Climate Change Adaptation in Coastal Regions: ODD+D Protocol

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1 Overview

1.1 Purpose

The purpose of this model is to provide a simple environment in which to explore how social network structure and rate of sea level rise influence community relocation from coastal regions vulnerable to sea level rise and flooding. It tracks adaptation decisions in the form of resistance, accommodation, and retreat at both the community and individual household scales. This simple model is loosely calibrated to Harford County, Maryland, but is likely too generic to draw conclusions about any specific place. However expanding the model to include location specific demographic and environmental data and processes could make it a useful tool for decision makers concerned with community relocation.

1.2 State Variables and Scales

1.2.1 State Variables

At the population level, state variables include the amount of community scale adaptation that has occurred and the number of agents, representing individual households, in the simulation area. Agent attributes are given in Table 1.

1.2.2 Environment

The landscape is represented as a grid. One grid cell can be assumed to be 50 m×50 m so that a 30×30 grid with 180 households has an area of 2.25 square km and a population density, assuming 2.69 people per household, of approximately 215 people per square km, matching that of Harford County, Maryland (U.S. Census Bureau Population Division, 2015; Maryland Department of Planning, 2012).

Each agent is assigned an elevation corresponding to its location on the grid, according to the function $E = \frac{10x}{w}$, where E is elevation in meters, w is the width of the modeled landscape, and x is the x-coordinate of the agent's location on the grid. The factor of 10 implies that a point 1.5 km from the shoreline has an elevation of 10 m relative to the initial sea level. Other than elevation above sea level, the environment is homogeneous and therefore does not require digital elevation model or other GIS data inputs.

1.2.3 Time

The model is run for 50 years using annual time steps.

1.2.4 Exogenous Drivers

There are three possible sea level rise scenarios: high, medium, and low. The initial rate of sea level rise (7×10^{-3} m/yr) and the high (1.63×10^{-4} m/yr^2) and low (6.3×10^{-5} m/yr^2) acceleration rates are taken

Table 1: Agent Attributes

Variable	Description	Fixed	Initial Value
Unique ID	Unique identification number	✓	
x	x-coordinate of agent location	✓	Placed randomly
y	y-coordinate of agent location	✓	Placed randomly
Connections	List of agents to whom ego has a social connection	✓	See Section 3.3
Elevation	Elevation in meters above initial sea level	✓	$\frac{10x}{w}$
Adaptive Capacity	Ability for agent to undertake adaptation actions		$\mathcal{N}(0,1)$
Resistance	Level of resistance implemented		0
Accommodation	Level of accommodation implemented		0
p_{action}	Probability that an adaptation action is undertaken		0
p_{resist}	Probability that an adaptation action undertaken is resistance		0.6
$p_{\text{accommodate}}$	Probability that an adaptation action undertaken is accommodation		0.3
p_{retreat}	Probability that an adaptation action undertaken is retreat		0.1
Flood Damage	Level of flood damage experienced and remembered		0
Attachment	Attachment to community, measured by proportion of connections that have not retreated		1
Relative Elevation	Elevation relative to current sea level		Elevation
Inundation	Level of inundation due to sea level rise, mitigated by adaptation actions		0
Retreated	Removed from vulnerable area or not (boolean)		False

from Boesch et al. (2013), using the high and low sea level projections for Maryland by 2100. The mid-range acceleration is the average of the high and low accelerations.

The maximum storm surge that occurs each year is calculated stochastically. The annual exceedance probability, AEP_t, of the maximum storm surge in year t is a uniformly distributed random variable between 0 and 1. Vickery et al. (2013) use the Advanced Circulation storm surge model to simulate storm surge return periods for several sites around the Chesapeake Bay. Using results for site 7483 in Figure 2-11 in Vickery et al. (2013), a logarithmic function was fit to the results presented in Vickery et al. (2013)'s Figure 2-12. It is assumed that storm surge, S, is 0 for $AEP > 0.5$. This results in $S_t = \max\left(0, \frac{-\ln 2AEP_t}{1.164}\right)$.

1.3 Process Overview and Scheduling

At each time step, the following processes occur in the given order:

1. Calculate current sea level
2. Calculate storm surge
3. Implement community level adaptation
4. Update agents:
    i. Calculate adaptive capacity
    ii. Calculate attachment factor
    iii. Calculate relative elevation and inundation level
    iv. Calculate damage in recent memory

   v. Make adaptation decision

5. Remove retreated agents from simulation area

All agents perform steps 4.i-4.iv before any agent makes its adaptation decision. In this way, the agents effectively act simultaneously at each time step.

2 Design Concepts

2.1 Theoretical and Empirical Background

The model is constructed to simulate managed retreat as a risk reduction strategy for coastal communities. It is becoming increasingly apparent that accommodation in place will be insufficient for reducing coastal hazard in many areas and that relocation will be necessary for some communities (King et al., 2014). Furthermore, proactive relocation can reduce costs in the long run (Roberts and Andrei, 2015). It is, therefore, helpful to understand who will retreat, when individuals choose to leave, and impediments to relocation.

The model can be run using three different sea level rise scenarios that follow a quadratic function. This follows the approach of Hall et al. (2016) who present a set of quadratic twenty-first century sea level rise scenarios and argue that considering a range of plausible futures, without assigning probabilities to scenarios, is appropriate for reducing risk.

The model assumes that, initially, resistance actions, such as building seawalls, are the most common adaptation decisions, followed by accommodation (i.e. improving the ability to withstand and recover from inundation and flooding) and that retreat is the least likely adaptation decision to be made. This assumption follows the observation that resistance is often the first response to sea level rise, and managed retreat, which is logistically challenging and expensive, is unlikely to occur except as a last resort (Wong et al., 2014). Factors that change the probability of each of these agent actions are community wide incentives to implement accommodation or retreat and an agent's attachment factor. The incentives and attachment factor therefore act as multiplicative scaling factors for the adaptation probabilities.

It is assumed that the maximum level of resistance and the maximum level of accommodation for each agent is 2 m. The other restriction on whether it is possible for an agent to adapt is its adaptive capacity, a unitless heterogeneous attribute. Adaptive capacity is defined as the ability for systems and individuals to take advantage of opportunities and to respond to potential and actual damage (IPCC, 2014). In the model, adaptive capacity is updated stochastically to simulate changes in the resources available to a household and a household's ability to use those resources. If an agent's adaptive capacity is too small, it is unable to implement an adaptation action.

The type of adaptation actions implemented can influence the ability for households to recover from damage. As opposed to resistance actions, accommodation builds resilience that allows people to recover from floods more quickly (Vis et al., 2003). To reflect this in the model, accommodation reduces the damage experienced by an agent when a storm hits, but resistance does not have this mitigating effect.

At the community level, adaptation can either take the form of resistance or of incentives that encourage individual accommodation or retreat. Community level resistance represents structural engineering endeavors aimed at reducing the prevalence of flooding, whereas accommodation and retreat take the form of a set of policies, such as zoning regulations, building codes, comprehensive community plans, and buyouts (Nettleman et al., 2016). In the model, community resistance cannot exceed 3 m. This flood protection is applied to all agents in the simulation. Community accommodation and retreat do not directly protect agents from flooding, but rather increase the probability of agents implementing adaptation or retreating individually and reduce the adaptive capacity necessary for these actions.

In the United States, as with much of the world, climate adaptation tends to be reactive as opposed to proactive, meaning that people generally wait until they experience a problem before attempting to adapt to future changes (Romero-Lankao et al., 2014). Thus in the model, adaptation decisions are made in response to sea level rise and storm surge that has already occurred. The probability of action at the community and household levels depends on both still water inundation and storm damage in memory.

2.2 Individual Decision Making

There are three possible types of adaptation actions: resistance, accommodation and retreat. At the beginning of the simulation, the probabilities for each of these actions are $P_{\text{resist}} = 0.6$, $P_{\text{accommodate}} = 0.3$, and $P_{\text{retreat}} = 0.1$. These probabilities for each agent evolve in the following manner:

- $P_{\text{resist}} = 0$ if the agent's level of resistance is currently at 2 m or adaptive capacity is less than or equal to 0
- $P_{\text{accommodate}} = 0$ if the agent's level of accommodation is currently at 2 m or adaptive capacity is less than or equal to -0.1 multiplied by the community level accommodation incentive
- $P_{\text{accommodate}}$ increases by a factor equal to the community level accommodation incentive
- $P_{\text{retreat}} = 0$ if adaptive capacity is less than or equal to -0.1 multiplied by the community level retreat incentive
- P_{retreat} increases by a factor equal to the community level retreat incentive
- P_{retreat} is divided by the agent's attachment factor

Provided at least one of P_{resist}, $P_{\text{accommodate}}$, and P_{retreat} is greater than 0, the three probabilities are scaled so that they sum to P_{action}, where P_{action} depends upon the agent's level of inundation and memory of storm damage. This scaling is achieved by multiplying each of P_{resist}, $P_{\text{accommodate}}$, and P_{retreat} by P_{action} and dividing by the sum $P_{\text{resist}} + P_{\text{accommodate}} + P_{\text{retreat}}$.

2.3 Learning

The probability that an agent implements an adaptation decision increases each time they experience storm damage. "Memory" of previous damage decreases by 10% each year.

2.4 Individual Sensing

Agents have awareness of flood damage. Flood damage is a parameter, measured in meters, that represents the amount of flooding experienced and remembered by a household. It is assumed that each year, agents "forget" 10% of the flood damage experienced in previous years. Because accommodation builds resilience, the new damage experienced by an agent i in year t is calculated as $h_{it} \times (1 - 0.05A_i)$, where h_{it} is the height of the storm surge in year t superimposed on the inundation level at agent i's location and A_i is the level of accommodation that i has implemented.

Agents are also aware of whether their connections have retreated or not. The attachment factor for an agent i is calculated as the proportion of i's connections that remain in the simulation area (i.e. have not retreated).

For both flood damage and retreat of connections, there is no cost to agents for obtaining information.

2.5 Individual Prediction

Agents do not predict future sea level rise, flood damage, or adaptation decisions of themselves, others, or the community.

2.6 Interaction

Each household is connected to a set of other households. A household's "attachment" is equal to the percentage its connections that have not retreated.

2.7 Collectives

There are no collectives in the model.

2.8 Heterogeneity

Table 1 identifies the agent attributes that are random, and therefore heterogeneous, at initialization. As the simulation progresses, the agents evolve such that all attributes may be heterogeneous. This increase in heterogeneity arises from the spatially dependent elevation and the different connection lists. Differences in elevation create heterogeneous damage and inundation, which drive the probability of an agent implementing an adaptation action. Heterogeneous connection lists create differences in attachment factors, which result in different relative probabilities for each adaptation action. Lastly, initial heterogeneity and stochastic changes in adaptive capacity limit the ability for some agents to adapt. However, all agents follow the same behavioral rules and are demographically homogeneous.

2.9 Stochasticity

Table 1 indicates which attributes are initialized using random variables. As the simulation progresses, random variables are used to calculate the height of the storm surge each year, changes in agent adaptive capacity, and the implementation of adaptation actions at the community and the household levels. The calculation of flood damage is explained in Section 1.2.4. The initial adaptive capacity of each agent is drawn from a normal distribution, centered at 0, with a standard deviation of 1. Each year, an agent's adaptive capacity changes by a random amount, drawn from a normal distribution with mean 0 and standard deviation 0.1.

The probability that a community level adaptation will be implemented is equal to $0.09\overline{D} + 1.8\overline{I} - 0.18\overline{DI} + 0.1$, where $\overline{D}$ is the minimum of 10 m and the average flood damage of the population and $\overline{I}$ is minimum of 0.5 m and the average inundation level of the population. This ensures that the probability of community adaptation will always be at least 0.1 and will attain a maximum value of 1 when average damage is 10 m or average inundation is 0.5 m. Additionally, in each year there is a 10% chance that the accommodation and retreat incentives will decrease by 1.

At the individual level, the probability that an agent, i, with sufficient adaptive capacity, will undertake an adaptive action in a given year is equal to $0.09D_i + 1.8I_i - 0.18D_iI_i + 0.1$, where I_i is the minimum of 0.5 m and the inundation for household i and D_i is the minimum of 10 m and the flood damage of household i. As with the probability of community adaptation, the probability of individual adaptation is always at least 0.1 and is 1 when $D_i = 10$ or $I_i = 0.5$. The relative probabilities of undertaking each possible action are calculated as explained Section 2.2.

2.10 Observation

The model data collector tracks the following model level variables at each time step: Mean Sea Level, Storm Surge, Num Agents, Accommodation Incentive, Retreat Incentive, and P_{adapt}. These values are stored in the variable "model_attributes" in the file "RunModel.py." The variables "model_attributes" and "agent_states" are stored as a tuple in the variable "output" in "Simulation.py." Also in the file "RunModel.py," the variable "agent_states" stores the following attributes for each agent at each time step: Flood Damage, Inundation, Adaptive Capacity, Resistance, Accommodation, Attachment, P_{action}, P_{resist}, $P_{\text{accommodate}}$, P_{retreat}, Relative Elevation, and Retreated. The file "Simulation.py" creates the following output visualizations:

- An animation of a single agent attribute (flood damage, inundation, adaptive capacity, attachment, P_{action}, P_{resist}, $P_{\text{accommodate}}$, P_{retreat}, or relative elevation) for one model run. The agent attribute is visualized on a grid that updates at each time step.
- A time series of the average value of a single agent attribute (flood damage, inundation, adaptive capacity, attachment, P_{action}, P_{resist}, $P_{\text{accommodate}}$, P_{retreat}, or relative elevation) at each time step for each model run
- A time series of the size of the population that has not retreated for each model run
- The percent decrease in population over the course of an entire model run and the number of years to reach 95% of the total decrease for each simulation
- A time series of extreme water level in each year for each model run

Other data stored in the "output" variable may be analyzed and visualized as the user desires.

3 Details

3.1 Implementation and Details

The model has been developed in Python 3.5.0 using the agent based capabilities of the Mesa 0.8.0 package and is available for download from the CoMSES Computational Model Library (openabm.org). The model is run from the file "Simulation.py" where the user can specify inputs (see Section 3.3 for details). This file also contains code to generate plots of the output (see Section 2.10 for details).

3.2 Initialization

The initial values of agent attributes are given in Table 1. Initial values of model level variables are given in Table 2.

Table 2: Initial Values of Variables

Variable	**Description**	**Initial Value**
Num Agents	Number of agents in simulation grid	180
Width	Width of simulation area (number of grid cells)	30
Height	Height of simulation area (number of grid cells)	30
SLR acceleration	Sea level rise acceleration rate	User selected (see Section 3.3)
Init SLR Increase	Initial rate of sea level rise (m/yr)	0.007
Network Structure	Either spatial (i.e. agents are connected to nearby agents) or aspatial (agents are randomly connected to any other agent)	User selected (see Section 3.3)
Network Parameter	Either radius of connection for spatial network or density of aspatial network	User selected (see Section 3.3)
Sea Level	Height of sea level relative to initial value (m)	0
Storm Surge	Height of storm surge (m)	0
Community Resistance	Level of resistance implemented at community scale	0
Accommodation Incentive	Community level incentive to implement accommodation actions	1
Retreat Incentive	Community level incentive to retreat	1
P_{adapt}	Probability of community level adaptation	0

3.3 Input

The model user must select a sea level rise scenario and social network structure. In the file, "Simulation.py," the user may set the parameter "slr_scenario" to be 'h', 'm', or 'l' for high, medium, and low sea level rise, respectively. These three scenarios are detailed in Section 1.2.4. The user may also specify whether the variable "network_structure" is 'spatial' or 'aspatial.' For the spatial network, all agents are connected to agents within a specified radius. The user must, therefore, also specify a value for "connection_radius." In the aspatial network, connections are formed randomly. The probability of a connection between any pair of agents is equal to the user specified parameter "connection_percentage." The user may also set the number of simulations to be run.

The user can also select one agent attribute to observe in an animation for each run. The possible attributes are: Flood Damage, Inundation, Adaptive Capacity, Resistance, Accommodation, and P_{action}. To select an attribute, the user must set the appropriate value for the variable "animated_attribute."

The model requires no external data files.

3.4 Submodels

The model can be broken into two submodels: community level adaptation and agent updating/decision-making. At the community level, the probability of implementing an adaptation action depends upon the average damage and inundation of all agents (see Section 2.9). There are three possible types of community level adaptation with the following effects:

- **Resistance** represents a community wide seawall. Each time community level resistance is enacted, the seawall is raised 1 m with a maximum height of 3 m.
- **Accommodation** represents incentives for individual households to implement accommodation actions. Each time community level accommodation occurs, the accommodation incentive factor increases by 1 and the adaptive capacity necessary for a household to implement accommodation decreases by 0.1 (with an initial value of 0).
- **Retreat** represents incentives for individual households to retreat. Each time community level retreat occurs, the retreat incentive factor increases by 1 and the adaptive capacity necessary for a household to retreat decreases by 0.1 (with an initial value of 0).

At each time step, there is a 10% chance that the accommodation incentive will decrease by 1 and a 10% chance that the retreat incentive will decrease by 1. At the beginning of the simulation, the relative probabilities of implementing each of these community level adaptations are 0.6 for resistance, 0.3 for accommodation, and 0.1 for retreat. These probabilities are equal to the initial values of the agent level variables P_{resist}, $P_{\text{accommodate}}$, and P_{retreat}, again assuming that resistance is the most likely response to sea level rise and that retreat is a last resort (Wong et al., 2014). If the community level resistance reaches 3 m, these relative probabilities change to 0 for resistance, 0.7 for accommodation, and 0.3 for retreat.

At the agent level, households first update their adaptive capacity, which changes by an amount x where x is a normally distributed random variable with mean 0 and standard deviation 0.1. Households then calculate their attachment factor, equal to the proportion of connections that have not retreated. Next, inundation is calculated as the sum of an agent's elevation relative to current sea level, the agent's accommodation level, and whichever is greater of the agent's resistance and the community wide resistance. Finally, agents apply new flood damage from the current year's storm surge and "forget" 10% of any previous damage. After all agents have updated these attributes, households make adaptation decisions, as described in Section 2.2. The three possible adaptation actions have the following effects:

- **Resistance**: The first time resistance is implemented, an agent's resistance level increases to 1 m. The second time, resistance increases to 1.5 m, and the third time, it increases to 2 m, which is the maximum possible resistance at the agent scale
- **Accommodation**: The first time accommodation is implemented, an agent's accommodation level increases to 1 m. The second time, accommodation increases to 1.5 m, and the third time, it increases to 2 m, which is the maximum possible accommodation for an individual
- **Retreat**: The agent is removed from the simulation area

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