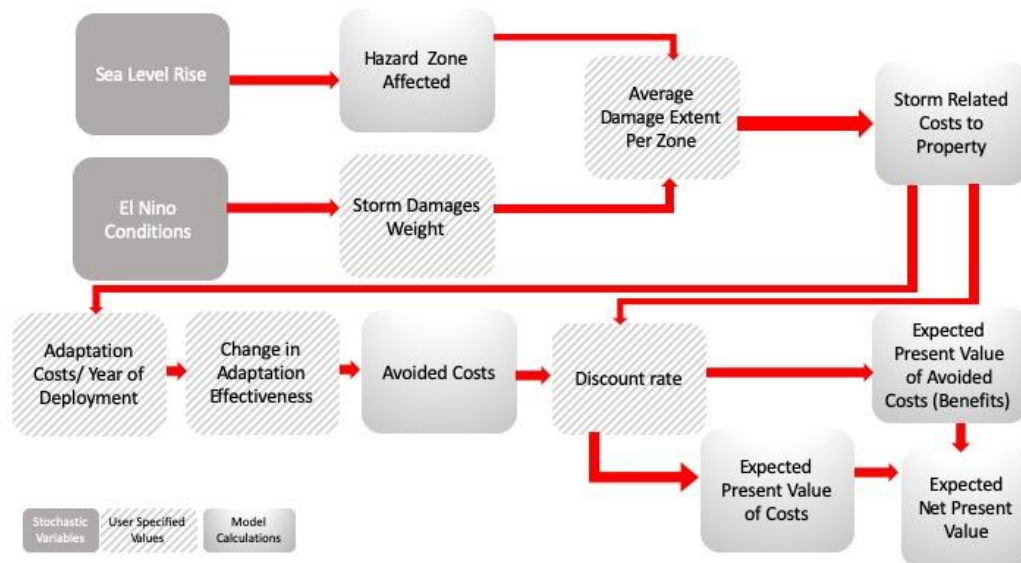


Figure 1 Model Overview

Figure 1 provides a schematic overview of the model, which is an annual model with mixed stochastic (Monte Carlo) and deterministic variables. The model is set to run over the period 2020-2100; in the prototype model, 10,000 iterations per year are used for each run. Each iteration varies all stochastic variables. The model uses flood damage on the structural values of properties as the source of costs and

(as avoided costs) benefits. The model uses the @RISK software from Palisade Corporation.

The model has three basic types of variables, which are described in greater detail in the next section. The first are exogenously specified stochastic variables measuring sea levels and El Niño conditions (the dark shaded symbols in Figure 1). El Niño, or more properly the El Niño Southern Oscillation (ENSO), is an irregular cycle of temperature shifts in the mid-Pacific Ocean that strongly influence the degree of winter storminess affecting the Pacific states. It is the interaction between storms and sea level rise that determines the risk of coastal flood damages. For purposes of this model, the probability distributions of sea level rise and ENSO storms are treated as independent of one another. Climate scientists have not yet settled on how or the extent to which ENSO may be modified by climate change. Both sea level rise and ENSO variation are estimated from exogenous data.

The second set of variables is a group of user-specified values. These cover the extent of possible property damage within a designated zone, the costs of adaptation strategies together with the year in which deployment is undertaken, and the depreciation rate of the adaptation measure chosen. The preceding variables are defined as stochastic, with triangular probability distributions and user specified top, bottom and modal values. The discount rate is also user specified but is defined as a scalar.

The third set of variables are computed endogenously. These include the area affected and the storm related damages to properties with and without the adaptation measures. These are estimated for each iteration across the 80-year period; the probabilities associated with the costs and benefits are estimated and the model reports the expected present values and associated risks across the number of iterations.

The model can be summarized in the following equations:

A. Calculate Costs

For any defined zone:

$$(1) V_t^i = (\pi L^i | \pi N^i)$$

Where:

V_t^i = Value of structures in a zone in iteration i and time t .

π = the probability of a given sea level, ENSO condition

$(\pi L^i | \pi N^i)$ = the joint probability for any iteration i of a given sea level and a given ENSO storm condition

$$(2) C_t^i = (V_t^i)(D_z^i)(K_z^i)$$

Where:

C_t^i = The costs in damaged structural property values

V_t^i = as defined in equation (1)

D_z^i = The storm factor, or the proportion of value affected within a specific zone depending on the value of N^i for that iteration.

K_z^i = The proportion of property damaged in each zone for each iteration depending on the extent of flooding in that iteration. This is a stochastic variable to reflect the chance effects of floods. A triangular function is specified ranging from 10% to 90% with a mean of 50%.

$$(3) TC_t^i = \sum_{z=1}^n C_t^i + c_t$$

Where:

TC_t^i = Total costs in time t for iteration i

$\sum_{z=1}^n C_t^i$ = The sum of damages to structures across all zones for iteration i.

c_t = Expenditures on flood mitigation made in time t for all zones.

B. Calculate Benefits

$$(4) A_t^i = (V_t^i)(T_t^i)$$

Where:

A_t^i = Avoided costs for iteration i and time t.

T_t^i = is a technology efficiency coefficient measuring the efficiency of the adaptation technology chosen. In the current prototype this is a depreciation factor over 5 or 10 years in the case of beach nourishment and 20 years in the case of armoring.

V_t^i = as defined in equation (1)

C. Calculate Net Present Value

$$(5) EPV = \sum_{t=1}^{t=80} \frac{A_t^i = TC_t^i}{(1+n)^t}$$

Where:

EPV = Expected present value

A_t^i = Avoided costs in time t for iteration i

TC_t^i = as defined in equation (3)

n = discount rate

3. MODEL ASSUMPTIONS AND SCENARIOS

Shifting sea level rise adaptation planning to better account for the climate uncertainties described above has been recognized as a key step in adaptation planning. In California, the Ocean Protection Council, a state government agency with broad responsibilities for setting ocean-related policies, commissioned a study in 2016 to examine the evolving state of scientific research on climate change and sea level rise. The resulting study (Griggs et al. 2017) focused particular attention on the work by Kopp et al. (2014) providing detailed probabilistic sea level rise forecasts for 11,000 tide gauge stations around the world.

The Kopp et al. data built on the global mean temperature changes resulting from three major GHG emission scenarios from the IPCC (Intergovernmental Panel on Climate Change 2014), and then localized the resulting estimates taking into account coastal geomorphology, known erosion and subsidence rates, glacial hydrostatic compression, thermal change, and the best available evidence on the probabilities of catastrophic failures of the Greenland or West Antarctic ice sheets.

The findings of the Griggs committee were then incorporated into an updated guidance document for state and local governments in California. (California Ocean Protection Council 2018) The key recommendation in this guidance was that planning for sea level rise should incorporate both the more and less likely possible sea levels given any assumption about future temperature changes. These recommendations are summarized in Table 1.

3.1 Sea Level Rise Scenarios

The OPC scenarios are divided into two groups defined by the decision maker's perception of the risks of climate change. These were a low risk aversion and a medium-high risk aversion scenario. The former corresponds to the IPCC 2.6 degree C scenario and the medium to high risk is a combination of the 4.5- and 8.6-degree C scenarios. "Low" risk levels are those which are more probable in terms of occurring but show lower rates of sea level rise. The implication of the low risk scenario for sea level rise is a higher level of success in mitigation. The medium-high risk scenarios are less probable of occurring but higher probabilities of damage. The implication is of lower levels of mitigative success. A third scenario, designated H++, is the result of the very low probability but very high sea level change situations where the ice sheets substantially collapse. The intention in the Guidance is that planning processes will begin by selecting the acceptable level of risk and then using the corresponding rates of sea level rise. Agencies are advised to undertake at least some planning for the H++ scenario.

	Centimeters		
	Low Risk	Medium-High Risk	H++ Scenario
2030	15.1	24.2	30.2
2040	24.2	39.3	54.4
2050	33.2	57.4	81.6
2060	45.3	78.6	117.9
2070	57.4	105.8	157.2
2080	72.5	136.0	199.5
2090	87.7	169.3	250.9
2100	102.8	208.6	308.3

Table 1: California Ocean Protection Council Sea Level Rise Recommendations

For purposes of this study, the data underlying the Ocean Protection Council Guidance was secured from the Kopp et. al team¹. The data is publicly available in MatLab format. The Ocean Protection Council guidance is based on average rates of sea level rise for the California coast. The data selected for the study was that specifically from the Monterey harbor tide gauge, located near the center point of the City's shoreline.

The SLR data acquired from Kopp et. al consists of the results of 10,000 Monte Carlo iterations for each of the IPPC scenarios for the decennial years from 2020 to 2100.² The data analyzed and the SLR for a given year was defined as the result of a log normal function based on the decennial estimates. Years between the decadal years were interpolated on a straight-line basis. The lognormal equations were then used to calculate the iterations of sea level rise for the model.

3.2 Storm Scenarios

The second stochastic variable is that for storms. California has a Mediterranean climate, meaning a wet season in the fall and winter and a generally dry season in the spring and summer. Major weather events tend to be associated with changes in the temperature of the mid-Pacific Ocean known as the El Niño Southern Oscillation (ENSO). ENSO is actually a somewhat more complex ocean-atmosphere phenomenon and is measured on multiple parameters that together comprise the ENSO Multivariate Index. (Wolter and Timlin 1993).

Figure 2 shows variations in the Multivariate ENSO Index from 1950 to 2016; points in red indicate above mean temperature conditions, those in blue represent

¹ (github.com/bobkopp/LocalizeSL)

² The data is available to 2300.

below mean. El Niño conditions are associated with strong warming trends in the Pacific; the opposite strong cooling trends are called La Niña.

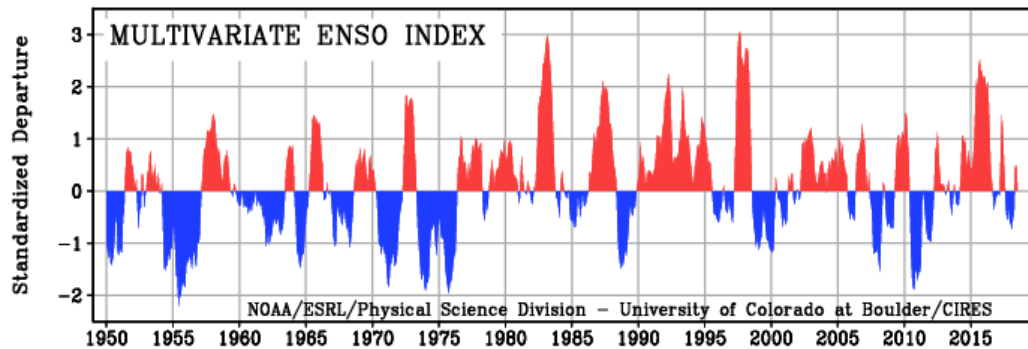


Figure 2: Multivariate ENSO Index³

The ENSO cycle can be characterized as having 5 states:

	Low MEI Value	High MEI Value
La Niña	<0.256	
Very Weak El Niño	>=0.256	<.525
Weak El Niño	>=0.525	<0.939
Strong El Niño	>=0.939	<1.439
Very Strong El Niño	>=1.439	

Table 2 El Niño Multivariate Index Values and El Niño State (See Footnote 3)

The effects on the Monterey shoreline depends on the state of the El Niño cycle in any given year. Generally, the stronger the warming effect the stronger the storms affecting the California coast, so the greatest flooding and damages have historically been associated with very strong El Niño conditions. Weak El Niño conditions are associated with fewer and less damaging storms, and La Nina conditions are associated with the least storm conditions as the winds shift to the north.

But this wind shift actually increases the risk to Monterey. Lying at the southern end of Monterey Bay, the City's shoreline is one of the few places on the California coast with a north and northwestward facing shoreline. The result is that La Nina-related storms may be less frequent but in Monterey they tend to be more damaging than all but the strongest El Niño conditions.

³ <https://climatedataguide.ucar.edu/climate-data/multivariate-enso-index>

The ENSO effect on possible flood damages in Monterey is thus somewhat bipolar, as shown in Figure 3, which shows a storm adjustment factor for damages predicted. For this model, the Multivariate ENSO Index was converted to a logistic function that calculated a stochastic value for the Index for any iteration in any year. That value then identified the state of El Niño for that iteration according to Table 2. The El Niño then defined the value of a variable which adjusted the extent of possible storm damages estimated as above by a factor which varies from 0.1 to 0.8 (D_z^i). That is, estimated damages from flooding are 80% of possible damages in the case of an iteration with a very strong El Niño but only 10% of possible damages in the case of a very weak El Niño. Reflecting the particular vulnerability of the Monterey shoreline, the possible damages during a La Nina year are almost as high as during a very strong El Niño (70% of possible damages).

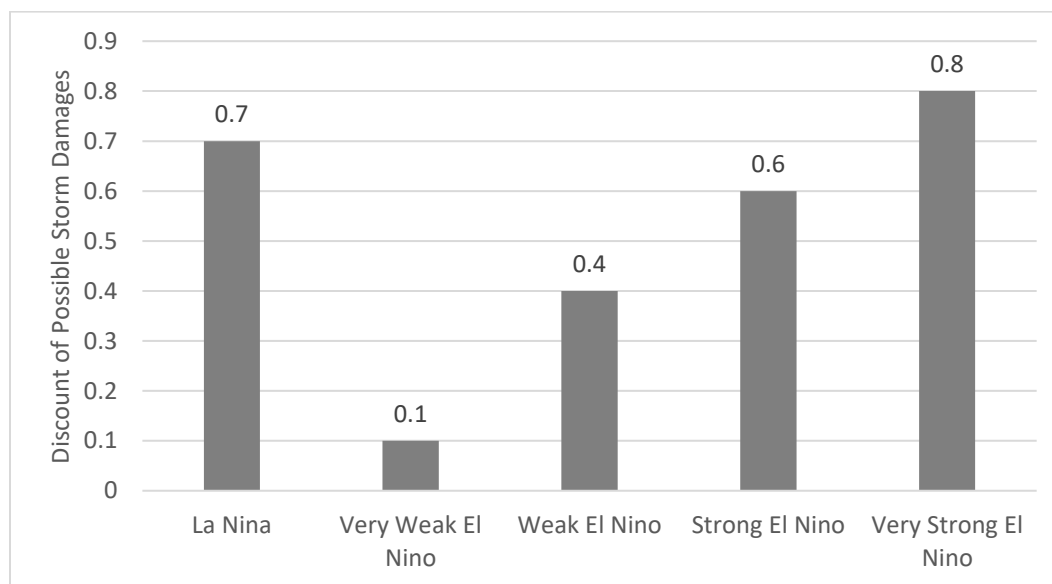


Figure 3: Storm Adjustment Factors

3.3 Flood Scenarios

The final element in the estimation of potential costs is the extent of property damage dependent on the extent of area flooded. There are various approaches to estimating the potential for damage from flooding, most commonly some version of depth damage function. (Huizinga, De Moel, and Szweczyk 2017; Davis and Skaggs 1992) But such approaches were not appropriate here for two reasons. First, depth damage functions assume that the depth of a flood can be predicted at any point. But flood depth modeling was not available for Monterey as depth was not critical to the LCP update process. Second, depth damage functions are also specific to structures, requiring a more detailed analysis than was appropriate for

the prototype model development undertaken here which relied on zonal damage estimates.

The basic form of the zonal damage function is shown in Table 3. The matrix of this function shows the zone projected to be affected in the columns and the extent of properties affected in the rows. The cells show the upper and lower ends of a triangular probability distribution used in each iteration to fix a coefficient of the amount of property valuable subject to damages.

Thus, a flood that reaches zone 5 will damage between 80 and 90% of the properties in zone 1, 70 and 80% in zone 2, 60% and 70% in zone 3, etc. The base assumption is between zero and 50% of the properties damaged in the corresponding zone of flood extent. The triangular function introduces a stochastic element to the damage function reflecting the randomness inherent in hazards such as floods.

Damage Matrix					
Zone Damage in each zone	Zone Affected in iteration i and time t				
	1	2	3	4	5
1	50%	60%	70%	80%	90%
2		50%	60%	70%	80%
3			50%	60%	70%
4				50%	60%
5					50%

Table 3: Zonal Damage Matrix

Simultaneous with the model development reported here, the City of Monterey was undertaking an update to its Local Coastal Program (LCP) required under the California Coastal Act, which grants cities and counties permitting authority for development in the coastal zone so long as the city or county has an approved Local Coastal Program. In 2014 the California Legislature required cities and counties with approved LCP's to update them to address climate change and sea level rise. As a result, the City had engaged coastal geological consultants to prepare new estimates of SLR-related flooding.(Revell Coastal 2016; ESA-PWA 2014) The project team secured the GIS files associated with these updated estimates of flooding and analyze them to create distinct zones of possible flood effects.

The coastline of Monterey can be divided into three principal areas (Figure 4):

- Del Monte Beach, a low-lying beach area (with one bluff area), which extends about 3 kilometers. (See Figure 5) At the southern end, a large

estuary (El Estero) extends inland about 1 kilometer; the estuary has connections to the sea that extend below the surface under the roadway through the area. The shoreline of the beach and estuary is the location for a mix of commercial and residential buildings.



Figure 4: Map of City of Monterey Shoreline with Flood-Vulnerable Parcels



Figure 5: Del Monte Beach, Southern End

- The Harbor, which is the location of the marina, two wharves (including the famous Fisherman's Wharf), and a recreation trail. The harbor is protected by wharves and sea walls and is thus much less vulnerable to flooding from sea level rise and storms than the other sections of shoreline. For that reason, the Harbor area was excluded from the model.
- Cannery Row is the stretch of shoreline extending from the western edge of the Harbor to the city line with Pacific Grove near Point Alones.

Cannery Row is a series of commercial buildings, many of which were once sardine canneries converted to hotels, retail, and restaurants. This area is well known from John Steinbeck's novel of the same name. Unlike Del Monte beach, Cannery Row's shoreline is for the most part rocky substrate with buildings and paths extending past the natural shoreline supported on structural girders. (See Figure 5). There is also a small pocket beach in this zone.



Figure 6: Cannery Row buildings support example

The Del Monte beach area is the most complex in terms of estimating flood potential, but it is also somewhat simpler in terms of adaptation options. For the model, the parcels within the Del Monte beach zone subject to flooding according to maximum SLR projected in the analysis for the City were divided into 5 zones based on Lidar-derived elevation data. These are shown in Figure 7. The sea level rise estimates from the City's consultants using the IPCC 8.5 reference scenario were used; the mean SLR extent under these scenarios was slightly smaller (~10 centimeters) than the Kopp et. al data.

The zones thus defined were intersected with property tax parcel data from Monterey County.⁴ Assessed values for property taxes in California are difficult to work with because of the continuing effects of Proposition 13, a tax limitation measured enacted in 1978. Proposition 13 effectively freezes residential property tax assessments at the most recent sale price (with an allowable 2% adjustment each year). Commercial property is not subject to the same limitations, but assessments

⁴ Property tax cadastral data is maintained by counties rather than municipalities in California.

tend to lag the rapidly appreciating California property markets. Because of this, adjustments have to be made to bring the assessed values closer to market values. by creating a housing price index (HPI) which tracks housing inflation in the area. The HPI is based on a number of sources including Zillow⁵ and the case Shiller Index.(Standard & Poors Dow Jones 2019) The resulting estimates of property value estimates for structures (land was excluded since the estimations are of storm-related flooding where waters eventually recede) are shown in Table 4.



Figure 7 Del Monte Beach Flood/Sea Level Rise Zones

⁵ www.zillow.com

Zone	Commercial	Residential	Total
1	\$36.38	\$50.06	\$86.44
2	\$14.29	\$5.00	\$19.28
3	\$25.37	\$6.67	\$32.03
4	\$0.00	\$8.96	\$8.96
5	\$10.48	\$11.51	\$22.00
TOTAL	\$86.52	\$82.20	\$168.71

Table 4 Estimated Market Values of Structures in Del Monte Beach area (\$ Millions)

The analysis of Cannery Row is somewhat different. Where Del Monte beach is a problem of flood waters penetrating inland some distance, Cannery Row presents primarily a problem of storm waves accelerating erosion and undermining structural supports. Only those buildings on the seaward side of the Cannery Row street are actually vulnerable under current SLR forecasts. (Figure 8)



Figure 8: Cannery Row vulnerable parcels.

The entire length of Cannery Row is commercial property and the entire length is vulnerable to SLR and storms. However, for purposes of the analysis, Cannery Row was divided into three zones as shown in Figure 8. The zones reflect some variations in the distribution of properties along the street. As shown in Table 5, Zone 1 has considerably lower commercial valuation than the other zones; this is due to a large vacant lot in that zone 1. The demarcation of the three zones allowed different timing of adaptation strategies to be deployed, though this was not tested.

Zone	Commercial
1	\$34.09
2	\$53.83
3	\$147.83
TOTAL	\$235.75

Table 5 Value of Commercial Structures on Seaward Side of Cannery Row (\$ Millions)

The adaptation options for Del Monte beach are relatively straight forward: the traditional response to loss of beach is some form of armoring, that is construction of sea walls comprised of stone or other material. Sea walls protect the adjacent properties, though at the cost of hastening erosion in unprotected parts of the beach. Alternatively, sand lost to erosion during storms can be replaced through a process of beach nourishment. Nourishment is preferred from a natural systems point of view but requires much more frequent expenditures than sea walls. Both of these options had already been extensively studied in terms of feasibilities and costs in the Monterey-Southern Monterey Bay region (ESA-PWA 2012; Jackson, J. R., R. T. Battalio 2015; Newkirk et al. 2016) so there were fairly detailed and recent cost estimates for adaptation responses on the Del Monte beach stretch of Monterey.

For purposes of this analysis, both a beach nourishment and an armoring option were analyzed. The cost estimates for these options varied somewhat across the previous studies, so a representative cost estimate was used. For beach nourishment, the assumption was that the cost would be \$3 million to be repeated every 10 years. The cost of the nourishment projects would increase \$1 million per year after 2050 to reflect increasing scarcity of sand. Two scenarios of depreciation were tested. The first assumed that after year 5, the effectiveness of the nourishment would decrease by 10% per year. The second assumed that effectiveness of the nourishment would fall by 10% per year beginning in year 2. The sea wall option was assumed to cost \$30 million and to last 20 years. It depreciated 10% per year after 15 years. Different runs of the model tested the effects of beginning beach nourishment in various years.

Cannery Row, as noted, is a much more complex adaptation challenge, and it is not one that has been extensively studied. The geology of the shoreline is considerably more resistant to erosion, but the exposure of the building foundations to the sea creates significant vulnerabilities. There are two broad options that are available: one is structural reinforcements to the buildings, though there are many different types of foundations (from wood to steel to concrete). The other is constructing some form of barrier just offshore to attenuate wave forces. This option would offer the most protection but constructing such a barrier in the waters of the Monterey Bay National Marine Sanctuary would present almost certainly insurmountable regulatory issues.

Since there was much less information about the available options for Cannery Row, including costs per linear meter of a barrier as well as the durability of the structural improvements, which would have to be unique to each of the buildings, a simplifying assumption of two options, one costing \$25 million and one costing \$50 million.

However, for Cannery Row, a different approach to deploying the adaptation measures was selected. Rather than choosing a specific year for deployment, the model was programmed to deploy adaptation in any iteration where sea level reached a chosen increase; these trigger points ranged from 10 to 30 centimeters.

4. RESULTS

Figure 9 shows the range of sea level rise (above 2000 mean levels) forecast from the re-estimation of the Kopp et. al data using the IPCC 8.6 scenario as an example. The mean SLR shown is the mean of 10,000 iterations of the log normal forecast, while the max SLR is the largest single SLR among the iterations at each decadal point. The mean SLR is the most commonly cited in discussions of SLR. But the maximum at each decadal point shows the range of possible outcomes given the underlying analysis in the Kopp et. al. models.

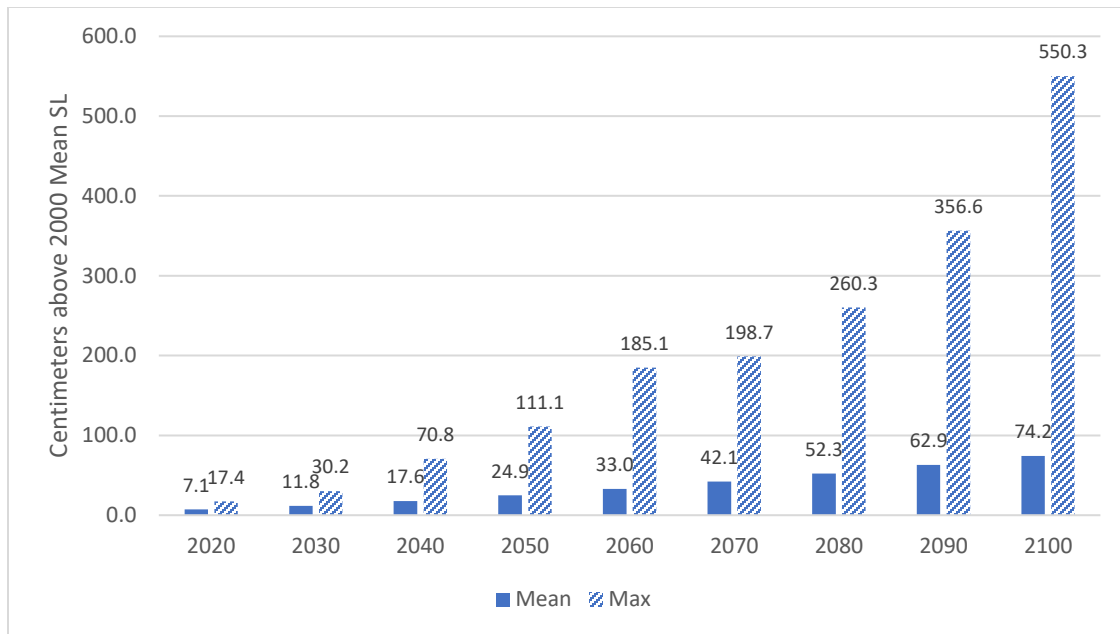


Figure 9: SLR mean and max SLR forecasts for IPCC 8.6 scenario.

The difference between the mean SLR (the average of all SLR possibilities in the Monte Carlo model for each of the years shown) and the max SLR for that year (the largest SLR value among the iterations for that year) reflects the possibility of much higher threats from sea level rise, though at low levels of probability. The possibility of these higher SLR values occurring demonstrates how the Monte Carlo approach converts the uncertainty about the extent of sea level rise into a measure of risk that can be converted to evaluative purposes.

					IPCC Emissions Scenario			IPCC Emissions Scenario		
					2.6	4.5	8.5	2.6	4.5	8.5
Scenario	Adaptation Option	Start Year	Rebuild Cycle (Years)	Depreciation	Mean NPV (\$ Millions)			Prob NPV>0		
D1	Beach Nourishment	2030	10	10% after 5 years	\$92.80	\$97.30	\$42.20	0.990	0.990	0.926
D2		2040	10	10% after 5 years	-\$22.70	-\$19.80	-\$75.20	0.338	0.370	0.146
D3		2030	10	10% each year	\$30.20	\$33.90	\$8.80	0.950	0.963	0.963
D4	Armoring	2030	20	10% after 10 years	\$24.80	\$29.30	-\$18.50	0.747	0.809	0.250
D5		2050	20	10% after 10 years	-\$150.00	-\$146.00	-\$155.90	0.010	0.010	<.010

Table 6 Results of Del Monte Beach Adaptation Evaluations (Selected Scenarios)

Table 6 shows the results of the analysis of five scenarios for adapting the Del Monte beach area to sea level rise, three involving beach nourishment and two involving coastal armoring. Different options for the year in which adaptation is begun are shown. A large number of options were examined, varying the start year and the period and rate of depreciation for beach nourishment (essentially erosion of the nourished beach). The initial scenario selected was to begin in 2050, the year in which the SLR models show accelerating rates of SLR. Table 6 shows the results for example scenarios to illustrate the effects of changes in input values for the model. For each scenario the mean net present value (NPV) over 10,000 iterations is shown, along with the probability across those iterations that the net present value will be greater than zero.

The results indicate that beach nourishment is a viable strategy if implemented around the year 2030 under any of the IPCC scenarios. Waiting until 2040 shows negative net present values even for the lesser IPCC scenarios, with only about a one third chance of a positive NPV in the 2.6 and 4.5 scenarios and less than a 15% chance of a positive NPV in the 8.6 scenario.

Figures 10 and 11 show the probability distributions of net present value from the analysis of the beach nourishment options initiated in 2030 v. 2040. The IPCC 8.5 scenario is shown. These figures, an output of the model, illustrate how the change in the start date for adaptation changes the probability of a positive net present value being realized.

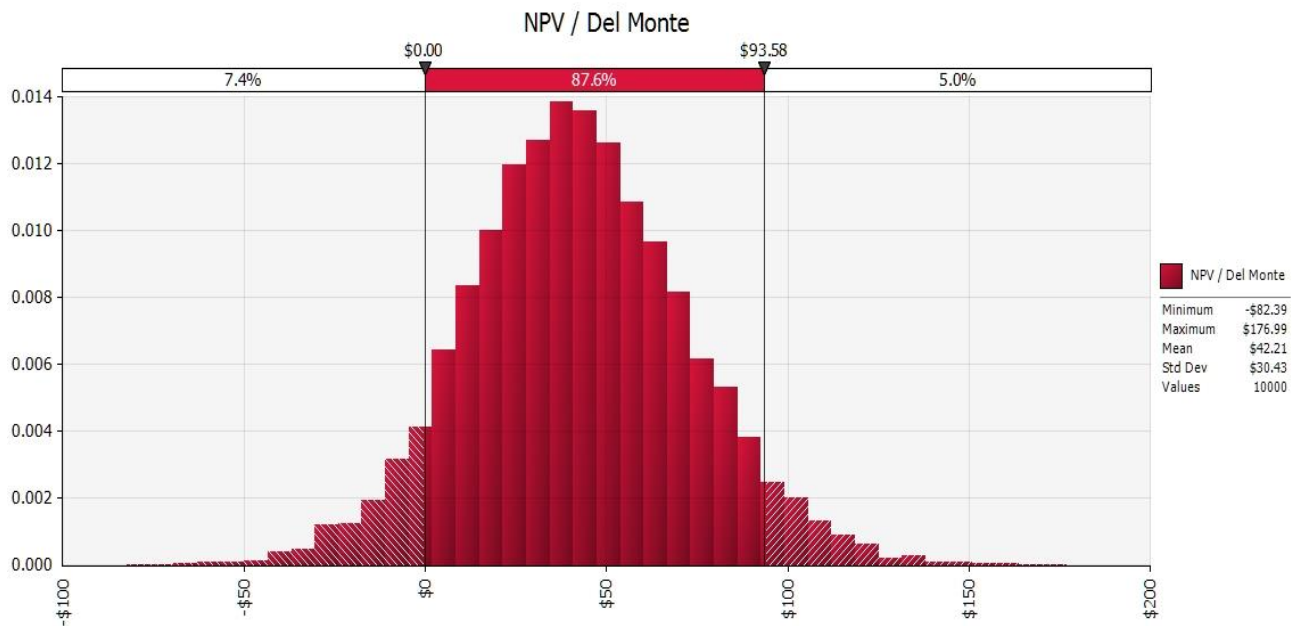


Figure 10 Probability of Positive Net Present Value if Beach Nourishment Begins in 2030

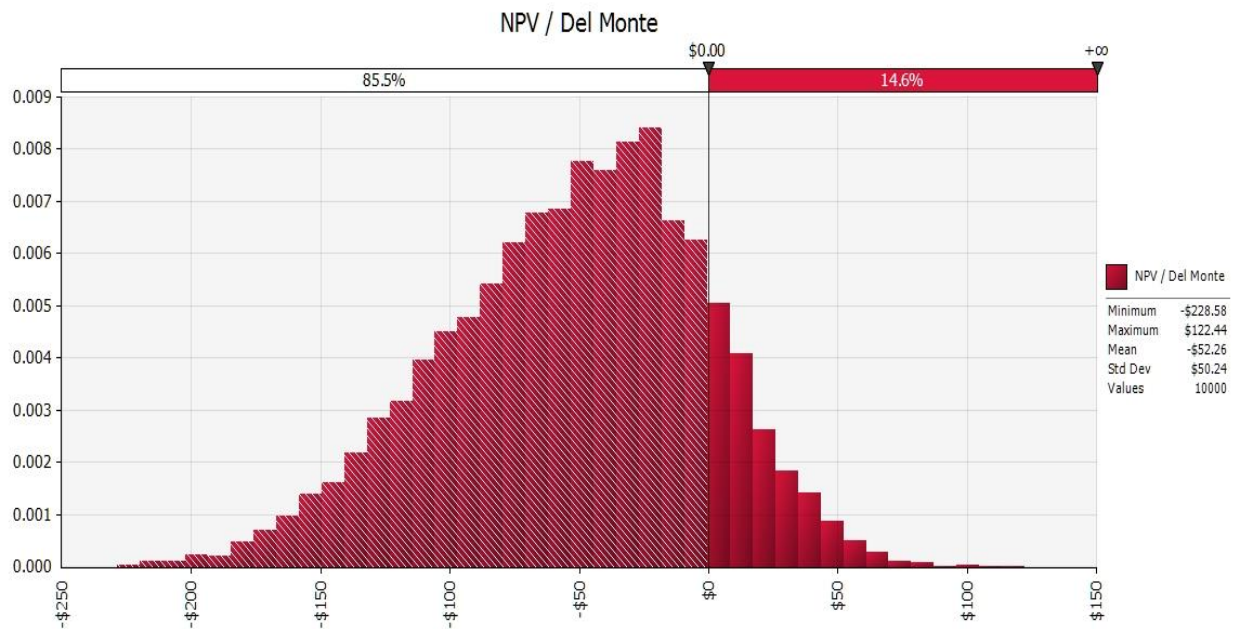


Figure 11 Probability of Positive Net Present Value if Beach Nourishment Begins in 2040

The model clearly suggests that early action is to be preferred to delay. There are two reasons for this. One is that even in the lower IPCC emissions scenario, flooding in Zones 1 and 2 is that the distribution of flood damages by zone does not vary significantly with SLR. (Figure 11). This is because even in those scenarios there is a probability that SLR will be higher than the mean, creating flooding up to Zone 5 in at least a few cases.

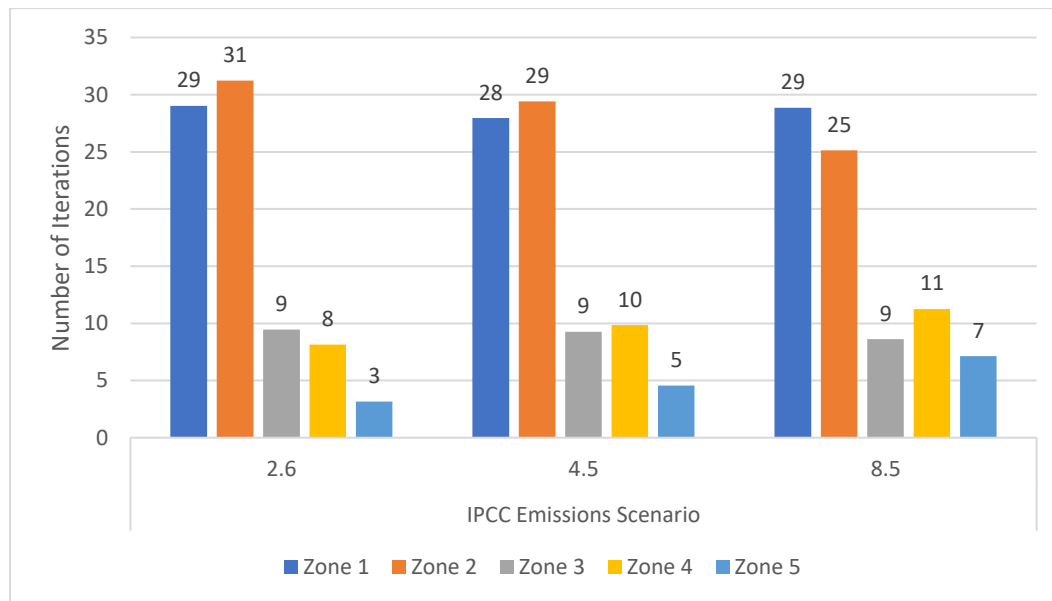


Figure 11 Flood Zones Affected by IPCC Scenario

The second reason that the analysis recommends acting sooner is the discount rate. The analysis uses a 5% discount rate, which means that the benefits accrued after 2050 will be heavily discounted. The choice of discount rates and timing will be discussed in the conclusions section below.

IPCC Emissions Scenario											
Scenario	Cost (\$Millions)	Sea Level Rise Trigger (cm)	2.6			4.5			8.5		
			NPV	P NPV>0	Mean Year	NPV	P NPV>0	Mean Year	NPV	P NPV>0	Mean Year
C1	\$50.00	30	-\$216.70	<.001	2062	-\$208.01	<.001	2059	-\$202.19	<.001	2060
C2	\$25.00	30	-\$220.27	<.001		-\$211.75	<.001		-\$205.36	<.001	
C3		20	-\$53.29	0.281	2046	-\$41.36	0.369	2044	-\$49.80	0.397	2047
C4		10	\$413.56	>.995	2026	\$387.95	0.951	2027	\$397.98	0.951	2026

Table 7 Results of Cannery Row Adaptation Evaluations

Table 7 shows the results of the evaluation of adaptation options for Cannery Row. As noted, this analysis took a different approach from that used for Del Monte beach. In preparing Local Coastal Program updates, communities in California have considered using trigger points for actions, rather than planning to launch adaptation measures in a specific year. This is of course, a strategy for dealing with the uncertainty of the actual timing of sea level changes. Analysis of the type carried out for Del Monte Beach reduces the uncertainty to a period when an adaptation option is likely to be economically efficient. The model can also be used to test for the efficiency of deployment adaptation based on a specific rise in sea levels.

For Cannery Row, there are two options examined, one costing \$50 million and one costing \$25 million. These are hypothetical combinations of strengthening building structures and constructing offshore wave barriers. The \$50 million option does not pass a benefit cost test under any of the analyses. The \$25 million option only exceeds zero NPV if the options are deployed at a relatively small rise in sea level of 10 centimeters, which in the Kopp et. al scenarios happens in the mid-late 2020s. These results are roughly consistent with that for Del Monte Beach indicating earlier action is preferred.

5. CONCLUSIONS

It is said that “all models are wrong; some models are useful”. There are clearly limitations in the prototype model described here, but even with these limitations there are several useful aspects.

Like all cost-benefit models, the real utility is not the final NPV estimate per se, but the process used to get that result. Models force assumptions to be made explicit and allow different assumptions to be tested. In the current model, decisions must be made about how much climate change to expect (through the choice of IPCC scenario), which adaptation options to consider, what timing considerations should be tested, how damages should be measured, how effective adaptation options will be over what time, and finally the discount rate. Since the overall framework is a Monte Carlo simulation, there are several opportunities to use stochastic variables, such as using probability functions for damage estimates reflecting the fact that different flood events even of the same size will produce different effects. The model thus allows a great deal of user input much of which must reflect the risk preferences of decision makers who will use the information. Eliciting those risk preferences on the specific elements of the model is the most important conversion of uncertainty to risk in dealing with climate change.(Nordhaus 2011)

In this sense they can be an essential part of stakeholder-based planning processes in which assumptions can be formed by stakeholders and the results communicated to stakeholders as a way of moving towards more consensus-based plans, which are likely to be the most effective approach to planning for climate change. (Susskind et al. 2015)

The timing of the development of this model did not coincide with key stakeholder processes in the Monterey Local Coastal Program climate update, although the research team did consult with city officials during the development of the model and the information generated did support the general direction in which the City was moving, particularly with respect to Del Monte beach, where the expectations were that there would be a focus on beach nourishment beginning sometime in the 2030s.

The results of the model show both the risk-adjusted (expected) net present value and the probability that the NPV will exceed a defined threshold. In the results presented here, the probability measured is that the $NPV > 0$. But the analysis could also be set to assess the probability of one option with respect to another. If two options show very similar NPV's, the probabilities associated with each could aid in choosing between them.

There are five broad areas that are needed for further development of the model.

1. *Local Data:* Any application of a model such as this requires detailed local data, particularly engineering data on the options, including at least conceptual design, cost estimates, and expected life span. These engineering estimates should be part of any adaptation planning and are highly location specific. The estimates should be at the conceptual level rather than detailed design information, since the model's basic purpose is to identify those options that merit more detailed design efforts.

2. *Expand analysis to other vulnerabilities:* The prototype model described here assessed potential damage risks to residential and commercial structures. But there are a number of other assets at risk from sea level rise for which assessment of adaptation options is needed. This includes infrastructure, such as transportation networks, and waste water and water facilities located in shoreline areas. It also includes changes in ecosystems, measured as changes in ecosystem service values.

3. *Representation of weather:* Sea level rise has three principal effects on shorelines. One occurs on a regular basis: increases in the tidal range with tidal waters inundating larger and larger areas. This becomes a major problem in low-lying areas. The second is an increase in erosional effects, and the third is increases in wave actions. All three of these are most destructive in storm events. Coupling SLR and cost-benefit models requires a weather module that

can incorporate the probabilities associated with frequency and intensity of storms. In the case of California described here, the El Niño Southern Oscillation creates a weather pattern that is irregular but somewhat predictable. In other coastal regions other weather patterns such as tropical and extra-tropical cyclones must be examined, and appropriate models developed.

4. *Cumulative Change*: Models such as that described here view the threat from sea level rise (and storms) as a series of repeated single events occurring on an annual basis. After each event, damaged property is replaced. In reality, damages from sea level rise will be much more complicated. Damage property repair or replacement will depend on combinations of insurance plus public and private resources. As damages become more frequent and the costs of repair escalate, decisions will have to be made about how much replacement and reinvestment should be made. (Colgan, Richards, and DePaolis 2018) For some assets, such as the hotels and retail establishments along Cannery Row, the economic viability may come into question after much less sea level rise than the model anticipates. These cumulative impacts of damages will need to be incorporated in the model.

5. *Discount rate*: As discussed, the results of the model tend to support earlier rather than later action. This is due in part to the use of discount rates. With evaluations extending well past the usual life spans of capital investments lasting thirty or forty years into the range of eighty to one hundred years, discounting reduces distant costs and benefits to very small amounts. The approach taken in this analysis treats decisions as being made in 2020 with a discount rate of 5% applied to the entire time period

There are numerous discussions in the literature on how discount rates should be used with such long period evaluations as those involving climate change-related actions. (Zaddach 2016; J. Weyant 2014; J. P. Weyant 2008). Though no clear consensus exists about how best to handle the discounting issue. There is an argument that given the stakes involved, discounting future benefits should not be done at all; that is, a discount rate of 0 should be used. (Stern 2007) This remains controversial, and theory and practice are supporting the use of declining discount rates so that future costs and benefits are subject to higher discount rates covering three to four decades into the future and lower discount rates thereafter. This has become a standard practice in various European countries. (Arrow et al. 2014; Heal and Millner 2014)

An alternative which might be considered in future applications of the model is to consider each deployment of an adaptation option and its rebuilds as a separate decision point and applying a discount rate representing the social opportunity cost of capital at that time. This will require assumptions that the future costs of capital will remain constant; until better understanding of how

consumption/investment preferences might change with alterations to the climate, this assumption may be the only reasonable one.

The project described in this paper is characterized as a prototype model. The purpose was to explore whether and how models of climate change, in this case sea level rise, can be directly coupled to specific adaptations in such a way as to provide useful information to decision makers while at the same time confronting the profound uncertainties that are inherent to all planning for climate change. We believe that a feasible approach has been demonstrated. The next phase of further development will need to address all of the major issues identified and applications extended to other types of sea level rise risk such as effects on infrastructure, coastal recreation, and on ecosystems.

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