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LETTER

Adapting to rates versus amounts of climate change: a case of adaptation to sea-level rise

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Abstract

Adaptation is the process of adjusting to climate change in order to moderate harm or exploit beneficial opportunities associated with it. Most adaptation strategies are designed to adjust to a new climate state. However, despite our best efforts to curtail greenhouse gas emissions, climate is likely to continue changing far into the future. Here, we show how considering rates of change affects the projected optimal adaptation strategy. We ground our discussion with an example of optimal investment in the face of continued sea-level rise, presenting a quantitative model that illustrates the interplay among physical and economic factors governing coastal development decisions such as rate of sea-level rise, land slope, discount rate, and depreciation rate. This model shows that the determination of optimal investment strategies depends on taking into account future rates of sea-level rise, as well as social and political constraints. This general approach also applies to the development of improved strategies to adapt to ongoing trends in temperature, precipitation, and other climate variables. Adaptation to some amount of change instead of adaptation to ongoing rates of change may produce inaccurate estimates of damages to the social systems and their ability to respond to external pressures.

1. Introduction

Anthropogenic greenhouse gas emissions are changing the Earth system at an unprecedented rate [1]. Despite efforts to limit the amount of climate change, anthropogenic greenhouse gas emissions are likely to continue causing Earth to warm for some time into the future [2] potentially leading to the melting of all the large ice sheets and 60 m of sea-level rise in the long-term [3]. In most scenarios of future concentrations of greenhouse gases, high rates of temperature increase are expected to exceed those that many ecosystems could tolerate [4]. Given that we are currently adapted to climates of the recent past, high rates of change risk large costs, no matter what climate might be considered optimal for the long-term. Regardless of whether some climatic end state would be 'better' or 'worse', rapid transition to that climate state could be extremely damaging.

Vulnerability of society to environmental change has made 'adaptation' a key element in climate policy, e.g. [5, 6]. Optimal adaption strategies would reduce costs and take advantage of opportunities posed by a changing climate. Policy and research communities have been focusing on adapting to some specified amount of climate change and not specified rates of change. For example, the Intergovernmental Panel on Climate Change (IPCC) has defined adaptation as 'the process of adjustment to actual or expected climate and its effects' [7]. The IPCC synthesis report recognizes the importance of rates of change [8] but the adaptation studies on which the IPCC relies use amounts of sea-level rise, rather than the rate of sea-level rise, to assess impacts on ecosystems and human populations [7].

However, there is a need to consider scenarios with prolonged and substantial ongoing change. Unrestrained fossil-fuel combustion with release of CO_2 to

the atmosphere has the potential to ultimately melt all of Antarctica at rates of sea-level rise averaging up to 3 cm yr^{-1} over the next 1000 years [3]. Here, using a stylized example of sea-level rise, we provide an analytical assessment of adaptation to ongoing sea-level rise considering both economic parameters (e.g. discount rate, capital depreciation rate) and rates of change of climate parameters (e.g. rate of sea-level rise).

In contrast to previous studies [9–13], we focus on adaption strategies for human systems designed to keep up with ongoing rates of change. Other economic studies have looked at the impact of sea-level rise on the risk to coastal infrastructure as it increases the probability of extreme water levels [14, 15] and imposes a potential land loss [16]. Some economic studies have looked at the impacts of coastal flooding under different scenarios for a certain amount of sea-level rise [17, 18] or for an uncertain amount of sea-level rise [19]. Adaptation is therefore translated into mobility (i.e. the ability of populations and economic activities to migrate to higher ground) when the expected amount of sea-level rise is reached. Most previous research related to adaptation to rates of climate change has focused on biological adaptation [9–11].

Uncertainty about the future rates of climate change especially in the context of sea-level rise has motivated the development of adaptation studies in a wide range of applications from water management policies [20] to an integrated approach to the coastal protection and the preservation of natural and recreational areas [21]. Although these and other studies have taken into account different scenarios of sea-level rise for designing robust adaptation strategies [22, 23], the interplay between climate and economic factors have not yet been explored explicitly in the adaptation decision models.

Designing an adequate adaptation strategy requires calculating the risks of climate change and the vulnerability of the human and natural systems to those risks [7]. The focus of this paper is, however, on the way that the rate of sea-level rise affects economic decision making in coastal areas. In the following sections of this paper we use a more explicit economic decision model for adaptation to sea-level rise. We divide adaptation strategies into four categories: (1) *No adaptation*, in which investors invest on land that will be flooded, but the threat of sea-level rise is ignored, (2) *Adaptation to amounts of change*, in which a coastal buffer zone is created where new development is prohibited in an effort to accommodate some future amount of sea-level change [24, 25], (3) *Adaptation to rates of change*, in which investors invest on land that will be flooded, taking future gains and losses into account when making the investment and (4) *Adaptation with protection*, in which dikes or seawalls are built to try to prevent the rising seas from damaging infrastructure [26, 27]. We calculate the return on investment under each scenario and show that the interplay between economic rates and the rate at which climate

is changing is a key factor in designing effective adaptation strategies.

2. Analytical model for adaptation to sea-level rise

We have developed a schematic model to illustrate key principles governing optimal investment in the face of ongoing sea-level rise. This is motivated by projections that sea-level may continue to rise on the millennial time scale, even with a cessation of emissions [3, 28]. In practice, adapting to ongoing change will involve learning and reduction in uncertainties about the climate system [29]; here, we consider the case in which the future rates of sea-level rise are known. In this model, described in greater detail in the supplementary information, sea-level is assumed to rise indefinitely at a constant rate. We use an annual time scale for the model. While uncertainty about the future rates of sea-level rise may change the quantitative results of our analysis, we expect our qualitative results to remain unchanged because uncertainty increases the need for more flexible adaptation strategies.

Adaptation strategies are modeled as economic decisions about investing a unit amount in developing the coastal area. Given a choice of economic discount rate and a given rate of sea-level rise, we find the location that maximizes the net present value (NPV) of the return on a unit of investment. The distance from the shoreline that maximizes the NPV of return on investment depends on both physical and economic factors.

We assume that the economic revenue from a unit investment is a function of the distance from the shoreline. Investments closer to the shoreline generates higher revenues but they are more susceptible to inundation. Therefore, designing an optimal investment strategy requires considering not only the intrinsic value of coastal zone but the risk of sea-level rise that threatens the productivity of the land in the future. We formulate the NPV of return on a unit investment (R) as the following function of time (t) and distance from the shoreline (x):

$$R(x, t) = e^{-\delta t}e^{-\theta x}, \tag{1}$$

where δ and θ are the economic parameters that control the investment depreciation and land attractiveness respectively. These parameters are chosen to illustrate key concepts; qualitative results do not depend sensitively on choices for model parameters or specific functional form.

Given any set of physical and economic parameters, we can find the optimal location for unit investment near the coastline where the higher benefits of investing in a distance from the rising sea-level is balanced with the lower productivity of the land. The NPV can be formally expressed as:

$$\text{NPV} = \frac{e^{-\theta x}}{r + \delta - \theta\vartheta/s}\left(1 - e^{-\frac{r+\delta-\theta\vartheta/s}{\vartheta/s}x}\right), \quad (2)$$

where ϑ is the rate of sea-level rise, s is the land slope, and r is the discount rate. We denote by x the distance from the shoreline. The optimal distance for new investment can be found to be:

$$x^* = \left(\frac{1}{\theta}\right)\frac{\ln\left(\frac{r+\delta}{\theta\vartheta/s}\right)}{\frac{r+\delta}{\theta\vartheta/s} - 1}. \quad (3)$$

As shown in the key equations above, the depreciation rate δ and the discount rate r have similar effect on the results. Using a higher discount rate (or depreciation rate) in this calculation will make the optimal location for unit investment closer to the shoreline as it is shown in figure S8 of supplementary information. We investigate the interplay among physical and economic factors further in section 4.

In the case of protection with dikes, we assume that the cost increases with the height of the dike. This is in line with other economic analysis of adaptation that consider the cost of protection to be a power function of its height [14, 16]. For simplicity and without loss of generality, we assume this relationship is linear. It is important to note that we have not included the environmental costs of building a dike in our study. Considering environmental costs such as beach erosion or blocking inland migration of wetlands can significantly influence the quantitative results of our study. Here, we have focused only on the direct construction and maintenance costs of built infrastructure.

The three parameters in our model that explicitly have a time component are the rate of sea-level rise (units of cm yr^{-1}), the depreciation rate (units of yr^{-1}), and the discount rate (units of yr^{-1}). From a dimensional analysis, it can be seen that overall losses may be dominated by sea level rise if a property has an elevation above sea level that is less than the rate of sea-level rise divided by the sum of discount and depreciation rates.

For our base case we assume a constant rate of sea-level rise, using $v = 1$ cm yr^{-1}. This is near the high end of the IPCC estimates [30] but lower than more recent estimates [3, 31]. Our qualitative results about the importance of considering rates are largely insensitive to the specific rate of sea-level rise chosen in our illustrative example. We consider a slope of land of 1 m of rise per each 1 km of distance inland ($s = 1$ m km^{-1}), which is characteristic of vulnerable coastlines [32]. Further, we assume that economic productivity of capital assets is higher near the shoreline and declines exponentially with a length scale of 1 km as we move farther inland ($\theta = 1$ km^{-1}). We assume a fixed depreciation time scale of 40 years for capital assets ($\delta = 0.025$ yr^{-1}) [33], but complete loss of those assets when the location becomes flooded. In

Table 1. Model parameters and their values in the baseline case.

Symbol	Description	Value	Unit
θ	Land attractiveness rate	1	km^{-1}
δ	Capital depreciation rate	0.025	yr^{-1}
r	Discount rate	0.05	yr^{-1}
v	Sea-level rise rate	1	cm yr^{-1}
s	Land slope	1	m km^{-1}

our base case, we assume an economic discount rate of 5% ($r = 0.05$ yr^{-1}) [34], although we examine consequences of varying the discount rate and the rate of sea-level rise in section S3.2 in the supplementary information. Table 1 summarizes the parameter values used in the baseline model.
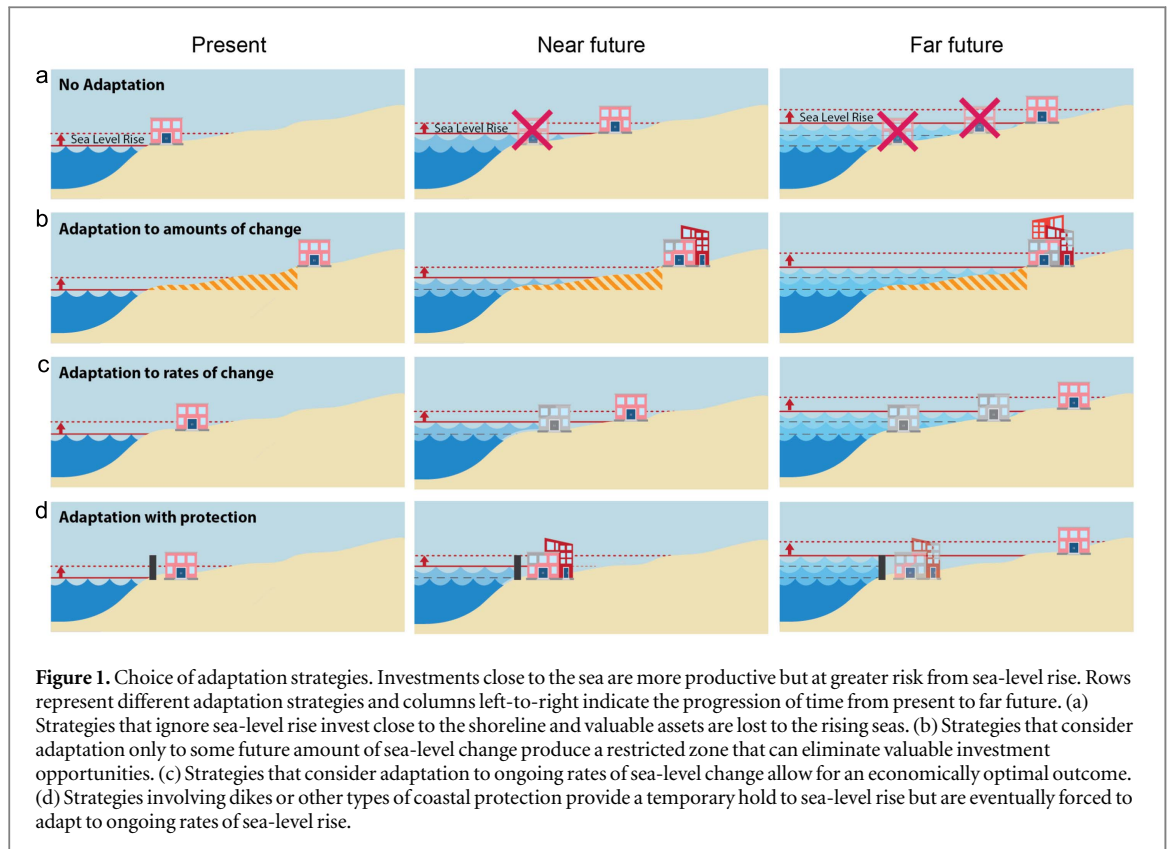
3. Assessing adaptation strategies

Adaptation strategies can be assessed economically by examining the NPV of return on investments. In principle, a wide range of considerations including, for example, the value of biodiversity and natural ecosystems, could show up as costs or benefits in such an analysis. Here, for simplicity we focus on direct costs and benefits associated with coastal urban development.

3.1. No adaptation
In our illustrative model in the absence of sea-level rise, areas close to the shoreline provide the highest return on infrastructure investments and thus, the most attractive location for investment is near the shoreline (row a in figure 1). However, this strategy fails when sea-level rises and with it, the earlier investment near the shoreline is lost. Decision makers may ignore the ongoing sea-level rise trend and dismiss it as a natural variability in the climate system. In this case the investment will be made again at the shoreline where the new sea-level stands. This causes a persistent loss of investment as sea-level continues to rise in the future (see section S2.1 and figure S2 in the supplementary information).

3.2. Adaptation to amounts of change
Adaptation strategies often create a buffer zone near the current shoreline where new developments are prohibited or restricted (row b in figure 1). Therefore, the investment is pushed away to the outer edge of the buffer zone. The problem with the buffer zone approach is that it only considers a fixed amount of future sea-level rise (see section S2.2 and figure S3 in the supplementary information). As a result, when sea-level approaches the end of the buffer zone, heavily invested areas beyond the buffer zone will be at a higher risk of flooding.

Figure 1. Choice of adaptation strategies. Investments close to the sea are more productive but at greater risk from sea-level rise. Rows represent different adaptation strategies and columns left-to-right indicate the progression of time from present to far future. (a) Strategies that ignore sea-level rise invest close to the shoreline and valuable assets are lost to the rising seas. (b) Strategies that consider adaptation only to some future amount of sea-level change produce a restricted zone that can eliminate valuable investment opportunities. (c) Strategies that consider adaptation to ongoing rates of sea-level change allow for an economically optimal outcome. (d) Strategies involving dikes or other types of coastal protection provide a temporary hold to sea-level rise but are eventually forced to adapt to ongoing rates of sea-level rise.

3.3. Adaptation to rates of change

The two responses illustrated above show that the optimal solution to this investment problem is the result of negotiating two opposite forces: other things equal, investments near the shoreline produce higher return because of the attractiveness of coastal environments, but infrastructure near the shoreline is more vulnerable to losses associated with sea-level rise. There is a balance between the loss of the value of an asset through inundation and the loss of value of an asset through depreciation and temporal discounting (see section S2.3 and figure S3 in the supplementary information). The optimal investment strategy avoids constructing too near the coast where assets would be shortly lost to sea-level rise but also avoids constructing too far inland where near term returns on investment would be expected to be small. The optimal location for new construction moves inland as sea-level rises (row c in figure 1). For the parameter values given above, our model predicts that the optimal location for new construction would be 310 m from the current shoreline. If the investment were made half as far from the shoreline, the expected NPV of return on this investment would be 14% less than this optimal investment. If the investment were made twice as far from the shoreline, the return on investment would be 17% less than the optimum (see figure S5 in the supplementary information).

Consider a simple comparison across adaptation strategies. In the case of a buffer zone that extends 500 m from the shore and can accommodate 0.5 m of
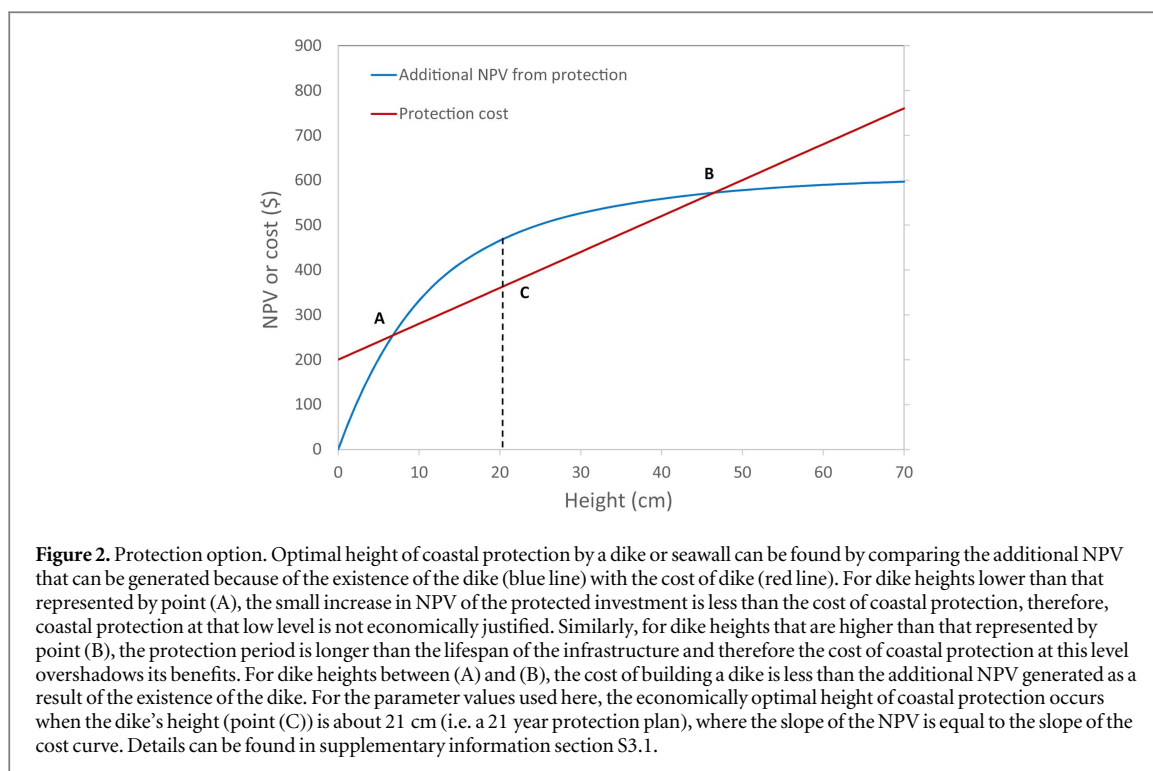
sea-level rise, given the other model parameters above, the NPV of a new investment beyond the buffer zone is calculated to be 8% less than the NPV of the optimal investment that would occur within the buffer zone by taking the future loss of land due to the ongoing sea-level rise into account (supplementary information section S3).

3.4. Adaptation with protection

The fourth strategy outlined in the Introduction section is to protect the coastal zone with a dike or seawall or other method. We consider the case where the dike is built once with a fixed height in anticipation of the future sea-level and note that the height of a dike cannot be raised infinitely (row d in figure 1). Under this assumption, dikes provide only a temporary hold to the ongoing sea-level rise and therefore, investment in the protected zone will be at risk as the sea-level approaches the dike's height. In the case of a dike that can protect the shoreline from a 0.5 m sea-level rise (i.e. a 500 m protected area), the optimal investment yields a NPV of return that is 33% greater than the return expected in the phased retreat strategy in the absence of dikes. If the cost of building the dike were less than the increase in expected NPV of return on investment that would result from the presence of the dike, then such forms of coastal protection would be economically motivated (supplementary information sections S2.4 and S2.5).

Beside the cost of building the dike, the optimal investment strategy depends on the initial amount of

Figure 2. Protection option. Optimal height of coastal protection by a dike or seawall can be found by comparing the additional NPV that can be generated because of the existence of the dike (blue line) with the cost of dike (red line). For dike heights lower than that represented by point (A), the small increase in NPV of the protected investment is less than the cost of coastal protection, therefore, coastal protection at that low level is not economically justified. Similarly, for dike heights that are higher than that represented by point (B), the protection period is longer than the lifespan of the infrastructure and therefore the cost of coastal protection at this level overshadows its benefits. For dike heights between (A) and (B), the cost of building a dike is less than the additional NPV generated as a result of the existence of the dike. For the parameter values used here, the economically optimal height of coastal protection occurs when the dike's height (point (C)) is about 21 cm (i.e. a 21 year protection plan), where the slope of the NPV is equal to the slope of the cost curve. Details can be found in supplementary information section S3.1.

preexisting infrastructure in the coastal land, the rate of capital depreciation and the discount rate. Even when the dike is too expensive to protect new investment, it might still be economically feasible to protect the preexisting infrastructure at the coastal area. Since depreciation rate δ has similar effect on the optimal investment decision as discount rate r does, buildings with higher depreciation rate can be located closer to the shoreline with less protection. Protecting buildings with relatively short life span (higher depreciation rate δ) is less attractive than building a dike to protect the long lasting coastal infrastructure (lower depreciation rate δ).

Optimal height of coastal protection can be found by comparing the cost of building a dike with the additional NPV that can be generated because of the existence of the dike. Figure 2 demonstrates the interplay between the additional NPV of investment in the protected area and the cost of protection. We have shown two points in figure 2 to indicate the range of feasible dike heights that generate positive revenue from investment in the protected area. For dike heights below the feasible range, the small increase in NPV of the protected investment is less than the cost of coastal protection; therefore, coastal protection at that low level is not economically justified. Similarly, for dike heights above the feasible range, the protection period is longer than the lifespan of the infrastructure and therefore the cost of coastal protection at this level overshadows its benefits. Only within the feasible range, the cost of building a dike is less than the additional NPV generated as a result of the existence of the dike. The economically optimal height of coastal protection occurs when the difference between the

additional NPV because of the existence of the dike and dike's cost is at a maximum.

4. Changes in rate of sea-level rise and discount rate

Sea-level continues to rise throughout this century (and beyond) in all climate change scenarios considered by the IPCC, even those that stabilize temperature this century [35]. Sea-level rise had been rising at a rate of about $0.33 \pm 0.04\,\text{cm yr}^{-1}$ over the past few decades [36] but has increased to about $0.44 \pm 0.05\,\text{cm yr}^{-1}$ in recent years [37]. If current greenhouse gas emission trends continue, these rates will likely increase in the coming decades and centuries [38]. Over the next 1000 years, sea-level is projected to rise at an average rate of $3.44\,\text{cm yr}^{-1}$, if all available fossil fuel resources are combusted and the CO_2 released to the atmosphere [3]. Ongoing sea-level rise will have a significant impact on optimal adaptation decisions. In the scenarios where rate of change is taken into account (row c in figure 1), the optimal distance from the shoreline for investment increases from 310 to 481 m as the rate of sea-level is doubled from 1 to $2\,\text{cm yr}^{-1}$. In contrast, the optimal distance reduces to 193 m when the rate of sea-level rise decreases to $0.5\,\text{cm yr}^{-1}$ (figure 3(a)).

Higher rates of sea-level rise and lower discount (and depreciation) rates result in optimal investments shifting to areas farther from the shoreline. (To a first approximation, the rate of sea-level rise divided by sum of discount and depreciation rates yields a scale height h. Other things equal, infrastructure built on
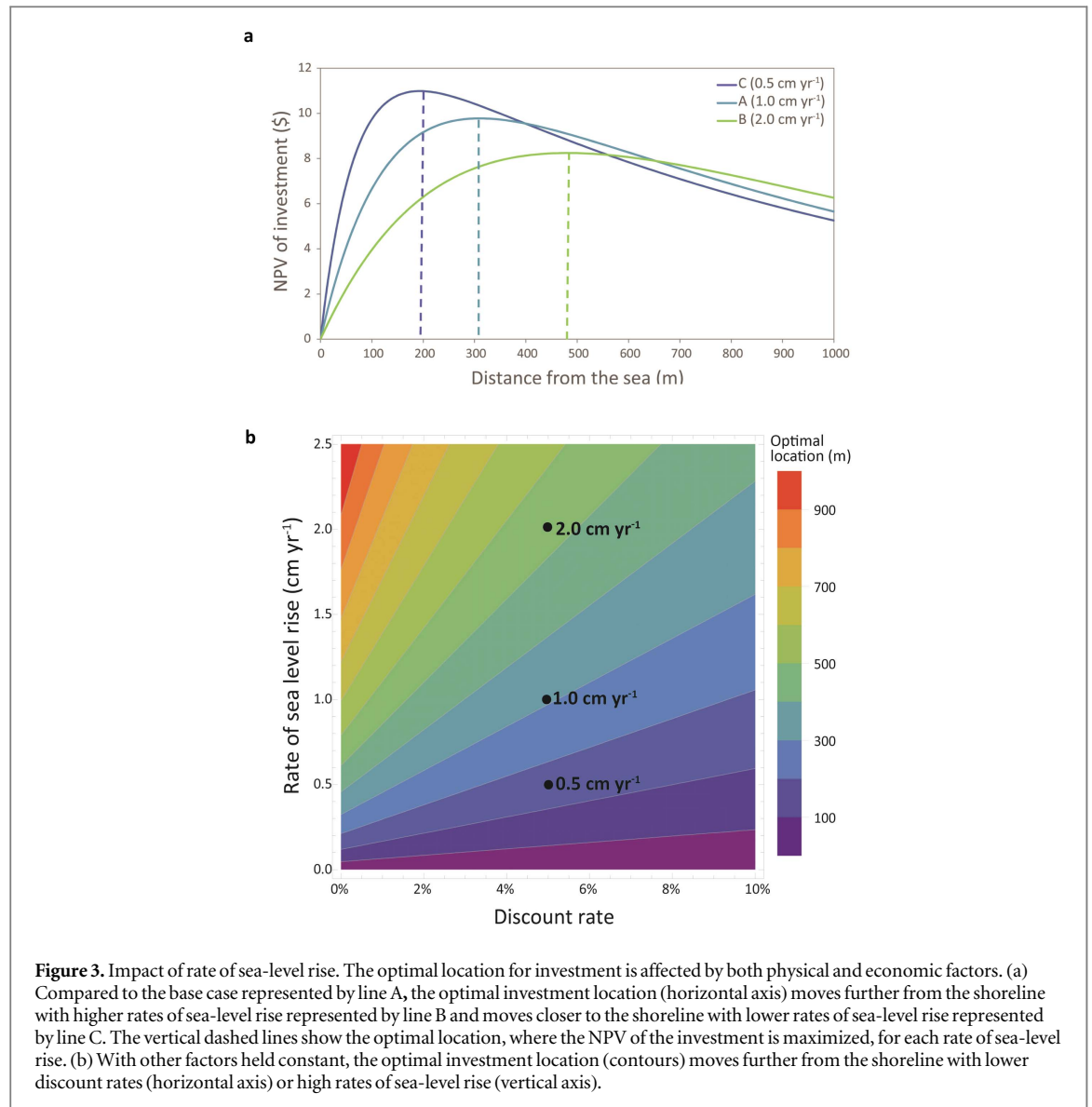
Figure 3. Impact of rate of sea-level rise. The optimal location for investment is affected by both physical and economic factors. (a) Compared to the base case represented by line A, the optimal investment location (horizontal axis) moves further from the shoreline with higher rates of sea-level rise represented by line B and moves closer to the shoreline with lower rates of sea-level rise represented by line C. The vertical dashed lines show the optimal location, where the NPV of the investment is maximized, for each rate of sea-level rise. (b) With other factors held constant, the optimal investment location (contours) moves further from the shoreline with lower discount rates (horizontal axis) or high rates of sea-level rise (vertical axis).

ground higher than *h* will tend to be more greatly impacted by discounting and depreciation than by sea-level rise.) Lower discount rates imply a greater incentive for long term investment and therefore, building the coastal infrastructure further from the shoreline. Figure 3(b) shows the optimal distance from the coastline, given a rate of sea-level rise and a discount rate.

5. Conclusions

Using the example of sea-level rise, we have shown how opportunities to reduce damage can be missed both by failing to plan for higher seas and by planning for some specified future amount of sea-level rise (e.g., by restricting development in coastal areas). In contrast, these opportunities can be realized if adaptation efforts focus on future rates of sea-level rise.

It will help to think about successful adaptation as adapting to moving targets. The need to focus on rates of change, and not just on amounts of change, is highlighted by studies of the velocity of climate change [39]. Temperature zones are moving poleward and ecosystem migrations may not be able to keep up with these rates in many areas of the world, possibly resulting in biodiversity loss. Human systems, similarly can benefit from adapting to rates of climate change.

In agriculture and business, adapting to the rate of climate change may involve increasing the rate of innovation so that adaptation efforts can keep up with future rates of change in patterns of precipitation and temperature [40–43]. Such adaptive measures will not only reduce the cost of a changing climate, but will also take advantage of emerging opportunities.

Failure to recognize the need for adapting to the rate of climate change undervalues the benefits of early adaptation strategies and increases vulnerability to climate change. Focusing on amounts of change rather than rates of change de-emphasizes the potential for progressive adaptation, and thus may tend to overestimate damages to the social systems while underestimating their ability to respond. In the adaptation to

sea-level rise example we provided in section 3, creating a buffer zone to adapt to a fixed amount of change instead of adapting to the rate of change will reduce the NPV of a new investment by 8% compare the NPV of the optimal investment, under the specific parameter choices we made in our baseline case.

Even with optimal strategies, there will be still uncertainties in both measuring the rate of sea-level rise and the socioeconomic factors that impact the return on investment. Flood insurance policies traditionally estimate the likelihood of a flood by assigning a probability to such event. New insurance policies can be designed by taking into account the ongoing rate of sea-level and updating the flood likelihood. This will help reduce the risk of investment and create a dynamically stable economic environment for coastal development.

Mitigation efforts can reduce rates of climate change, but adaptation efforts can engage the rates projected in order to manage and minimize the risks of future climate damages. As the climate is likely to continuously change for the foreseeable future, social systems will have to constantly adapt to this moving target. Our study of adaptation strategies in the case of sea-level rise shows that adaptation to rates of change can provide the flexibility necessary to cope with the consequences of uncertainty in a changing world. In the face of ongoing climate change, adaptation to any fixed amount of change will be inadequate and insufficient in the long run. However, adaptation to rates of change can be updated as uncertainty about climate change reduces over time. This means at any given point in time, the decision maker can decide about the future investment based on the best available knowledge about the rate of sea-level rise.

Many major cities of the world are vulnerable to sea-level rise (e.g., New York, London, Tokyo). Recent studies indicate that sea-level may continue to rise for millennia, ultimately leading to up to 60 m of sea-level rise [3, 31]. Societies will be faced with the decision of whether to defend or abandon cities threatened by sea-level rise. The rate of sea-level rise is a key factor to consider when making such decisions. Owners of assets threatened by sea-level rise are likely to exert political pressure with the aim of socializing the costs of coastal protection. The likely net result in the short run would be overinvestment near the coast by both public and private sectors in order to develop and protect these assets. However as sea-level continues to rise this goal will no longer be feasible and eventually the political system will be unable to justify further public investment in protecting current beneficiaries. A more complete evaluation of optimal decision making would need to consider the political constituencies that might be created, rewarded, or damaged by a decision, and how those political constituencies might affect the future evolution of the system. Nevertheless, good adaptation decisions will consider rates, and not only amounts, of change.

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