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A coupled physical and economic model of the response of coastal real estate to climate risk

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Barring an unprecedented large-scale effort to raise island elevation, barrier-island communities common along the US East Coast are likely to eventually face inundation of the existing built environment[1] on a timescale that depends on uncertain climatic forcing. Between the present and when a combination of sea-level rise and erosion renders these areas uninhabitable, communities must choose levels of defensive expenditures to reduce risks and individual residents must assess whether and when risk levels are unacceptably high to justify investment in housing. We model the dynamics of coastal adaptation as the interplay of underlying climatic risks, collective actions to mitigate those risks, and individual risk assessments based on beliefs in model predictions and processing of past climate events. Efforts linking physical and behavioural models to explore shoreline dynamics[2–4] have not yet brought together this set of essential factors. We couple a barrier-island model with an agent-based model of real-estate markets[5] to show that, relative to people with low belief in model predictions about climate change, informed property owners invest heavily in defensive expenditures in the near term and then abandon coastal real estate at some critical risk threshold that presages a period of significant price volatility.

Barrier-island dynamics that determine risks to the built environment are fundamentally affected by climate change through sea-level rise (SLR) and storminess. We use a previously published physical barrier-island model[6] to simulate the cross-shore response of a barrier island to SLR and storminess. The barrier-island model simulates beach erosion and island overwash during storms, and beach accretion, and dune and vegetation growth between storms. The model is forced by rising sea level, with rates varying between historical and projected[7] values, and storm surges, where we use historical records[8] along the US East Coast to specify a probability distribution that generates storm surge outcomes (see Methods for model details).

Barrier-island property has been most commonly protected by defensive engineering through nourishment—moving sand from other locations to increase the width and change the profile of the beach—and dune restoration[9]. The effectiveness and desirability of these interventions has been the subject of an extensive debate among geologists and engineers[10,11] and these projects continue to be undertaken regularly and at significant financial cost. The effectiveness of these actions changes as SLR and storm regime changes affect the width and profile of the shoreface and the height and stability of dunes. Our model directly incorporates defensive interventions into both the physical and economic components of the model. When nourishment actions are chosen in the economic model, the physical model is altered to increase both the cross-shore width of the aerial beach and the height of dunes.

We use an agent-based framework to drive the interaction between human decisions and physical processes (see Methods for model details). Agents are economic optimizers who differ from each other in their beliefs about climate-driven property risks. The distribution of agent beliefs is structured to reflect the widely divergent opinions in the US public about climate change[12] and present legislative debates about SLR at the state level[13,14]. Agents differ in the weight they give to historical trends and scientific model predictions about environmental characteristics associated with the barrier island and storm behaviour. Specifically, an agent generates a projection of a future environmental characteristic, E, as

$$E_i^j(t) = \alpha_i M^j(t) + (1 - \alpha_i) S_i^j(t) \quad (1)$$

where i is the agent index, j is the environmental characteristic index ranging from one to eleven, α is the weight given to model predictions (normally distributed across agents with first and second moments of 0.05 and 0.02—see Supplementary Information for sensitivity analysis of variations in α), M is the model prediction and S is the agent's calculation of past behaviour. The eleven environmental characteristics are the rate of coastal erosion, the loss of beach due to storm surges from categories one to five, and the return interval in years of storm surges from categories one to five. Agent calculations of past behaviour of a given characteristic are found from

$$S_i^j(t) = \beta_i E^j(t) + (1 - \beta_i) S_i^j(t - 1) \quad (2)$$

where β is the weight given to the most recent value of the environmental characteristic (normally distributed across agents with first and second moments of 0.2 and 0.01—see Supplementary Information for sensitivity analysis of variations in β). Model predictions, M, are found at each model time step, t, by running the coupled barrier-island and economic model forward to model time $t + 50$, and evaluating the mean behaviour of environmental characteristics over that time span. The model is not perfectly predictive, but rather describes the central tendency of a distribution from which random draws determine the actual climatic outcomes that drive property damage in the model (see Supplementary Information for sensitivity analysis of variations in the amount of forecast error in model predictions).

Agents make two sets of decisions—how much to pay for property and how much to spend on defensive engineering.

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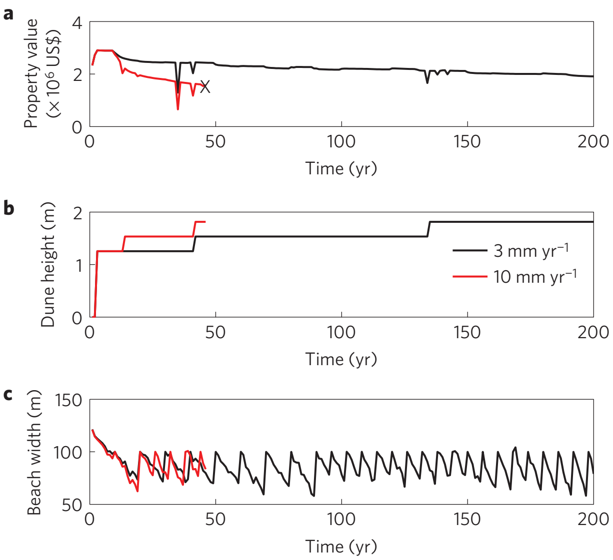

Figure 1 | Property value and defensive engineering. Model simulation results for SLR rates of 3 mm yr^{-1} (black) and 10 mm yr^{-1} (red) representing recent and potential future rates of SLR along regions of the US East Coast respectively. **a**–**c**, The model attributes property value (**a**), dune height measured relative to the barrier island (**b**) and beach width (**c**) plotted versus time. The time of abandonment for coastal property is denoted by X (the 3 mm yr^{-1} simulation reaches abandonment after 314 years).

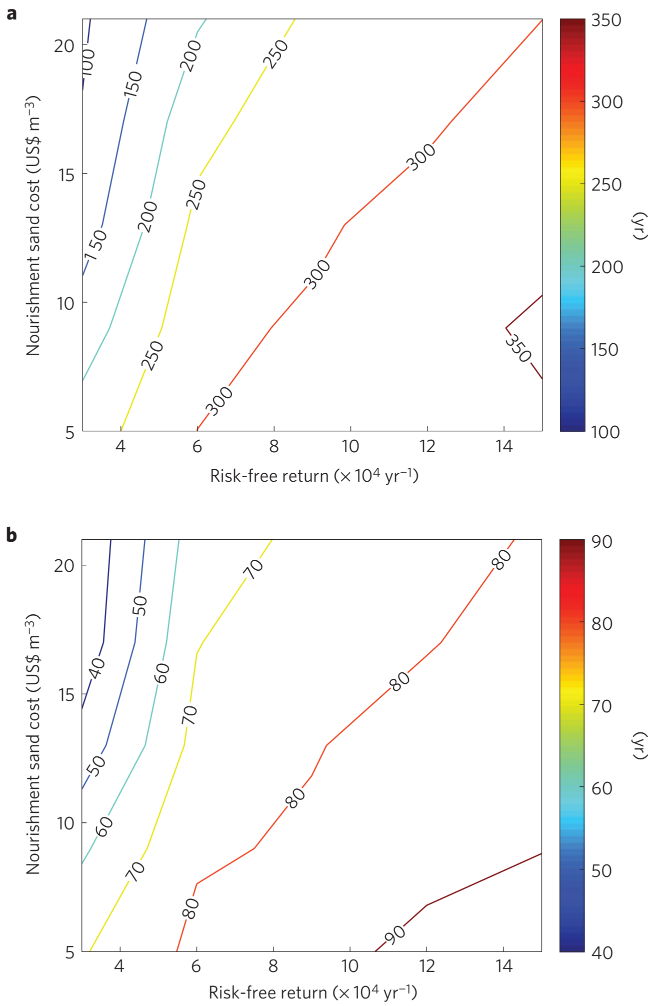

Figure 2 | Time to abandonment for a range of nourishment costs and coastal property returns. a,**b**, Contour plots showing the time to abandonment in years for a range of nourishment sand cost and financial return on property for SLR rates of 3 mm yr^{-1} (**a**) and 10 mm yr^{-1} (**b**). The values used to generate the contour plots were found using the mean time to abandonment from ten simulations at each respective value of nourishment sand cost and risk free return on property.

Individuals' valuation of property depends on rental income less expenses and the expected cost of their share of tax liability for defensive engineering. Flood insurance costs are part of this calculation; the financial returns to owning coastal real estate will be higher if insurance rates are explicitly or implicitly subsidized. Agents also reduce their bid prices for property by the discounted expected cost of property damage from storms and erosion. The agents that bid the highest become the property owners in any given time period.

Property owners collectively make decisions about defensive engineering through an iterative referendum. Each property owner chooses an engineering plan from among ten candidate plans (including no intervention) that gives them the largest positive difference between expected reductions in property damage and their costs. The plan with the lowest number of votes is dropped, and the process repeats until one plan receives a majority of votes.

Within each model year, agents form their property bids and the real-estate market clears and determines which agents own property. Those agents then determine the expenditure plan for defensive engineering. The model then simulates barrier-island response to SLR and storm forcing having taken into account physical alterations from the chosen mitigation strategy. Agents observe the climatic events and the extent of damage to real-estate property and update their expectations, and the cycle repeats. The model runs until risks and defensive expenditures grow so large that there is no longer a positive price for real estate in the market, which is the model's version of the conditions where the market crashes and properties are abandoned.

Large storms that overwhelm the dune and beach nourishment protection are significant events in the model. The value of property drops sharply as agents must factor in the cost of rebuilding and repair to their valuation decisions. They also increase the level of spending on defensive actions as beach widths narrow and dunes suffer height decreases. In addition, agents that are most prone to updating on the basis of recent events experience sharp declines in their property valuations as their pessimism about hazard risk jumps upward. Crashes in the model almost always happen after a significant storm event. This behaviour is qualitatively similar to the abandonment of Diamond City[1] along the coast of North Carolina after 1902 and Ocean Beach along the coast of Maryland[6] in 1962. In both cases storm events caused a discontinuity in the costs and benefits of coastal habitation.

Figure 1 illustrates model outcomes from a representative run at SLR values of 10 mm yr^{-1} and 3 mm yr^{-1}. The rate of SLR is a major determinant of real-estate market outcomes; property values decline almost immediately and much more sharply at high levels of SLR, and abandonment comes far sooner. The higher SLR case shows investments in beach nourishment that are on a slightly shorter and more expensive cycle than at the lower SLR rate, and also exhibits more augmentation of dune heights at a higher cost. As risks get higher in the low-SLR scenario, nourishment cycles get shorter and result in lower beach widths and higher risks as the effectiveness of nourishment diminishes and people with high perceptions of risk get out of the market.

Figure 2 shows the way that the cost of defensive expenditures relative to financial return affects the viability of coastal real estate. At 3 mm yr^{-1} of SLR, relatively low returns lead to early

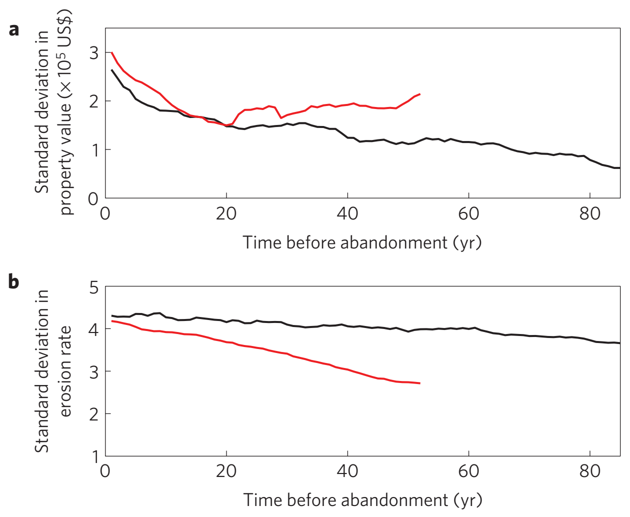

Figure 3 | Coastal erosion and real-estate volatility. a,**b**, The standard deviation (measured over the latest five years averaged across 1,000 simulations for each SLR scenario) in property price (**a**) and coastline erosion rate (**b**) from model simulations with SLR rates of 3 mm yr^{-1} (black) and 10 mm yr^{-1} (red) plotted against the time until abandonment of property occurs. A distinct increase in standard deviation of property price occurs just before abandonment whereas the standard deviation in the coastal erosion rate gradually increases.

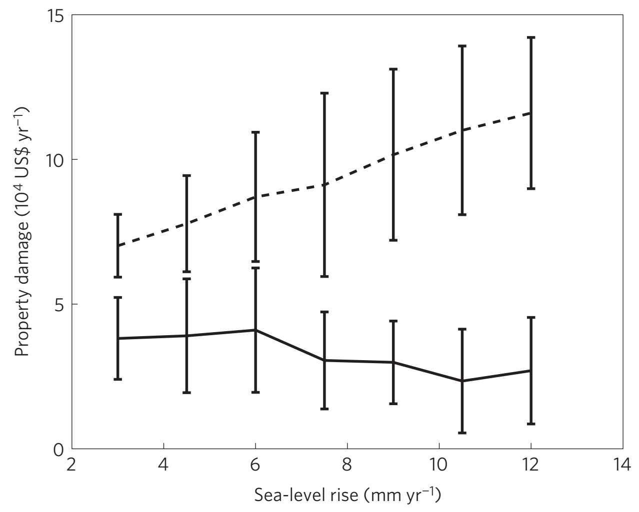

Figure 4 | Property damage as SLR increases. The mean property damage per model year versus a range of SLR rates (averaged over 10 model runs at each SLR rate) for simulations with agents that do not believe central model predictions (dashed) and simulations with a subset of agents that do believe in model predictions (solid). Error bars represent one standard deviation from the mean.

abandonment that is insensitive to the cost of defensive engineering. As underlying property values rise, the cost of sand becomes more influential in determining when coastal real estate loses its viability as an investment. At 10 mm yr^{-1} of SLR, the same relationship holds but the trade-offs are not as significant—risk levels accelerate faster and the influence of financial returns on time until abandonment is not as strong. Lower sand costs still stretch out the period of viability, but by a much smaller number of years than in the low-SLR scenario. These results suggest that higher climate risks increase the incentive to engage in defensive activities in the near term, but that even substantial cost differences may not drive large variations in time until abandonment. Subsidies in the cost of nourishment or insurance premiums would act to increase time to abandonment, but have less of an effect when the rate of SLR is higher.

Our model sheds some light on how price volatility in real-estate markets may be affected by increasing hazard risks. Figure 3 shows the volatility of the erosion rate and housing prices (measured as the standard deviation of the latest five years averaged across 1,000 simulations for each SLR scenario). The volatility of the erosion rate increases gradually whereas that for housing prices increases more markedly in the years before abandonment. The gradual increase in volatility of erosion rate is due to the steepening of the barrier shoreface in combination with continued nourishment as SLRs (ref. 6). The sharp increase in volatility of housing prices reflects the onset of conditions where risks and defensive expenditures begin to approach rental values for active market participants. Both SLR scenarios show a period of increased price volatility at the point where agents more influenced by model predictions no longer think that defensive expenditures are worthwhile and begin to exit the market.

To explore the degree to which belief in well-informed prediction impacts the amount of property damage, we compared simulations in which agents give zero weight to model predictions ($\alpha = 0$ for all agents) with simulations presented earlier in which agents have varying beliefs in model predictions. The amount of property damage is larger when model predictions do not inform beliefs, and the magnitude of this difference rises as the rate of SLR increases (Fig. 4). As model non-believers are more likely to own property during periods of high risk, this highlights an important equity issue. Disaster assistance typically represents income transfers from taxpayers as a whole to affected populations[15], and the systematic selection of model non-believers into the property market means that broader society is funding repairs for damages that the average citizen would not have suffered.

In addition to underlying risks and the costs and effectiveness of coastal defence[16], subjective expectations about climate risk are critical in determining when coastal properties will no longer be inhabitable. These results highlight the role of real-estate markets in integrating information that affects adaptive behaviours, and suggests that volatility in real-estate markets could be a signal of imminent discontinuous change. Future work will investigate how key policy and market variables—risk aversion, infrastructure finance and construction choices—affect risk and adaptive behaviour in coastal environments.

Methods

A barrier island in the model comprises nodes distributed in three-dimensional space that pinpoint the barrier cross-section (Supplementary Fig. S1), which sits on a non-erodible continental shelf. In addition, the model includes sediment contained in an offshore sand reservoir representing sediment found in sandbars and other offshore sources. Along the barrier top, nodes are used to describe a coastal dune and a variable is used to characterize vegetation on the dune.

In response to storm-surge events, rising sea level, waves, wind and current, dynamics are simulated that cause the barrier-island nodes to move and exchange sediment with the offshore reservoir and coastal dune. The simulated dynamics include shoreface accretion and erosion, dune growth and destruction, and barrier-island overwash. In all cases, dynamics are simulated using representations for sediment transport adjusted to apply to the barrier geometry[6].

The economic real-estate model comprises agents who bid on and purchase coastal property. Each agent i makes a bid every model year, $P^i(t)$, as

$$P^i(t) = V^i_o(t) - V^i_l(t) - C^i(t)$$

where V_o is net present value return on the property with no risk assumed, V_l is net present value of the expected property loss from storm damage, and C is net present value of the cost of a chosen mitigation strategy. The net present value return on the property is given by

$$V^i_o(t) = \sum_{j=0}^{50} \frac{R}{(1+d)^j}$$

where R is annual return on the property with no risk assumed and d is discount rate. The net present value of the property loss from storm damage is calculated as

$$V_l^i(t) = \sum_{j=0}^{50} \frac{H^i(j)}{(1+d)^j}$$

where $H^i(j)$ is an agent's expected property loss from storm damage j years into the future. The agents expect property damage in the future from either storm surge overtopping the dune system, storm erosion of the dune and surge overtopping the barrier, or dune destruction from erosion due to rising sea level and surge overtopping the barrier. To calculate the expected damage from these impacts, each agent uses their expected values for storm return intervals, storm erosion and erosion from rising sea level. The way that these are determined is given in equations (1) and (2). Equation (2) describes how recent events affect expectations. High values of β mean that expectations are dominated by recent events, and past outcomes decay quickly in expectation formation—for example, an individual that significantly increases their prediction of future storm risk on the basis of the previous year's hurricane, and then revises that prediction to a much lower level after a number of years without storms. Low values of β bring about the opposite result—agents give more equal weight to events over a longer time horizon, and expectations are more stable because past events decay more slowly in forming expectations.

In addition, each agent calculates the expected loss for each of 10 possible mitigation strategies. The strategies involve nourishing the beach to 100 m in cross-shore width every 4, 6 or 10 years in addition to building the vertical dune height to be larger than surges from storms of category 3, 4 or 5. There are a total of 9 mitigation strategies representing combinations of nourishment frequency and dune building. We also include a tenth mitigation strategy of no nourishment or dune building. The nourishment frequencies and dune heights are within the range of historical nourishment behaviour on the US East coast[9]. The amount of damage (as a reduction in property value) that occurs from storms that overtop the dune system is assigned on the basis of a damage vector of

$$D = [\,0.05 \quad 0.2 \quad 0.4 \quad 0.6\,]$$

where values are associated with storms of categories 2, 3, 4 and 5 (ref. 17). This damage vector is applied to V_o, the net present value return on the property, in the year of the storm occurrence. The net present value of the cost of each mitigation strategy is found from

$$C^i(t) = \sum_{j=0}^{50} \frac{c^i(j)}{(1+d)^j}$$

where $c^i(j)$ is the expected cost of the mitigation, j years into the future and is found from projecting how often dune repair and beach nourishment occur given agent expectations about storms.

Once the net present value of the costs and damages is found for each mitigation strategy, each agent computes a cost benefit analysis for each strategy. The benefits of a mitigation strategy come from the potentially reduced damages as compared with no mitigation expenditures. Each agent then votes for the mitigation strategies as described in the article text.

The bid prices for each agent are then calculated on the basis of the cost of the winning strategy. The agents with the highest N bids become property owners (for the N properties) and coastal property value is set to the Nth highest bid price. Property bids for agents not owning property at present are reduced by a real-estate transaction cost, reflecting the real expenses associated with a change in ownership. Refer to the Supplementary Information for values and sensitivity to model parameters.

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Author contributions

D.E.M. conceived and designed the study, designed and conducted model experiments, and wrote portions of the manuscript and Supplementary Information. A.K. also conceived and designed the study, provided advice on model experiments, and wrote portions of the manuscript and Supplementary Information.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to D.E.M.

Competing financial interests

The authors declare no competing financial interests.