

**Coastal Communities and Climate Change:  
A Dynamic Model of Risk Perception,  
Storms, and Adaptation**

by  
Travis Read Franck

Submitted to the Engineering Systems Division  
in partial fulfillment of the requirements for the degree of  
Doctor of Philosophy in Technology, Management, and Policy  
at the  
MASSACHUSETTS INSTITUTE OF TECHNOLOGY  
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**Abstract**

Climate change impacts, including sea-level rise and changes in tropical storm frequency and intensity, will pose significant challenges to city planners and coastal zone managers trying to make wise investment and protection decisions. Meanwhile, policymakers are working to mitigate impacts by regulating greenhouse gas emissions. To design effective policies, policymakers need more accurate information than is currently available to understand how coastal communities will be affected by climate change.

My research aims to improve coastal impact and adaptation assessments, which inform climate and adaptation policies. I relax previous assumptions of probabilistic annual storm damage and rational economic expectations—variables in previous studies that are suspect, given the stochastic nature of storm events and the real-world behavior of people. I develop a dynamic stochastic adaptation model that includes explicit storm events and boundedly rational storm perception. I also include endogenous economic growth, population growth, public adaptation measures, and relative sea-level rise.

The frequency and intensity of stochastic storm events can change a region's long-term economic growth pattern and introduce the possibility of community decline. Previous studies using likely annual storm damage are unable to show this result.

Additionally, I consider three decision makers (coastal managers, infrastructure investors, and residents) who differ regarding their perception of storm risk. The decision makers' perception of risk varies depending on their rationality assumptions. Boundedly rational investors and residents perceive storm risk to be higher immediately after a storm event, which can drive down investment, decrease economic

growth, and increase economic recovery time, proving that previous studies provide overly optimistic economic predictions. Rationality assumptions are shown to change economic growth and recovery time estimates.

Including stochastic storms and variable rationality assumptions will improve adaptation research and, therefore, coastal adaptation and climate change policies.

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# Chapter 1

## Introduction

Coastal communities must adapt to climatic changes throughout the current century and beyond. Climate change impacts, including sea-level rise (SLR) and changes in tropical storm frequency and intensity, will pose significant challenges to city planners and coastal zone managers. Meanwhile, national and international policymakers are working to mitigate future climate impacts by regulating greenhouse gas emissions. To define more effective policies, policymakers need more accurate information to better understand how coastal communities will be affected by climate change.

To inform the policy decision making process, researchers develop tools and models to understand and analyze coastal adaptation. These coastal models, like all models, are based on assumptions about the how society makes choices and how the climate system will behave in various scenarios. It is important to better understand if and how the assumptions shape study results and, by extension, influence policy recommendations.

This research aims to improve the methodology used to conduct coastal impact assessments, which will provide better information to policymakers as they craft climate policies. Of particular interest are previous assumptions of probabilistic annual storm damage and rational economic expectations. These assumptions are suspect given the stochastic nature of storm events and the real-world behavior of people.

This research focuses on two main questions:

- What are the important community dynamics if storms are modeled more explicitly?
- What are the implications for adaptation studies if a boundedly rational, disequilibrium model is used?

This dissertation demonstrates a new assessment methodology that incorporates variables previously not explored in past studies: boundedly rational risk perception and stochastic tropical storms. These assumptions are examined in a unique simulation model with endogenous economic development. Including these variables provides a more realistic interpretation of events affecting coastal communities.

## **1.1 Motivation for the Research**

### **1.1.1 Climate and the coast**

Future climatic changes are inevitable. The response of the Earth's natural systems to human-caused greenhouse gas forcing will require society to adapt to the resulting changes in weather patterns and coastal conditions. For coastal communities, these climate conditions will translate into an increase in relative sea level and changing tropical storm patterns. Local coastal zone managers will need to implement protective measures to regulate the coastline as these changes take hold.

Coastal zone planning is a complex process that requires managers to prioritize many different factors and interests across stakeholder segments. For example, managers must consider cities' needs to zone for industrial, commercial, and residential spaces (McCune, 2009). Additionally, they must also consider how their decisions impact nearby natural ecosystems, such as local wetlands (Axtman, 2009). The complexity of these issues is compounded by the dynamics of the system in which they are

embedded—for example, infrastructure developers change their investment decisions in response to urban planning choices, like levee construction and zoning laws.

Previous research has examined two main coastal impacts: SLR and storms. SLR has been studied more extensively, including studies of potential impacts (e.g., vulnerability studies of Titus, 1988; Nicholls, 2002; Ericson et al., 2006) and studies of how society might react (e.g., adaptation studies of Yohe et al., 1996; Titus et al., 1991; Fankhauser, 1995; Anthoff et al., 2006). These studies explore SLR scenarios that range from 0.18 m to 1.5 m of global SLR by 2100 (Meehl et al., 2007; Rahmstorf, 2007). The models often include projections of economic growth with exogenous growth rates, or growth rates defined outside the model.

Storm impacts are sometimes included in SLR adaptation studies because of their potential to cause damage. Most studies calculate the annual probable storm damage by multiplying the likelihood of an event by the damage by that event (Hinkel et al., 2009). Damaged infrastructure is then removed from the community at that constant expected annual rate. The result is a smooth removal of a capital, instead of a sudden reduction caused by a distinct storm event. The dynamics of storm events, including the potential for large storm damage, evacuations, and subsequent change in economic and population recovery, are lost in the analysis, especially if the model is driven by exogenous economic growth rates.

Tropical storms may become more intense and/or more frequent as global atmospheric and sea-surface temperatures rise (Emanuel, 2005). It is important for coastal managers to be able to examine and understand the underlying risks associated with such a trend. Explicit storm representation will be important for future coastal adaptation studies.

### 1.1.2 Behavior and risk

The way people understand and perceive risk underlies planning for and adapting to climatic threats. A large literature in psychology and behavioral economics suggests that coastal communities may not respond to these climate threats in a rational manner (i.e., maximize their well-being when making decisions) because of limited or poor understanding of risk (Tversky and Kahneman, 1974; Kydland and Prescott, 1977; Kunreuther and Pauly, 2006). Instead, decision makers within communities may act according to their perceived risk of storms and coastal flooding, reflecting a more boundedly rational decision process that uses limited information.

For example, many property owners in Gulfport, Illinois, situated along the Mississippi River, believed they were protected by the presence of a levee system surrounding their town. In the summer of 2008, the levee broke and flooded the land behind it. Though residents had been eligible for flood insurance through the National Flood Insurance Program (NFIP), only 28 of 200 property owners had actually purchased policies. They had not perceived a risk of levee failure and felt they did not need insurance. Town officials, who had promoted the protection provided by the levee, reinforced this belief (Mattingly, 2008; Webber and Fisher, 2008). The actions were taking even though hundreds of levees failed along the Mississippi River in 1993 (Larson, 1996).

As with flood risk, the public also poorly understands hurricane risk. State officials in hurricane-prone Florida worried that residents would be ill prepared for the 2008 hurricane season due to the relatively quiet hurricane seasons of the previous three years (Cave and Almanzar, 2008). Officials believed people had forgotten the storms of 2004 even though the probability of a storm hitting a community in Florida had not changed. With time, the public's awareness of the risk had faded. Without the awareness of likely storm damage, officials feared citizens were not taking normal precautionary measures, such as keeping an emergency food pantry at home.

These anecdotes are supported by academic research. Tversky and Kahneman (1974) studied the human tendency to forget the likelihood of an event or disaster. Kydland and Prescott (1977) described how flood plains could be developed under circumstances that are economically suboptimal. Kunreuther and Pauly (2006) found that property owners did not internalize the risk of flooding when deciding whether to build homes or buy flood insurance.

Previous coastal adaptation studies have assumed that decision makers are rational agents who make decisions in contexts with no uncertainty. In these studies, decisions to build protection mechanisms are based on optimized benefit-cost analysis studies. Fankhauser (1995) developed an optimization framework that assumed that an agent with perfect foresight (i.e., certainty) could choose the optimal degree of protection in the model's first time-step. Additionally, the framework assumed no feedbacks between adaptation decisions and capital investments.

These assumptions are unlikely to be appropriate when viewed through the lens of behavioral economics, risk analysis and management, and climate change. Global adaptation studies could be improved by relaxing the assumption that agents make rational decisions. For example, Hallegatte (2006) provides an initial study of how some of these assumptions influenced New Orleans after Hurricane Katrina. His study highlights the need to design coastal protections in a manner that protects current infrastructure but does not attract more investment, which would ultimately put more people and property at risk.

Community decision makers will be designing policies that will change the behavior of a community's investors and residents. Coastal adaptation studies should include a reasonable behavioral representation of the community's actors to better understand policy implications.

## 1.2 Present Research

This work focuses on how the assumptions of integrated coastal adaptation models can influence policy analysis. I extend previous climate change adaptation frameworks by relaxing many limiting modeling assumptions. I develop a dynamic simulation model to explore how risk perception and climatic threats affect adaptation in coastal communities. The model highlights the feedbacks among important processes that determine economic development and coastal adaptation performance (e.g., how risk perception influences capital investment), and is not intended to predict coastal development precisely. The goal of the research is to improve future global coastal adaptation studies and, therefore, future adaptation policies.

The Feedback-Rich Adaptation to Climate Change (FRACC) model follows system dynamics methodology (Sterman, 2000), consisting of stochastic nonlinear differential equations solved by simulation. The model includes components such as:

1. Global and relative SLR scenarios
2. Stochastic storm events and climate scenarios
3. Risk perception of storm frequency by investors
4. Storm damage and evacuation
5. Population growth including immigration and emigration
6. Private investment in capital and housing
7. Coastal adaptation including levees and beach nourishment
8. Fragility of coastal defenses, including levee breaching
9. Wetland succession

These components interact with each other, producing the system's behavior. In this system, a community's economic development depends on the amount and rate of SLR, storm events, the performance of coastal adaptation measures, and the reaction of investors and residents to these factors and events.

The model has a broad system boundary, integrating economic processes, stochastic tropical storms, limited foresight, and poor risk perception. The decisions in the model are made by three separate “agents”: adaptation planners who understand climate science and probability, and investors and residents, who are represented as having boundedly rational perception of storm events.

I developed the FRACC model because we need a dynamic feedback model to examine how storms and decision making influence the outcomes of adaptation studies. Previous models did not have endogenous economic adjustment mechanisms (i.e., economic processes defined in the model), and instead used exogenous economic growth rates (i.e., assumed external economic processes).

By including an endogenous economy and stochastic storms, the model provides an opportunity to study a community’s economic resiliency to storm events. The FRACC model illustrates that under some circumstances, economic growth may stagnate and decline after SLR and storm events. Stagnation depends on model assumptions, including bounded rational versus rational agents. The possibility of economic decline reflects the challenges that coastal communities face in the real world.

### **1.3 Dissertation Overview**

The next chapter provides additional context and background for this research and includes a discussion of previous climate and adaptation studies along with specific information about coastal management practices in the United States. Chapter 3 presents the FRACC model equations and assumptions and describes the components and their feedbacks. Chapter 4 provides details about three different US coastal communities, which serve as case studies to test the model. Chapter 5 presents base case model results. Sensitivity tests are presented in Chapter 6, including the implications of rationality assumptions and tropical storm distributions. Chapter 7 explores a policy scenario, demonstrating the use of the model for policy analysis.

Chapter 8 concludes the dissertation with a discussion of the results, including their implications for policy and for global coastal adaptation studies.



# Chapter 2

## Climate Change and Coastal Adaptation

This chapter provides an overview of climate change and coastal adaptation literature. The first section covers the scientific aspects of coastal adaptation to climate change—namely sea-level rise (SLR) and storms. The next section considers how people perceive risks associated with natural disasters, which has important implications for coastal adaptation research. Previous economic studies are discussed next, highlighting the assumptions that are changed later in this dissertation. The final section presents various techniques for protecting coastal communities against climatic risks, including practices that are common in the United States.

### 2.1 Climatic-induced Sea-Level Rise

Contrary to public perception, SLR is not the same around the world. Different communities will experience varying amounts of SLR depending on local conditions. The actual height of SLR in a particular region is referred to as the “relative sea-level rise” (RSLR) of the region. RSLR is the sum of the global SLR trend, plus the location-specific uplift and subsidence factors. While the next section discusses the important factors increasing SLR and RSLR, Chapter 4 defines in more detail the rates of subsidence and uplift for the communities in this dissertation.

### 2.1.1 Global sea-level rise trends

Climate change and the resulting higher global temperature increase long-term rates of global SLR. The four major sources of global SLR are 1) thermal expansion of oceans, 2) alpine glacier melt, 3) melting of the Greenland ice sheet, and 4) melting of the Western Antarctic Ice Sheet (WAIS) (Gornitz, 1995).

Thermal expansion refers to the effect of warmer global temperatures on the oceans. As the oceans warm, the water expands and the same number of water molecules occupies a larger volume. Thermal expansion is a slow process because it is a consequence of mixing the different layers of the ocean, and each layer has a different time constant for mixing. The long time constant for deep-water mixing means that the oceans will expand for centuries to come, even if the global air temperature were stabilized today. This is often called the “commitment to sea-level rise” (Nicholls and Lowe, 2004; Solomon et al., 2009).

The second main contributor to global SLR is glacial melt. There are two sources of glacial melt: Mountain glaciers and the large ice sheets in Greenland and Antarctica. During the 20th Century, many mountain glaciers melted, and their runoff flowed through rivers into the oceans. The new mass of water, which was previously stored on land, raises the global sea-level. The World Glacier Monitoring Service surveys mountain glaciers annually and has found that mountain glaciers are receding at a rapid rate (World Glacier Monitoring Service, 2007).

Greenland and the Western Antarctic Ice Sheet (WAIS) are both melting but the rate of melting and their net additions are actively debated. Greenland appears to be melting along both its perimeter and its interior. The rates of melting are more extensive than previously thought, according to satellite and land-based instruments (van de Wal et al., 2008). There is also a process of “lubrication” in which the melt water flows between the glacier and the bedrock, increasing the rate of ice flow toward the ocean. This appears to be a seasonal phenomenon, but is currently poorly

understood (Joughin et al., 2008).

Researchers previously disagreed about whether Antarctica experienced a net change in ice mass. Some researchers wondered if the continent's interior gained ice faster than its perimeter melted; however, Velicogna and Wahr (2006) used satellites to measure the continent's mass and discovered a net loss. Now it appears that both the WAIS and Greenland ice sheets are net contributors of water to the oceans.

The Greenland and Antarctic ice sheets pose a large uncertainty risk in global SLR predictions. The Intergovernmental Panel on Climate Change's (IPCC) Fourth Assessment Report (AR4) published estimates for future SLR. Their estimate for 2090–2099 is 0.18–0.58 m (Meehl et al., 2007). This range includes SLR caused both by melting mountain glaciers and thermal expansion, but does not include the impact of the Greenland and WAIS ice sheets. Instead, the IPCC stated that up to an additional 0.2 m of SLR could occur by 2100 due to “large ice sheet melt,” scaling up recent discharge rates as a function of global mean temperature. The final range of SLR estimated in the IPCC AR4 is 0.18–0.78 m by 2100 (90 percent confidence interval).

When the IPCC released its study, researchers suggested that their global SLR estimates were too optimistic and that the risk of larger SLR was much greater. Pfeffer et al. (2008) state that a likely range of SLR by 2100, including increased ice dynamics, is 0.8–2.0 m. They acknowledge that their study contains large uncertainties. Their study agrees with Rahmstorf (2007), who also estimates a higher SLR range of 0.5–1.4 m by 2100, using IPCC AR4 temperature projections.

Projections of SLR by 2100 may vary, but the rate of global SLR in the next hundred years (2000–2100) will likely be faster than in the previous hundred years (1900–2000). The IPCC reports that the recent rates of 3.1 mm/year (1993–2003 average) exceeded the average  $1.8 \pm 0.5$  mm/year from 1961 to 2003. It's important to consider that these historic rates may not reflect the actual amount of change

to date. Measured SLR rates might be lower than would naturally occur because humans have entrapped water inland in reservoirs, preventing a significant volume of water (0.55 mm/year) from reaching the ocean (Chao et al., 2008).

Going forward, the annual rate of SLR will depend significantly on the stability of the large ice sheets (Overpeck et al., 2006). Additionally, a recent study concluded that contributions from WAIS may not spread uniformly throughout the oceans, causing higher SLR than the global average in only some coastal areas, such as the southern US (Mitrovica et al., 2009). Uneven distribution of ice sheet melt could mean that regions in the United States face higher levels of SLR than any current estimate, which explained further in the next section.

### **2.1.2 Relative sea-level rise factors**

The actual rise in sea-level for a particular location, or relative sea-level rise (RSLR), will likely vary from the global mean SLR. Local trends can offset or exacerbate the global rate. For this reason, it is important to use the RSLR rates when planning coastal management strategies for protection or retreat.

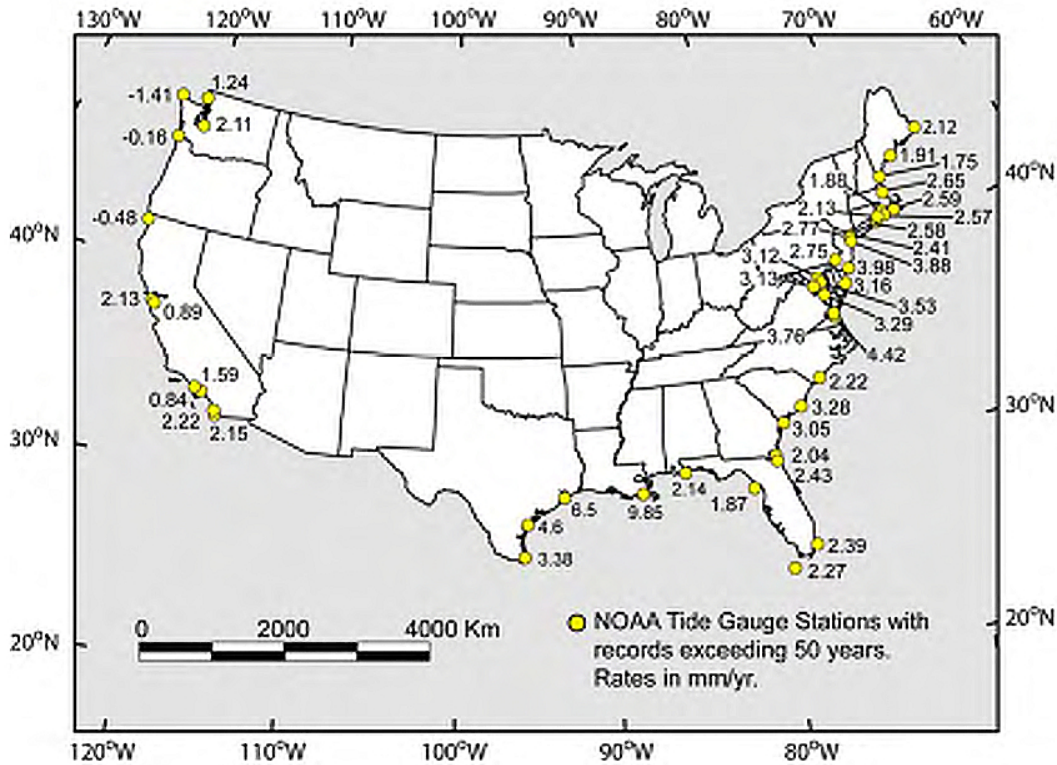
The location-specific forces influencing RSLR include 1) plate tectonics, 2) isostatic adjustments, 3) uneven landmass in the Northern Hemisphere, and 4) sediment compaction (Emery and Aubrey, 1991). Plate tectonics is the shifting of the Earth's plates either closer or farther apart. Either process can change the shape and size of an ocean basin. For example, if two plates on either side of an ocean basin are moving away from one another, the ocean basin will become wider, which results in a lowering of that ocean basin's sea-level.

Isostatic adjustments include post-glaciation rebound. During an ice age, ice sheets weigh down the Earth's crust, pushing polar ends of the plates down while lifting the opposite end. The action reverses as the ice retreats at the end of an ice age. Today the Earth's crust continues to rise and fall due to the retreating of glaciers from

the last glacial period, approximately 10,000 years ago. While tectonic rebound is a slow process, the rise will be an important factor to offset global SLR in some US communities.

The uneven distribution of land changes the shape of the layer of water covering the Earth. If land were evenly distributed, the water would evenly distribute. Instead, the gravitational pull of the large area of land in the Northern Hemisphere attracts water and raises the RSLR as compared to the South Hemisphere (Emery and Aubrey, 1991). Mitrovica et al. (2009) recently discussed how water from the WAIS might impact RSLR, noting that it will be unevenly distributed across the Earth. The mass of large ice sheets currently attracts ocean water, raising the relative sea level nearby. As a large ice sheet melts, the decrease in mass will lower relative sea level for land within approximately 2,000 km, even with the addition of melt water. Instead, the relative sea level will rise disproportionately for locations farther from the ice sheet. In the case of the melting WAIS, the Northern Hemisphere will experience relatively more SLR than locations in the Southern Hemisphere. The gravitational effect has largely been ignored in SLR studies, with the exception of Katsman et al. (2008) who generated SLR scenarios the Northeast Atlantic with gravitational effects.

Along with plate tectonics and other large-scale forces, land may be sinking because of small-scale trends at specific locations. Pumping resources from underground reservoirs can cause subsidence, the sinking of land above. In many places, water is being pumped to prevent flooding (e.g., New Orleans) or to supply drinking water (e.g., Bangkok). Land may also be sinking because of oil extraction (e.g., Long Beach, CA) (Emery and Aubrey, 1991). Additionally, land may be sinking because of sediment compaction. In particular, the soils of river deltas compact as they settle, which increases RSLR. New Orleans, in the Mississippi River delta, is experiencing 9.85 mm/year of RSLR, compared to global SLR mean of 1.7 mm/year (CCSP, 2009). Rates of RSLR for the United States are depicted in Figure 2-1.



**Figure 2-1:** Rates of relative sea-level rise around the United States. (Sources: Figure 1.4 from CCSP (2009); Data from Zervas (2001))

## 2.2 Climate Change and Tropical Storms

Tropical storms are another important driver for coastal adaptation. Coastal managers regularly take into account storm frequency and severity when considering how to protect property that is vulnerable to coastal flooding.

Tropical storms only affect a fraction of the world’s coastline. Other types of non-tropical storms also affect coastal communities. Nor’easters, for instance, can cause severe damage in New England. Tsunamis and other large weather systems also cause damage in other parts of the world. This dissertation only considers the impacts of tropical storms and other storm types would need to be included for a more complete global study.

While current planning processes use estimates of storm frequency and intensity, the assumed distributions of storm events may not accurately reflect future climatic con-

ditions. If storm characteristics do not represent the future, then coastal protection might not protect adequately. Emanuel (2005) concluded that tropical storm intensities have increased in the past three decades. He shows a correlation between the warmer sea-surface temperatures and higher tropical storm intensity because warmer surface temperatures provide more energy for storms.

Some researchers debate Emanuel's conclusions. Landsea (2005) and Pielke Jr (2005) argue that there is no statistically significant trend during the last 30 years. Furthermore, they argue that any increase in storm damage is positively correlated with real estate development in coastal communities because there is now more property in harm's way than there was 30 years ago. The debate is still active, but a reanalysis of the studies by Kossin et al. (2007) concludes that a statistically significant trend exists for storms in the Atlantic Ocean basin, where the communities in my case studies are located.

To further study the changes in storm frequency and intensity, Emanuel et al. (2008) developed the Coupled Hurricane Intensity Prediction System (CHIPS), a physics-based storm event model. The CHIPS model randomly seeds storm events throughout an ocean basin. These locations of "genesis" vary in both the time of the year and latitude and longitude. After a storm is seeded, whether it develops into a full-blown hurricane depends on the conditions at its specific location. For example, sea-surface temperatures, winds, and other environmental characteristics must be conducive to creating a storm. Under certain conditions, a storm will develop and the model will simulate its track, size, wind speeds, and pressure differentials.

Emanuel uses his storm model to compare current climate conditions to future conditions. He finds that, overall, storm frequency and intensity will likely increase in the future. Emanuel uses outputs from several large global circulation models (GCMs) that were used in the IPCC AR4. Emanuel's emissions scenario was drawn from the Special Report on Emissions Scenarios (SRES) A1B, a mid-range emissions scenario developed by the IPCC (IPCC, 2000). The A1B scenario embodies lower

| <b>Storm Category</b> | <b>Wind Speed (km/hr)</b> |
|-----------------------|---------------------------|
| Category 1            | 119–153                   |
| Category 2            | 154–177                   |
| Category 3            | 178–209                   |
| Category 4            | 210–249                   |
| Category 5            | 250+                      |

**Table 2.1:** Wind speed ranges for Saffir-Simpson categories. (Source: NOAA, 2008)

emissions than the current emissions trajectory, which is closer to the SRES A1FI (Raupach et al., 2007).

### **2.2.1 Tropical storm classification**

For this dissertation, a “storm” is a tropical storm, or storms that form near the equator in tropical air masses. The Saffir-Simpson storm scale is used to classify tropical storms (NOAA, 2008). The Saffir-Simpson scale classifies storms into five categories (Category 1, Category 2, etc.) depending on wind speed (Table 2.1).

### **2.2.2 Storm surge**

The Saffir-Simpson scale broadly describes each storm category, providing a range of possible surges (NOAA, 2008). The storm surge ranges (Table 2.2) are estimates based on historical storm surges. Actual storm surge depends significantly on the approach angle of the storm relative to the shoreline, the bathymetry of the coast, physical characteristics of the storm (e.g., internal air pressure), coastal structures guiding the water, and the phase of the tide (Irish et al., 2008). The Saffir-Simpson scale has been critiqued as a poor predictor of storm surge (Resio and Westerink, 2008). The scale provides an initial estimate and is easier to use, given the intensive data requirements of other methods.



| Storm Category | Surge Height (m) |
|----------------|------------------|
| Category 1     | 1.22–1.52        |
| Category 2     | 1.83–2.44        |
| Category 3     | 2.74–3.20        |
| Category 4     | 3.96–5.49        |
| Category 5     | 5.49+            |

**Table 2.2:** Storm surge ranges according to Saffir-Simpson classification. (Source: NOAA, 2008)

## 2.3 Risk Perception and Decisions

The way people understand and perceive risks underlies planning and adaptation to climatic threats. While coastal managers and city planners may have a solid understanding of storm and RSLR risk, these experts are the exception rather than the rule. Generally, people have a poor understanding of natural hazard risk (Kydland and Prescott, 1977; Kunreuther and Pauly, 2006). Distinguishing between expert knowledge and general knowledge is important when considering adaptation responses because expert knowledge cannot be assumed for all actors. Previous economic studies assumed a “socially-optimal planner”—a single optimizer who maximizes a societal benefit, e.g., the lowest cost of adaptation (Fankhauser, 1995; Tol, 2002). A large body of literature in psychology and behavioral economics support relaxing the assumption that all actors in society behave as if they were making fully rational decisions that optimize social welfare. Climate change adaptation could be studied as a two-actor problem involving the actions of expert planners and less-expert citizens.

### 2.3.1 Perception anecdotes

For example, many property owners in Gulfport, Illinois, situated along the Mississippi River, believed they were protected by the presence of a levee system surrounding their town. In the summer of 2008, the levee broke and flooded the land behind it. Though residents had been eligible for flood insurance through the National Flood Insurance Program (NFIP), only 28 of 200 property owners actually purchased policies. Town officials promoted the protection provided by the levee and

residents interviewed believed they did not need insurance (Mattingly, 2008; Webber and Fisher, 2008). The actions were taking even though hundreds of levees failed along the Mississippi River in 1993 (Larson, 1996).

As with flood risk, the public also has a poor understanding of hurricane risk. State officials in hurricane-prone Florida worried that residents would be ill prepared for the 2008 hurricane season due to the relatively quiet hurricane seasons of the previous three years (Cave and Almanzar, 2008). The probability of a storm hitting a community in Florida had not changed, but the awareness of the risk had faded. Without the awareness of likely storm damage, officials feared citizens were not taking normal precautionary measures, such as buying food for emergency pantries.

### **2.3.2 Perception literature**

These anecdotal events are supported by academic literature. Tversky and Kahneman (1974) studied how a person's memory influences their perception of the likelihood of an event or disaster, calling the phenomenon the "availability heuristic." They found that a person perceived the probability of an event to be higher if he or she could recall a recent occurrence. Eventually, as his or her memory of the event faded, their perception of the probability decreased. The perceived probability of an event was inversely proportional to the time since the last occurrence. The availability heuristic describes the worries of disaster managers in Florida after a few quiet hurricane seasons.

Kydland and Prescott (1977) describe how flood plains could be developed under circumstances that are economically suboptimal. People move into an area assuming that they will be protected by levees. Once the people are there, the flood plain hosts capital infrastructure that deserves protection by the government. Levee protection causes more capital investment in the flood plain, which increases the exposure to flooding. Instead of investing to protect property in these flood-prone areas, Kydland and Prescott concluded that, with the level of protection in the US, it was socially

optimal to prevent people from building in the flood plain in the first place.

Kunreuther and Pauly (2006) extend Kydland and Prescott by studying flood insurance coverage. They found that property owners did not internalize the risk of flooding when deciding whether to build dwellings or buy flood insurance. Instead, homeowners screened risks by using a “risk threshold.” If a particular risk were above one’s internal risk threshold, one would consider the risk and evaluate preventive actions. In the case of flooding, if the risk of flood was perceived to be high relative to one’s threshold, one might avoid building in a flood plain or purchase insurance to cover possible damage. Surveys, however, show that natural disasters are below most people’s thresholds except immediately after an event (Palm, 1990, 1995). For instance, earthquake insurance coverage in California increased from 40 to 51 percent in one year after the 1989 earthquake, but then fell as time wore on. As with hurricanes in Florida, people’s perception of earthquake risk rose above their risk threshold after an adverse event, but then became less salient over time.

### **2.3.3 Risk perception and climate adaptation**

Risk perception has important implications for coastal adaptation research. The example of levee protection illustrates how adaptation to climatic risks can influence population growth and economic output. The empirical research above describes how residents discount the risk of flooding events after levee construction, beyond the protection the levee actually provides. Subsequently, the rate of infrastructure investment can increase, creating more economic output, faster population growth, and larger capital infrastructure in the flood plain. While the risk of small floods is reduced by the presence of the levee, the risk from larger events remains. When these larger, but less-frequent, floods occur, the community faces greater economic loss than it would if the levee protection were not in place.

New Orleans provides a recent example of the interaction between risk perception and infrastructure investment. The population of New Orleans increased through the

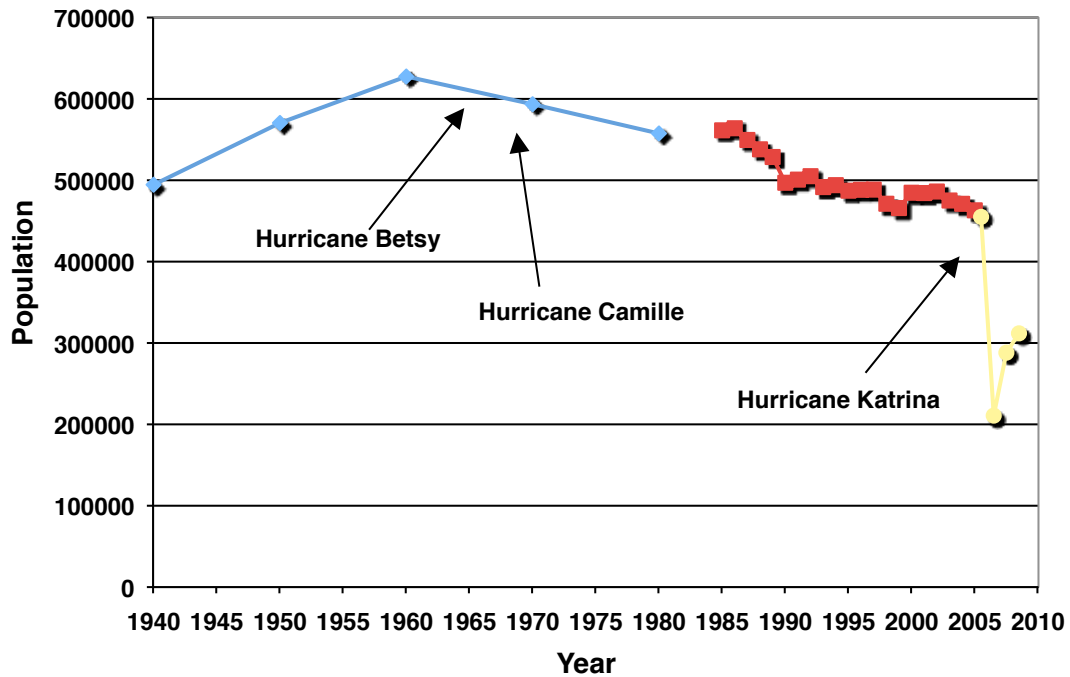
19th Century to 1960, during a relatively quiet period of hurricane activity. After two severe river floods, levee protection was improved, providing the illusion of protection. In the 1960's, two tropical storms reached landfall near the city. Hurricane Betsy, a Category 3 storm, struck the city in 1965. The protective levees were breached, causing then-record hurricane damage. In 1969, Hurricane Camille approached the Gulf Coast, missing New Orleans but reminding the residents again about hurricane risk. The city experienced another period of quiet from 1970 through 2005, yet the population of New Orleans never recovered from Hurricane Betsy (Figure 2-2). Then, in August 2005, Hurricane Katrina struck, breaching the levees and causing major damage and widespread evacuation (Figure 2-3). In the three years since Hurricane Katrina, the population of New Orleans Parish has begun to level off with the return of 76.4 percent of households (Lui and Plyer, 2009). The growth and stagnation of a city such as New Orleans contrasts against other cities (e.g., in Florida) that have experienced positive long-term economic growth after storms. New Orleans might have passed a point of economic resiliency—a point at which economic growth is derailed and stalls.

## **2.4 Coastal Adaptation Economics**

Climate change and coastal zones have been studied for several decades (Schneider and Chen, 1980). Economic studies of coastal impacts fall into two broad categories: 1) vulnerability studies and 2) adaptation studies. The following section discusses the relevant literature for this dissertation.

### **2.4.1 Vulnerability studies**

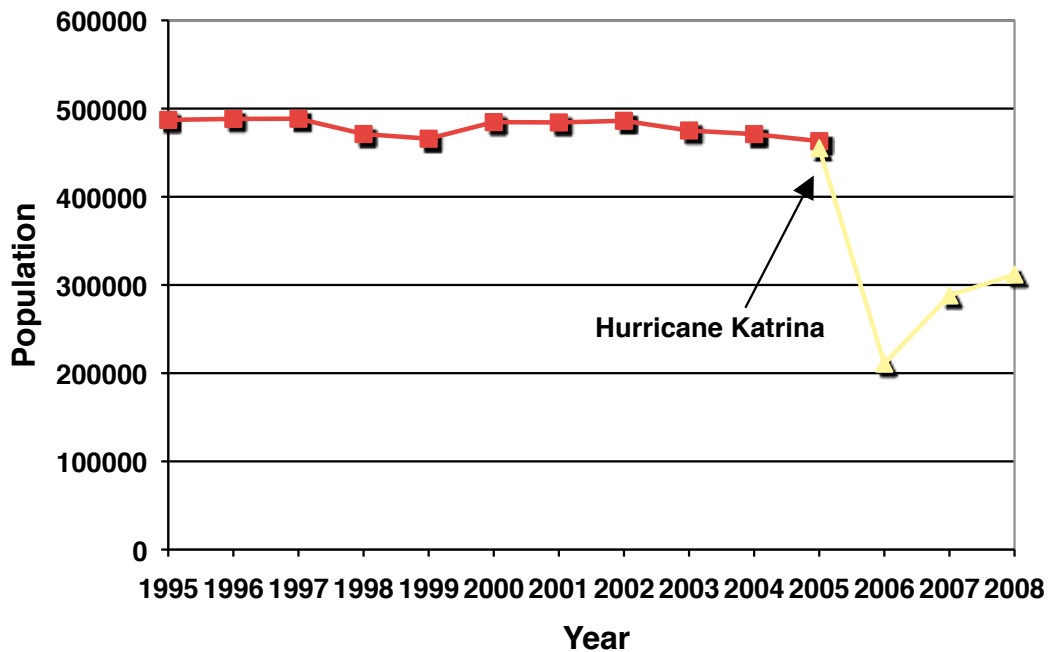
Vulnerability studies estimate exposure to RSLR for a particular region or country, e.g., the amount of capital (i.e., housing, industrial and commercial facilities, and infrastructure) that would be flooded by a given amount of RSLR. The results from vulnerability studies tend to be eye-catching because the studies do not assume any coastal protection measures or other societal responses. Instead, vulnerability studies



**Figure 2-2: New Orleans Population (1940–2007).** The population of New Orleans since 1940, showing the downward trend after Hurricanes Betsy (1965) and Camille (1969) and the evacuation and repopulation after Hurricane Katrina (2005). (Sources: US Census Bureau data in Gibson, 1998; Lui and Plyer, 2009)

focus on understanding risk exposure (e.g., Titus, 1988; Nicholls, 2002; Ericson et al., 2006).

Vulnerability studies report metrics that may be important to decision makers, including both people and property. Past vulnerability studies reported people at risk to flooding (Nicholls et al., 1999), acres of rice production lost (Hoozemans et al., 1993), wetland area lost, capital that would be inundated by RSLR, and simply the land area lost to RSLR, no matter its current vegetation or use. Researchers report different metrics depending on their purpose. Some studies attempted to report only a sense of the widespread change that RSLR would cause (i.e., total number of people flooded), while other studies included only parameters that could be assigned monetary values (i.e., wetlands and protection costs).



**Figure 2-3: New Orleans Population (1995–2007).** Population trend highlighting the effect of Hurricane Katrina (August 2005). (Sources: US Census Bureau data in Gibson, 1998; Lui and Plyer, 2009)

Vulnerability studies provide an upper bound to the costs of climate impacts in coastal regions. It is reasonable to assume that communities will respond to climatic threats by protecting their shoreline from flooding and/or setting financial and legal structures to cope with a rising sea level.

### 2.4.2 Adaptation studies

Contrary to vulnerability studies, adaptation studies include some form of response by the coastal community. These responses may be via market mechanisms (Yohe et al., 1996) or public coastal protection programs, such as levees (Titus et al., 1991; Fankhauser, 1995; Anthoff et al., 2006).

Adaptation researchers tend to argue against static vulnerability studies, stating that vulnerability damage estimates are too high and cannot be used to justify climate policy action. Instead, researchers prefer to assume that communities consist

of rational actors who want to protect their property, which means that adaptation measures would significantly reduce the absolute level of RSLR impacts. Fankhauser (1995) concluded that adaptation reduces the impacts of RSLR.

Fankhauser developed an economic model of RSLR adaptation that determined the optimal level of protection over the entire century. The optimal protection level was a trade-off between the cost of protection, the value of dry land, and the value of wetlands (Equation 2.1). The total discounted cost is minimized by choosing the length of the coastline protected and the height of the protection. Shorter lengths of coastline and lower protection heights would lower both protection costs and wetland loss, but increase the amount of dry land damage.

$$\min_{L, h_t} Z = \int_0^\tau [p(L, h_t, G_\tau) + d_t(L, S_t) + w_t(L, S_t)] e^{(-rt)} dt \quad (2.1)$$

where

$L$  is the fraction of the coastline protected

$h_t$  is the levee height at time  $t$

$p$  is the function for annual protection costs

$G_\tau$  is the final height of protection

$d_t$  is the function for value of dry land

$S_t$  is the RSLR at time  $t$

$w_t$  is the function of the value of wetlands

$r$  is the discount rate

Fankhauser assumed a uniform distribution of capital along a coastal segment and linear RSLR over time. He concluded that OECD countries would construct levees for a large fraction of their coastline—protecting approximately 97 percent of their urban coastline and 80 percent of their open coasts.

Fankhauser and other economics-based adaptation studies used traditional economic assumptions of perfect foresight and rationality. For example, they assumed there was one “socially optimal planner” who could evaluate all the options and make the best choice. The single planner was a rational actor and made decisions that optimized economic welfare over all future time. The economic studies also assumed equilibrium conditions, either partial or general. Traditional economic adaptation models do not include adjustment delays or allow for flawed decision making. The optimistic assumptions used in these studies means that they provide the lower limit to adaptation costs. Real-world adaptation costs will likely be greater because communities may not preemptively adapt.

Most studies include only one “hard” adaptation or protection measure: levee construction (e.g., Fankhauser, 1995; Tol, 2002). More recent studies include “soft” engineering techniques, such as beach and wetland nourishment (Hinkel and Klein, 2003). Models that include these protection measures effectively change the overall shape of the adaptation cost curve by providing for lower-cost options. Some of these protection techniques may have secondary benefits, such as saving wetlands and reducing storm surge.

Yohe et al. (1996) studied how the real estate market might react to long-term RSLR. They assumed that property would be slowly devalued as it was encroached upon by water. Land values inland would rise, transferring the value of coastal properties to those inland. The slow devaluation and the transfer of value resulted in a significant reduction in the economic costs of coastal adaptation. RSLR was found not to cause significant economic losses because newly inundated land had already been devalued by real estate market forces. Additionally, Yohe et al. (1996) relaxed the perfect foresight assumption of the real estate market. RSLR losses were greater and the fraction of communities building coastal protection was larger, because land had not been devalued.



Along with assumptions of foresight, different economic studies have tested assumptions of economic equilibrium. Bosello et al. (2004) highlight how differences in economic modeling can influence measures of vulnerability. Their general equilibrium model allows countries to fund protection infrastructure through trade and foreign debt, as opposed to their own internal economic capacity based on GDP. External financing increases the adaptive capacity of exporting countries. Darwin and Tol (2001) use a general equilibrium model also, finding the inclusion of secondary economic effects increases the global costs of RSLR adaptation 13 percent over a partial equilibrium calculation. The increased costs of RSLR occur because of price changes, which affect consumption and economic welfare.

Few coastal adaptation studies have utilized disequilibrium economic assumptions. Hallegatte et al. (2007) studied the importance of disequilibrium assumptions when assessing climate change impacts, but illustrated the point more broadly about large extreme weather events. While they mention storm events, they did not focus on coastal adaptation specifically.

More recent studies have brought in different RSLR impacts, other than slow flooding from RSLR, and integrated across disciplines. The Dynamic Interactive Vulnerability Assessment (DIVA) study optimizes protection decisions based on a variety of impacts (tourism, flooding, protection costs) (Vafeidis et al., 2008). The DIVA model consists of several modules each focusing on different impacts or responses to sea-level rise. For instance, one module calculates the population that is expected to be flooded while another module calculates the area of wetlands that will be lost. A final module takes these impacts as inputs and calculates the optimum level of protection for that period of time, using a user-defined decision rule such as benefit/cost, “no protection,” or “full protection.” The model then calculates subsequent periods in a recursively. No other areas of the economy except those associated with coastal protection are considered.

### 2.4.3 Storm representation in adaptation studies

Some previous coastal adaptation studies have incorporated storms and flooding into their models. Two approaches have been used to combine RSLR and storm effects. Some studies adjust the flood water height of return period storms (e.g. Vafeidis et al., 2008). For example, if the hundred-year storm (storm with a hazard rate of occurrence=0.01 per year) has a water height of 1.0 m and RSLR has been 0.5 m, then the new total water height of the hundred-year storm is 1.5 m. Adjusting the flood water height by RSLR is a first-order approximation of storm flooding behavior.

Other studies have focused on including explicit storm events. West et al. (2001) modeled whether or not a property would be damaged and the extent of any such damage as two random processes. Their model focused on the interactions of storm damage and coastal erosion. They modeled erosion according to the Bruun Rule (Bruun, 1962), which states that, as sea level rises, the shore erodes, exposing property to storm damage. West et al. (2001) calibrated their random storm damage model according to insurance claims through the National Flood Insurance Program. Their storm model was not based on any climate scenarios, surge models, or hurricane arrival models. The model fits storm strength to insurance claim data to estimate storm damage.

Some studies have used Markov-chain hurricane models to estimate storm damage under present and future climates. Hallegatte (2007) utilized synthetic storm tracks from Emanuel's hurricane model to estimate damage along segments of the US coastline. Hallegatte concluded that hurricane damage was significant and should be considered when justifying climate policy. While this study included storm probabilities, it did not integrate storm arrivals with endogenous coastal adaptation and an endogenous economy.

#### 2.4.4 Handling of uncertainty and sensitivity

Researchers have the opportunity to explore model sensitivity and uncertainty, but these results have not been reported for many studies. Early studies may have lacked the techniques and/or computational power required. More recent studies have provided ranges of damage estimates from sensitivity and uncertainty exercises. These ranges can overlap, which mitigates some conflicting data between different studies.

One parameter explored in many studies is the absolute amount of sea-level rise. Yohe et al. (1996) critiqued the commonly used 1 m-scenario because scientific consensus was much lower, around 0.5 m by 2100 (in 1996). In their study, the total cost of protection and damage varied significantly, depending on the amount of RSLR. Many studies have since included varying amounts of RSLR in their analyses, including the IPCC SRES range (e.g., Nicholls and Tol, 2006).

Climate models predict that the world will warm and sea-level will rise faster over time. The rate of global SLR will likely be higher toward the end of the 21st Century than at present. Many economic studies assume linear SLR, allowing for more tractable models, that likely misallocates the SLR over time. A linear assumption likely results in incorrect damage estimates, especially if costs and benefits are discounted. Sugiyama et al. (2008) included non-linear SLR in their economic study. They concluded that total discounted costs would be lower with the non-linear assumption because adaptation costs would be postponed until later in the century.

Most studies do not present a multi-variate analysis of their uncertain variables. SLR is the main variable of uncertainty, with more recent studies commonly using the IPCC scenarios. Studies rarely present the uncertainty results of varying population or economic growth assumptions.

### 2.4.5 Global data sets for economic studies

Information about the coastal zone drives many assessment models. Data quality is important for coastal adaptation studies.

The Global Vulnerability Assessment (GVA) study (Hoozemans et al., 1993) is a widely cited global data source and has been updated in subsequent studies (e.g., Nicholls et al., 1999). Their data was collected from a variety of sources, checked for global consistency, and aggregated into 192 coastal segments. These segments were predominantly decided by country boundary.

While the GVA produced a reasonable data set, its data resolution was very coarse. A European funded research project, DINAS-COAST, recently created the Dynamic Interactive Vulnerability Assessment (DIVA) model and companion database. The DIVA database contains more information at a higher resolution, dividing the world's coastlines into 12,148 segments (Vafeidis et al., 2008). This data set was created with the intention to improve coastal assessment studies.

Consistent global economic data sets are difficult to develop. The distribution of capital along the coastline is important to estimate flooding and storm damage accurately. Typically, geographic data about capital infrastructure has been hard to attain, especially at a global scale. Even in the US, a country with relatively good data, federal-level census data divides infrastructure into census blocks. These census blocks are intentionally large enough to not accurately pinpoint property, so as to preserve the privacy of property owners.

Most adaptation studies assume a uniform distribution of capital along a coastline (Fankhauser, 1995). Sugiyama et al. (2008) compares this uniform distribution with a quadratic distribution of capital and concludes capital distribution influences the fraction of coast protected. Also, Nordhaus (2006) has developed a database of economic data sets that include spatial distribution information.

## 2.5 Coastal Adaptation Options

Communities have three generic adaptation strategies to deal with climate threats: 1) protect, 2) accommodate, or 3) retreat. Each form of adaptation reduces potential impacts to SLR and storm. Klein et al. (2001) define the purpose of each strategy as:

**Protect:** to reduce the risk of the event by decreasing its probability of occurrence,

**Accommodate:** to increase society's ability to cope with the effects of the event,

**Retreat:** to reduce the risk of the event by limiting its potential effects.

These three different methods can be used depending on the conditions in the community. If a community has a significant amount of infrastructure on or near the coastline, protecting the infrastructure with physical structures (e.g., levees, sand dunes, and/or sea walls) may be the best option.

If the infrastructure can be easily modified or flooding is not expected to be frequent, accommodating the floodwaters might be the best choice. To accommodate the water, communities would raise their buildings above the average flood height or construct small levees around critical infrastructure (e.g., water treatment plants) and let the remaining infrastructure flood temporarily. Damage would occur, but would be rare and minimized.

Communities may choose to retreat or let the water permanently inundate land. Retreat makes the most sense if there is land available inland that people can move to.

Today, coastal adaptation choices differ around the world. The most prominent coastal protection and adaptation measures are in the Netherlands, which has constructed protective levees and dunes along large portions of its coastline and rivers. The Dutch have a strong ethic of protection and “holding the line” with their protection structures.

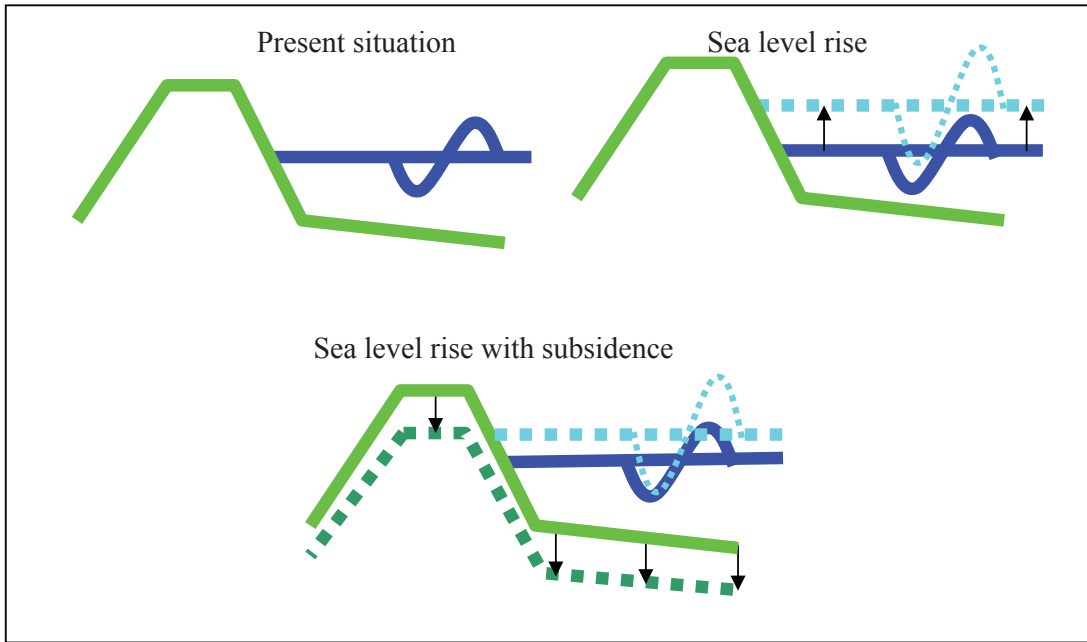
Recently, the Dutch have also started building floating houses along their rivers. The Dutch form of accommodation is a response to inland threats of water inundation. The Netherlands has many rivers flowing through it and, while levees and dunes are good at holding the ocean back, the Dutch have chosen accommodation measures to deal with interior flooding. Water management in the Netherlands is extensive, and includes large systems of pumps, channels, and plans for flooding agricultural fields.

Two other prominent flood protection projects are the gates on the Thames River and the floodgates for Venice, Italy. Both of these systems protect important and historic cities. The gates can be closed when conditions align for flooding or storm surge. Surge and sea-level barriers are other options for protecting coastal communities.

In the United States, public adaptation options differ by region. Louisiana uses levees extensively to control flooding. The US Army Corps of Engineers (USACE) operates and maintains miles of control structures in the region. Additionally, Louisiana and the USACE are considering wetlands preservation and restoration as a means of storm protection. Louisiana has lost extensive coastal wetland acreage in the last 50 years, which has increasingly exposed coastal infrastructure to storm surge.

The levee system in Louisiana is currently being reviewed by the USACE. Hurricane Katrina struck New Orleans and the surrounding coastline in 2005. In Katrina's aftermath, the USACE was charged with conducting an extensive evaluation of coastal protection options for the surrounding regions. Titled the Louisiana Coastal Protection and Restoration (LACPR) project, the USACE will publish their findings in 2009. A draft report indicates that many different options will be considered, ranging from wetland restoration to large-scale levee upgrades and new construction (USACE, 2009c).

Florida's primary form of public adaptation is beach nourishment, which differs from their first attempt at shoreline management in the 1960's. Then, many communities and private landowners constructed sea walls and groins. These structures

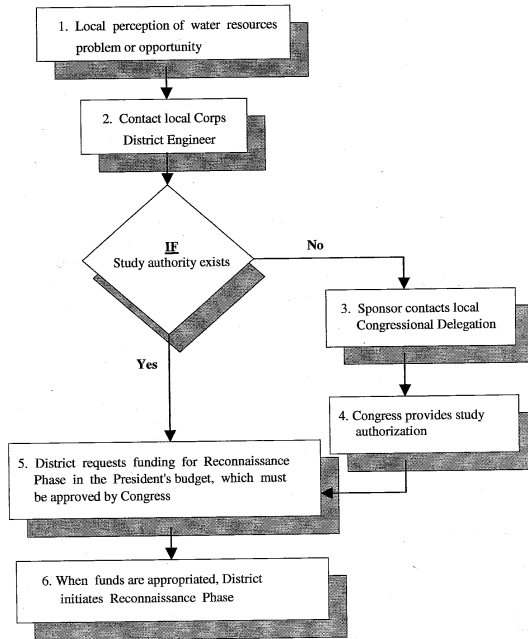


**Figure 2-4:** A structure’s protective height relative to the sea level may change if land sinks or sea level rises. (Modified from Figure 4-5 in USACE, 2009b)

were designed to prevent flooding or beach erosion by trapping sand. These structures were not built in a systematic way and often created problems for other nearby communities along the coast.

Today, Florida has a more holistic and systematic coastal management system. Beach nourishment is the primary form of public adaptation because it increases protection while providing beaches for public use. Additionally, the Florida Department of Environmental Protection works with local and county agencies to manage the coastline for both wildlife and recreation (Elko, 2009).

No matter how a coastline is protected, coastal defenses need to be designed for both present and future coastline conditions. In the future, the land underneath a structure may sink lower, affecting its height relative to sea level. Additionally, RSLR will raise the height of the sea relative to the structure (Figure 2-4). If a structure is not designed with future conditions in mind, then it will likely not protect to the level that the community expects.



**Figure 2-5:** The steps involved in starting a US Army Corps of Engineers project. (Source: Blakey and Whittington, 2001, pg. 29)

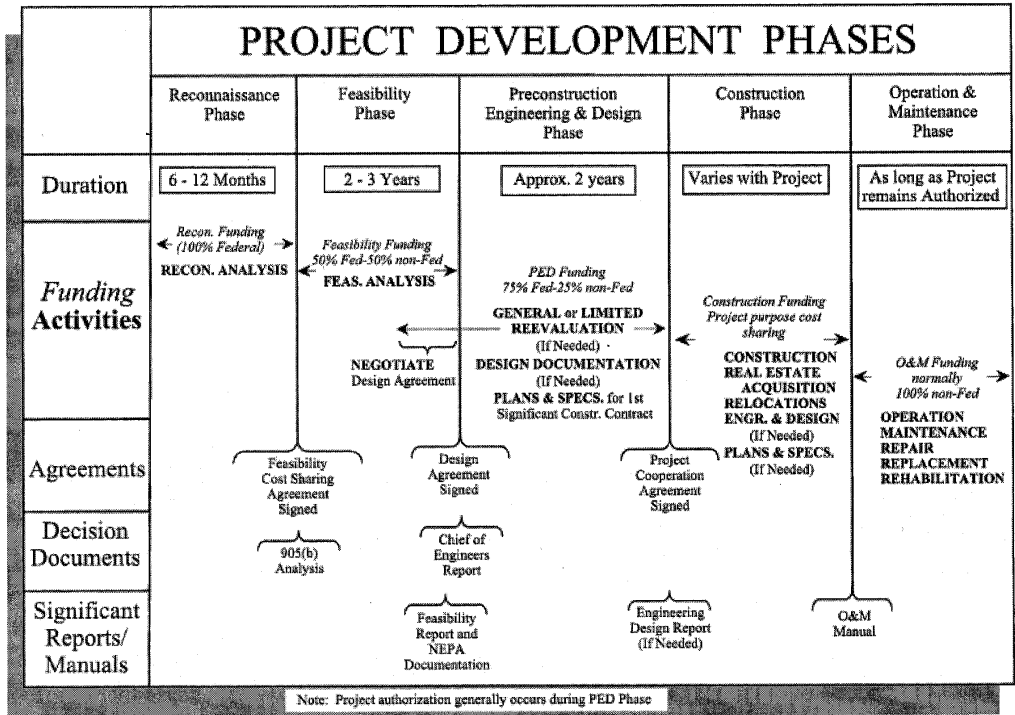
### 2.5.1 Public adaptation in the United States

In the US, the USACE is the federal agency with responsibility for public adaptation projects. Typically, states and local communities work with the USACE to design and construct. State and local governments partnering with the USACE on projects are eligible for cost sharing funds from the federal government. These funds offer a strong incentive to work with the USACE.

The USACE has specific stages and guidelines for its projects. Figure 2-5 shows the initial USACE stages. Projects originate from the local partner, not the USACE itself. In order for a project to proceed, the USACE needs congressional authorization. The USACE then needs to receive funding, which is separate from the authorization legislation. Once the funding is secured, the project enters the “reconnaissance phase.”

Figure 2-6 shows a timeline of project phases and deliverables. Additionally, the normal cost-sharing structure for each of the stages is listed. The planning phases of





**Figure 2-6:** Project development phases for US Army Corps of Engineers projects. (Source: Blakey and Whittington, 2001, pg. 32)

the project take several years, and the length of the construction phase depends on the size of the project. Beach nourishment is a relatively short construction project (one year), while levees and other projects can take a decade or more to complete. Lawsuits arising from local opposition (e.g., NIMBY concerns) or funding shortfalls can further delay completion.

The final phase of a project is operation and maintenance. The USACE is available for advice and guidance, but the operation and maintenance phases of coastal defenses are normally funded entirely by the local partner, not the federal government.

The USACE is authorized to evaluate projects based on the economic benefit to the national economy. They consider flood damage to local property, increased values of tourism and shoreline use, and damage to trade if a commercial port is involved. Wetlands are not considered in the main economic evaluation. Additionally, projects typically do not communicate risk reductions clearly for the local partner to choose

from. The local partner may ask that only certain options to be evaluated (e.g., because of budget constraints or the bare minimum to meet NFIP requirements), instead of seeing a complete picture of risk reduction projects.

After Hurricane Katrina, the USACE was mandated by Congress to use a risk-based approach to evaluate the coastal protection options for Louisiana. The mandate was for the LACPR project, mentioned above. The USACE involved many local and regional stakeholders to come up the priorities of the projects. The most important performance goal of a project is to reduce the risk to people and property (Table 2.3). Stakeholders also felt that the environment and local heritage should be preserved (USACE, 2009c).

| <b>LACPR Planning Objectives</b>  |
|---|
| <ul style="list-style-type: none"> <li>● Reduce risk to public safety from catastrophic storm inundation</li> <li>● Reduce damage from catastrophic storm inundation</li> <li>● Promote a sustainable ecosystem</li> <li>● Restore and sustain diverse fish and wildlife habitats</li> <li>● Sustain unique heritage of coastal Louisiana by protecting historic sites and supporting traditional cultures</li> </ul> |

**Table 2.3:** LACPR planning objectives as identified by a stakeholder-driven process. (Source: Russo, 2009; Axtman, 2009)

Through the stakeholder interview process, the USACE also generated a list of project performance metrics (Table 2.4). These metrics were reported when evaluating the coastal defense options for the Louisiana coastline (USACE, 2009c; Russo, 2009).

The USACE historically has not utilized significant community involvement in the entire planning process. Also, the USACE has been limited in evaluating projects on dimensions other than “national economic development,” a restriction place on them by congress. The LACPR provides them a unique mandate, which some feel will become the standard process for future USACE projects (Axtman, 2009; Russo, 2009).

| <b>LACPR Performance Metrics</b> |   |
|----------------------------------|---|
| <b>Category</b>                  | <b>Metric</b>   |
| People                           | Resident/exposed population   |
| Economy                          | Expected annual damage<br>Regional economic development (jobs, income, regional output)<br>Life-cycle costs; Implementation, O&M<br>Residual risk |
| Environment                      | Sustainability; acreage loss index<br>Habitat relative abundance<br>Surge/wave reduction  |
| Culture                          | Cultural sites protected  |

**Table 2.4:** LACPR metrics for project performance, as identified by a stakeholder-driven process. (Source: Russo, 2009; Axtman, 2009)

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# Chapter 3

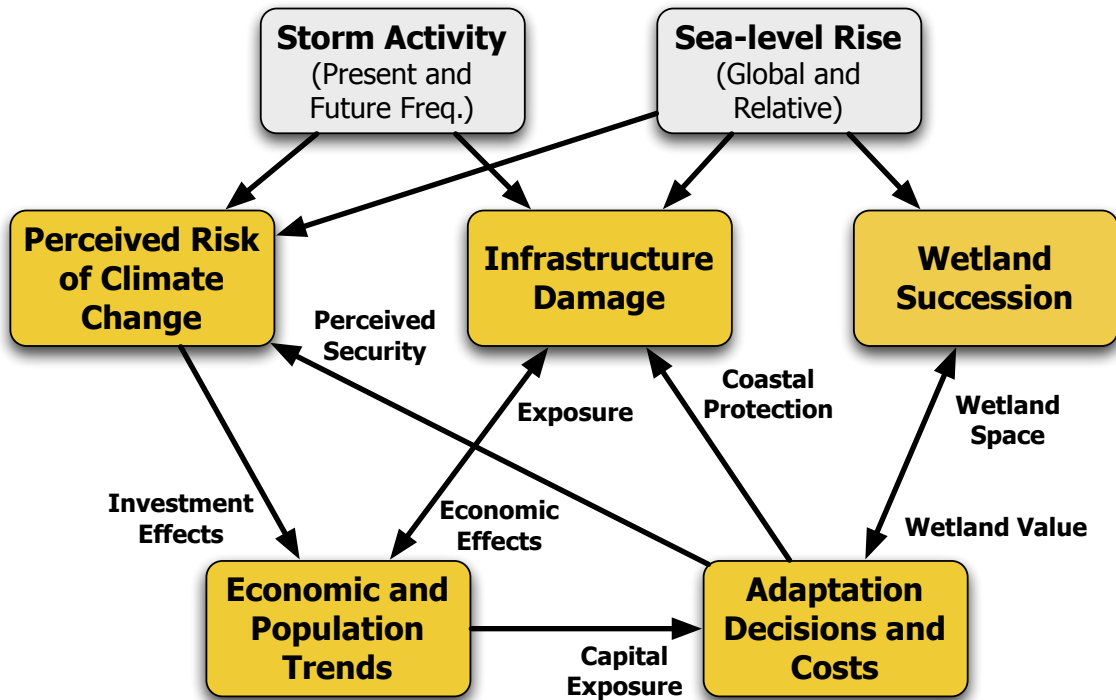
## Model Description

### 3.1 Introduction and Overview

The Feedback-Rich Adaptation to Climate Change (FRACC) model combines many different disciplines to better understand the complexity of coastal adaptation. Its main goal is to provide a framework for evaluating the impacts of climate change on coastal communities.

The model calculates policy performance metrics across economic, environmental, and social contexts to provide a comparison between adaptation alternatives. These metrics are a subset of those identified by stakeholders during the US Army Corps of Engineers' Louisiana Coastal Restoration and Protection project (Section 2.5.1). To compare economic performance, the model reports employment and community gross domestic product (GDP); for environmental performance, it reports wetland acreage as a proxy for ecosystem health; and for social impacts, it reports the number of people who evacuate because of storms.

Before describing the model in detail, it is useful to review its overall structure. The model follows system dynamics methodology (Sterman, 2000), consisting of stochastic differential equations simulated numerically. Figure 3-1 depicts the model's components and the flow of information between them.



**Figure 3-1:** High-level diagram of the model, including sub-models and the information flows among sub-models.

The grey boxes at the top are the two exogenous climatic drivers—storms and sea-level rise (SLR). The storms component contains a stochastic storm arrival structure based on the projected frequency and intensity distribution for a specific community. When a storm occurs, its intensity is passed from the storm arrival component to the risk perception and economic components. Likewise, the annual amount of RSLR is passed from the SLR component to the economic and wetlands components.

The FRACC model represents important processes relating to economic development and coastal adaptation. Storms and SLR disturb economic growth and the local ecosystems of coastal communities. When a community is disturbed, the residents and investors in a community respond by changing their economic behavior. What actions they take depends in part on their perception of storm and SLR risk (i.e., "Perceived Risk of Climate Change" in Figure 3-1). If a storm occurs, investors and residents might decrease their economic investment in the community. Economic investment is fundamental to economic and population growth (i.e., "Economic and Population

Trends” in Figure 3-1). Investment in capital infrastructure can increase economic production, creating more jobs and attracting more residents.

Economic growth, though, increases the amount of infrastructure exposed to storms and SLR risks. The amount of exposed infrastructure is a primary factor in determining the adaptation response by the community (i.e., ”Adaptation Decisions and Costs” in Figure 3-1). Adaptation measures, such as building a levee, can decrease the perceived risk of climate change, decrease the actual damage from storms and SLR (i.e., ”Infrastructure Damage” in Figure 3-1), and limit the inland migration of wetland ecosystems (i.e., ”Wetland Succession” in Figure 3-1).

The components of the FRACC model interact with one another through important feedback links. These feedbacks create a dynamic community that responds to climate change impacts.

Three classes of decision makers are represented in the model: Investors, residents, and coastal managers. These three agents use storm and RSLR information differently to decide whether or not to invest in infrastructure or move into the community.

Investors do not have a full understanding of climate science nor of RSLR. Instead, they base their assessment of risk on their first-hand experiences with storms, and then extrapolate trends based on those experiences. Investors change their investment behavior immediately after a storm because they believe that storms will become a more likely occurrence. Their perceived increase in storm frequency decreases their investments in capital, providing a feedback among storms, investment, and long-term storm damage.

Residents use their perceived storm information when evaluating where to live. They perceive storm risk relative to the historical average for the community. If the perceived storm frequency increases, the community becomes less attractive. Residents are less likely to move into, and more likely to move out of, the community.

| <b>Endogenous</b>  | <b>Exogenous</b> | <b>Excluded</b>  |
|--------------------|------------------|------------------|
| Storm arrival      | Storm frequency  | National economy |
| Storm damage       | Storm intensity  |                  |
| Immigration rate   | Birth rate       |                  |
| Emigration rate    | Death rate       |                  |
| Economic growth    | Urban density    |                  |
| Disaster relief    | Sand resources   |                  |
| Coastal adaptation | Levee unit costs |                  |
| Private adaptation | Sea-level rise   |                  |

**Table 3.1:** Important endogenous, exogenous, and excluded variables of the model.

Coastal managers, on the other hand, are assumed to understand the science of RSLR and storm events and use scientific data to determine how to best provide coastal protection. The simulated coastal managers are assumed to use the actual rate of RSLR to project future sea-level height, which determines how high to construct coastal protections such as levees and beach nourishment projects. RSLR also drives the wetland succession component, which changes the nature of the surrounding ecosystems and their economic valuation.

The model simulates a community from 2000 to 2100. Storms can begin perturbing the community in 2010.

The model’s geographical scope is a single coastal community. The geographic scope of the model helps define which model parameters are exogenous and which are endogenous (Table 3.1). The model includes the community’s economic performance but assumes the national economy is unaffected by storms and other economic activities in the community. In the United States, it is a reasonable assumption that a single natural disaster will not significantly affect the national growth rate. Large disasters, such as Hurricane Katrina, have reduced the national growth rate (e.g., 0.5 percent per year Holtz-Eakin, 2005), but smaller events tend to have only local economic effects. Excluding the larger economy allows the research to focus on the dynamics within a specific coastal community. I examine three communities, whose parameters are described in the Chapter 4, after the model is presented.



The following sections describe the structure of the model. The narrative begins with assumptions about the primary climatic drivers, SLR and storms. Section 3.4 discusses how storm risk is modeled. The macroeconomic formulation is defined in Section 3.5. The subsequent section describes population and employment. Sections 3.8 and 3.10 describe adaptation responses, which include levee construction, beach nourishment, property mitigation, and insurance.

The following conventions have been used to help guide the reader:

- *Italics* are used for model variables that are shown in a figure. This will help the reader match the text and equations with the diagrams. For example, *Gross Output* refers to the model variable “Gross Output,” which is the gross product of the region.
- In the diagrams, variables with boxes surrounding them are stocks. Mathematically they are integrals that accumulate the difference between their inflows and outflows.
- Flows are arrows pointing into or out of a box, or stock.
- Other arrows indicate a causal relationship between the two variables. An arrow with a plus sign is a positive relationship and an arrow with a negative sign is a negative relationship. A positive relationship  $\text{ParameterA} \rightarrow^+ \text{ParameterB}$ , reads as, “If ParameterA increases, then ParameterB will also increase, all else held constant.” Mathematically, the notation  $\text{ParameterA} \rightarrow^+ \text{ParameterB}$  denotes  $\frac{dy}{dx} > 0$ , and  $\text{ParameterA} \rightarrow^- \text{ParameterB}$  denotes  $\frac{dy}{dx} < 0$ .
- Variables surrounded by corner brackets “<, >” are parameters that are calculated elsewhere in the model and not shown in a given diagram.
- Unitless variables may be labeled “dmnl”, standing for “dimensionless.” These variables that have no units—often fractions where the units cancel out (e.g., area flooded divided by total area has units square kilometers over square kilometers, or dmnl).

The model formulation and parameter values were informed by existing literature and/or expert judgment gathered through primary interviews. Parameter values that are for all communities (e.g., global sea-level rise) are described in this chapter. Parameters specific to a particular community (e.g., coastal uplift) are described in Chapter 4. The full model, including all equations and initial values, is documented in Appendix C.

## 3.2 Sea-Level Rise Forcing

Sea-level rise in the model is divided into a global SLR trend and the relative SLR trend. As described in Section 2.1, the global trend is the average amount of SLR worldwide. The relative SLR is the global SLR adjusted for local conditions. In the FRACC model, global SLR scenarios are input into the SLR component, and RSLR is passed to other model components.

### 3.2.1 Global sea-level rise

Sea-level rise has been parameterized to test the full range of the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emission Scenarios (SRES) as well as a user-defined value. The FRACC model does not explicitly represent the carbon cycle, temperature change, nor specific processes related to SLR (e.g., thermal expansion). Instead, global SLR paths are exogenously chosen to approximate SLR paths generated by global circulation models. For any given estimate of SLR in 2100, two different functional forms can be used. A linear fit can be used to test the assumptions of past SLR research (e.g. Fankhauser (1995)). A quadratic fit has also been included, which better approximates the SLR path of the IPCC SRES scenarios in the AR4, and has been used in some SLR studies (e.g., Sugiyama et al., 2008). The quadratic fit means that the rate of SLR increases during the simulation, which is consistent with the lags in ocean thermal expansion and the increased melting of glaciers.

| Global SLR Scenario | SLR in 2100 (meters) | Functional Form | Source    |
|---------------------|----------------------|-----------------|-----------|
| SLR-018L            | 0.18                 | Linear          | AR4, 2007 |
| SLR-018Q            | 0.18                 | Quadratic       | AR4, 2007 |
| SLR-049L            | 0.495                | Linear          | AR4, 2007 |
| SLR-049Q            | 0.495                | Quadratic       | AR4, 2007 |
| SLR-079L            | 0.79                 | Linear          | AR4, 2007 |
| SLR-079Q            | 0.79                 | Quadratic       | AR4, 2007 |
| SLR-150L            | 1.5                  | Linear          | NRC, 1987 |
| SLR-150Q            | 1.5                  | Quadratic       | NRC, 1987 |

**Table 3.2:** The eight global SLR scenarios defined in the model.

Three predefined SLR levels cover the full range of 2100 SLR estimates from the IPCC Fourth Assessment. The scenarios chosen were the SRES B1 (*IPCC B1 Low SLR*; 0.18 m), A1B (*IPCC A1B Mid SLR*; 0.495 m) and A1FI (*IPCC A1FI High SLR*; 0.79 m) (IPCC, 2000; Meehl et al., 2007). The lower bound (the 5 percent confidence interval) is used for this B1 scenario with no additional large ice sheet melt; therefore, this is the lowest estimate from the IPCC. The A1B value is the midpoint of the A1B range (0.21–0.48 m) plus mid-point of ice sheet addition (0.1–0.2 m). The high scenario uses the upper-bound of the A1FI range (the 95 percent confidence level; 0.59 m) plus the full amount of ice sheet melt (0.2 m).

The FRACC model also includes a fourth SLR scenario that can be arbitrarily chosen by the user. The default value of *Exogenous Global SLR in 2100* is 1.5 m, which is the high scenario suggested in the U.S. Army Corps of Engineers guidance document (National Research Council, 1987; White, 2009). The formulation for the final SLR amount and the shape of the fit allows many different global SLR scenarios to be quickly compared.

The model’s SLR scenarios have been named according to the total SLR and the mathematical fit. “SLR-150Q” is the USACE projection of 1.5 m (150 cm) fit with a quadratic (Q) function. Table 3.2 lists the SLR scenarios.

Figure 3-2 depicts the model structure for both the linear and quadratic SLR paths. A switch chooses which mathematical fit and SLR scenario drives the other model

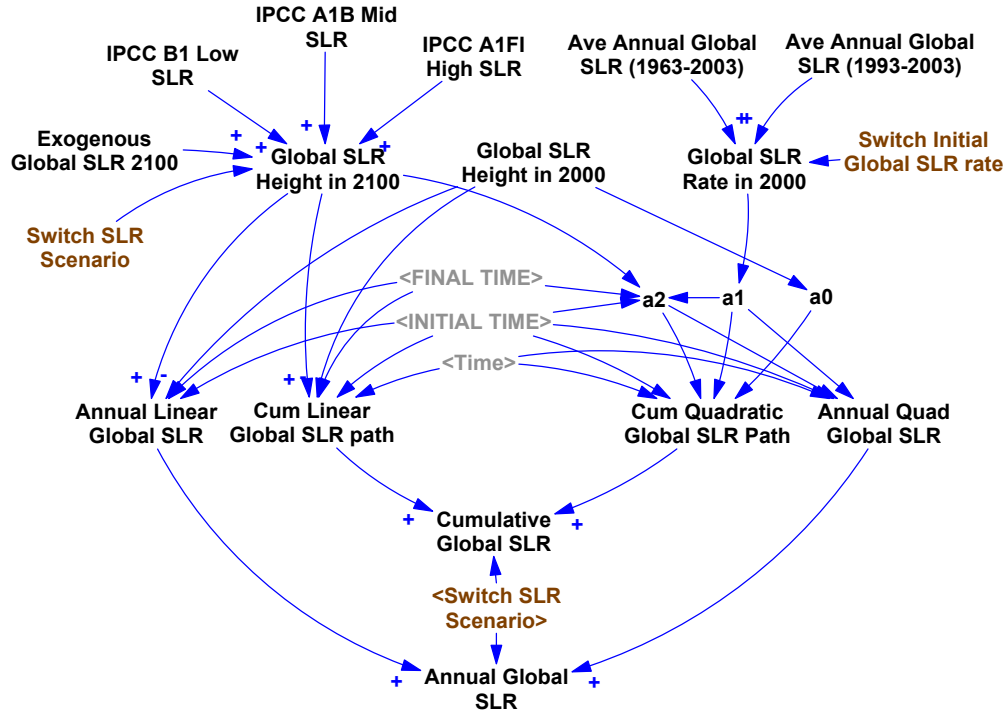


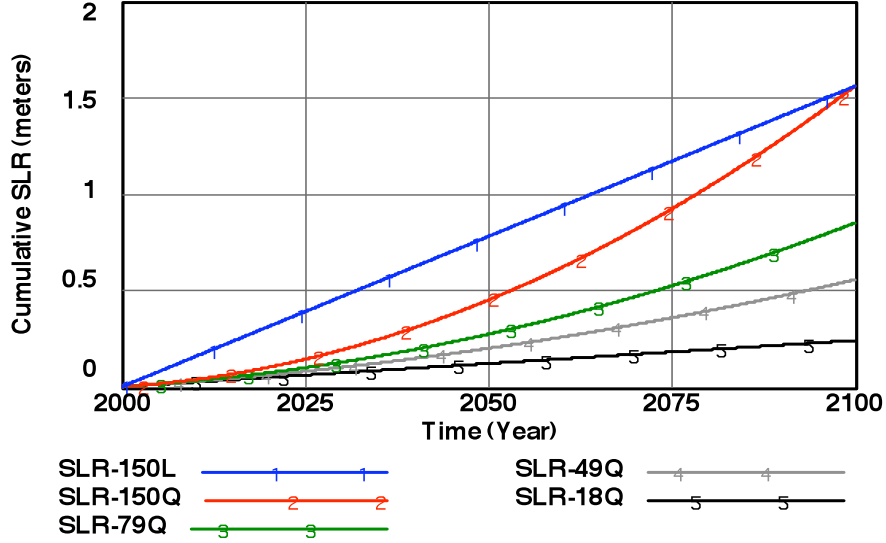
Figure 3-2: Global sea-level rise model structure.

components.

For comparison, five different SLR paths are plotted in Figure 3-3. The three IPCC SRES are projected using the quadratic equation. Both SLR-150L and SLR-150Q are plotted to depicted how the functional form changes the timing of SLR. Approximately two-thirds of the 1.5 m comes between 2050–2100 when the quadratic fit is used.

For the linear fit, the cumulative SLR at a given time in the model is calculated by:

$$SLR_t = (SLR_T - SLR_{t_0}) / (T - t_0) * (t - t_0) \quad (3.1)$$



**Figure 3-3:** Comparison of five global sea-level rise scenarios. The path of cumulative SLR between 2000–2100.

where

$SLR_t$  is the *Cum Linear Global SLR* (meters)

$SLR_T$  is the *Global SLR Height in 2100* (meters)

$SLR_{t_0}$  is the *Global SLR Height in 2000* (meters)

$T, T_0, t$  are the *FINAL TIME, INITIAL TIME, and Time* (years)

The annual rate of SLR for the linear fit is the slope of the above fit:

$$r_{t,slr} = \frac{SLR_T - SLR_{t_0}}{T - t_0} \quad (3.2)$$

where

$r_{t,slr}$  is the *Annual Linear Global SLR* (m/year)

Some additional coefficients  $a_2, a_1, a_0$  are required to calculate the quadratic SLR paths. To fit a quadratic curve, the *Global SLR Rate in 2000* and the *Global SLR*

*Height in 2100* are used. The historical rate of SLR differs according to the IPCC AR4. The average rate of SLR from 1963-2003 was 1.8 mm/year but during the most recent decade, 1993-2003, the rate averaged 3.1 mm/year (Meehl et al., 2007). The default value for the model is the more conservative estimate of 1.8 mm/year, but the modeler can choose between *Ave Annual Global SLR (1963-2003)* and *Ave Annual Global SLR (1993-2003)*. The quadratic equations are:

$$SLR_t = a_2 * (t - t_0)^2 + a_1 * (t - t_0) + a_0 \quad (3.3)$$

$$a_2 = \frac{SLR_T - (T - t_0)a_1}{(T - t_0)^2} \quad (3.4)$$

$$a_1 = r_{0,SLR} \quad (3.5)$$

$$a_0 = SLR_{t_0} = 0 \quad (3.6)$$

where

$r_{0,SLR}$  is the *Global SLR Rate in 2000* (m/year)

The annual rate of SLR accelerates during the simulation with a quadratic fit. The *Annual Quadratic Global SLR* is the derivative of the above quadratic equation:

$$r_{t,slr} = 2a_2(t - t_0) + a_1 \quad (3.7)$$

where

$r_{t,slr}$  is the *Annual Quadratic Global SLR* (m/year)

During a simulation, the *Switch SLR Scenario* allows the researcher to choose the final *Global SLR Height in 2100* and whether to use the quadratic or linear fit. The two main outputs of the global SLR component are *Cumulative Global SLR* and

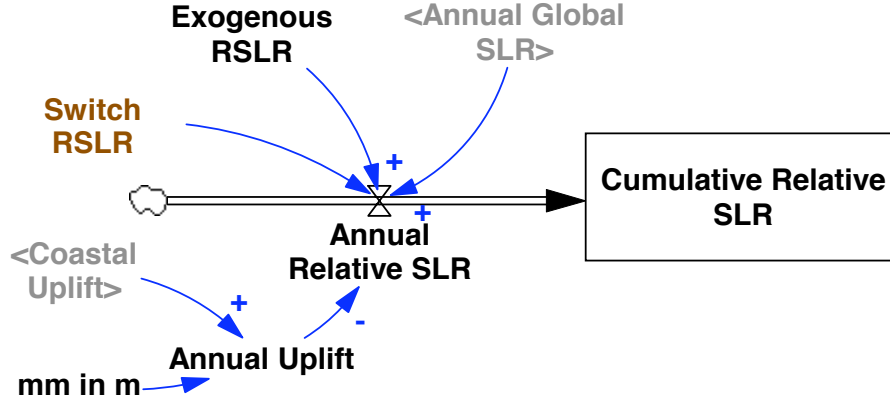


Figure 3-4: Cumulative RSLR model structure.

*Annual Global SLR.* *Annual Global SLR* is passed to the relative SLR component.

### 3.2.2 Relative sea-level rise

For adaptation studies it is important to translate the global sea-level rise trends above into relative sea-level rise (RSLR) rates (see Section 2.1.2). To derive RSLR the *Annual Global SLR* rate is adjusted by the *Annual Uplift* rate for the particular segment. The subsidence/uplift values were estimated from Nicholls and Leatherman (1996). Miami-Dade County's, a case study community described in Chapter 4, annual RSLR rates for five global SLR scenarios are shown in Figure 3-5. The cumulative SLR for a community, or the cumulative RSLR, is the integral of the annual rate of RSLR (Equations 3.8 and 3.9).

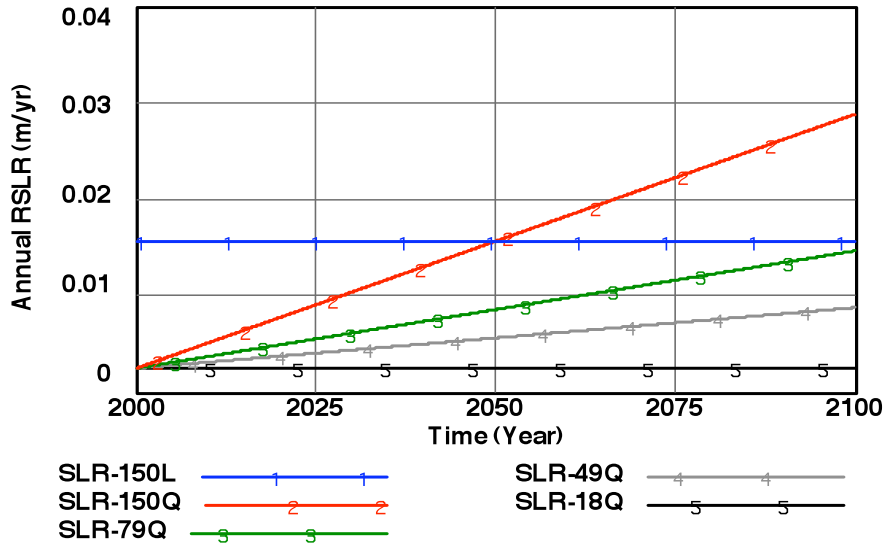
$$r_{t,rslr} = r_{t,slr} - u \quad (3.8)$$

$$RSLR_T = \int_{t_0}^T (r_{t,rslr}) dt \quad (3.9)$$

where

$r_{t,rslr}$  is the *Annual Relative SLR* (m/year)

$u$  is the *Annual Uplift* (negative subsidence) (m/year)



**Figure 3-5:** Annual RSLR from 2000–2100 for five global SLR scenarios for Miami-Dade County.

The model can be simulated using an *Exogenous RSLR* to drive the other components. This parameter is useful for testing various assumption and can be activated using *Switch RSLR*.

### 3.2.3 Sea-level rise and land loss

The amount of land in the community is the area of the region (e.g. a county). The total land area is partitioned between dry land that can be developed and wetlands that will be preserved. Dry land is suitable for either housing or capital infrastructure development. Wetlands are habitat for local wildlife and have economic value because of the environmental services they provide. The initial areas of dry land and wetlands for case study communities are in Table 4.2.

$$DL_0 = k_{dl}A_0 \tag{3.10}$$

$$WL_0 = (1 - k_{dl})A_0 \tag{3.11}$$



where

$DL_0$  is the initial area of dry land (sq. km)

$WL_0$  is the initial area of wetlands (sq. km)

$A_0$  is the total initial area of the community (sq. km)

$k_{dl}$  is the fraction of total area that is dry (dmnl)

Without a levee or some other form of public adaptation, sea-level rise will permanently inundate dry land. The model calculates the area of inundated land using the slope of land in the community. I assume that land has a constant slope rising from the ocean, a simplifying assumption that is necessary without a higher level of spatial resolution in the model.

The current area of dry land in the community is the initial area of dry land minus any loss of dry land due to RSLR.

$$DL_T = \int_{t_0}^T (-L_{loss,t})dt + DL_{t_0} \quad (3.12)$$

where

$DL_T$  is the amount of dry land (sq. km)

$L_{loss,t}$  is the amount of land lost to RSLR (sq. km/year)

Public adaptation, such as a levee or beach nourishment, provides protection against the rising ocean. It is assumed that if the protection height is greater than the water height, it is 100 percent effective at preserving the dry land. If a levee were never upgraded to protect land from a rising sea, and the water height of the ocean exceeded the levee height, dry land would be lost as if no protection existed. The following equations detail the process represented in the model:

$$L_{loss,t} = \begin{cases} MIN(AIA_t, \frac{DL_t}{\lambda_{dl}}) & \text{if } RSLR_t > H_{prot} \\ 0 & \text{if } RSLR_t \leq H_{prot} \end{cases} \quad (3.13)$$

where

$AIA_t$  is the annual inundated area (sq. km/year)

$\lambda_{dl}$  is a time constant to experience land loss (1 year)

$H_{prot}$  is the public protection height (meters)

The land lost is the minimum of either the annual inundated area  $AIA_t$  or the amount of dry land remaining. The MIN condition prevents losing more land than is in the community at time  $t$ .

The coastal slope is used to calculate the annual inundated area. The general equation below has been simplified for clarity. The equation used in the model contains several checks to prevent division by zero (Appendix C). Also, land is only flooded in the model if there is positive RSLR. The area of dry land does not increase if RSLR is negative, meaning that land is not reclaimed from the sea. This is a constraint on the model that is similar to the coastal flood module of the DIVA model.

$$AIA_t = \frac{r_{t,rslr} l}{k_{m,km} TAN(\varphi)} \quad (3.14)$$

where

$AIA_t$  is the annual inundated area (sq. km/year)

$l$  is the length of coastal line (km)

$\varphi$  is the coastal slope (degrees)

$k_{m,km}$  is a unit conversion constant (m/km)

Cumulative flooded land area is not used in the model as an input to any particular component, but is also calculated for accounting and reporting purposes. The cumulative flooded land is the integral of all the annual dry land losses.

### 3.3 Storm Events

Storms strike coastal communities unexpectedly at varying intervals and with varying intensities. The FRACC model represents storms in a similar manner. The timing and intensity of the storms are the outputs of Emanuel's physics-based tropical storm model (Section 2.2).

This dissertation examines trends and impacts of tropical storms, and does not evaluate the damage caused by extra-tropical storm events (e.g., nor'easters). Tropical storms were the largest single source of catastrophic insurance losses in the United States from 1986–2005, at 47.5 percent (Hartwig, 2007). Excluding tornadoes, all other weather-related losses totaled 10.6 percent. Tropical storms are the dominant driver for catastrophic loss in most coastal communities. At higher latitudes, extra-tropical storms may cause a larger portion of damage, but the effect is not studied.

The structure of the stochastic storm arrival component in the FRACC model is described in the next sections. In particular, each community has different storm frequency value and storm intensity distributions. Information regarding the construction of the storm frequency and intensity parameters is in Section 4.5.3.

### 3.3.1 Storm arrivals

The FRACC model defines both storm frequency and intensity for its communities. These characteristics are outputs of Emanuel’s Coupled Hurricane Intensity Prediction System (CHIPS) model, which generates thousands of synthetic storm tracks (Sections 2.2 and 4.5.3; Emanuel et al., 2008).

Storms arrive in the FRACC model according to a Poisson distribution. The output of the function is either zero or one, with a one indicating the arrival of the storm.

### 3.3.2 Storm intensities

The intensity of each simulated storm is classified according the Saffir-Simpson scale. The distribution of storms (i.e., the number of Category 1, Category 2, etc.) is an output of Emanuel’s model (Section 4.5.3).

When a storm arrives, the intensity of the storm is randomly chosen from the appropriate distribution. The storm intensity distributions were generated by binning the storms that made landfall into the Saffir-Simpson scale and differs by community. In the FRACC model, the distributions are characterized by their CDF. For every storm, a random number between 0–1 determines the intensity of the storm event.

### 3.3.3 Storm surge

A storm’s barometric pressure, wind speed, and radius, along with coastal morphology and the storm approach angle, are needed to predict storm surge reliably.

For this research, storm surge is crudely approximated using the Saffir-Simpson classification system. The Saffir-Simpson scale broadly describes each storm category, providing a range of possible surges (NOAA, 2008). The mid-points of the ranges were used for Categories 1-4. For Category 5, NOAA’s surge estimate was “18 feet plus.” For this research, a small margin was added and value of 20 feet (6.1 m) was used. All values were converted to meters for use in the model (Table 3.3).

| Storm Category | Modeled Surge Height (meters) |
|----------------|-------------------------------|
| Category 1     | 1.37                          |
| Category 2     | 2.13                          |
| Category 3     | 3.20                          |
| Category 4     | 4.72                          |
| Category 5     | 6.10                          |

**Table 3.3:** Storm surge as a function of storm category—the midpoints of the Saffir-Simpson scale.

### 3.4 Risk Perception

The FRACC model can test various assumptions about risk perception. The two main categories of assumptions are “rational” and “boundedly rational.” Rational actor assumptions are commonly used in previous coastal adaptation research (e.g., Fankhauser (1995), Yohe et al. (1996) and Tol (2002)). Rational decision makers are assumed to utilize all available information when taking an action. Rational decision makers also comprehend the full extent of exposure to a risk. For example, a “rational” person would know the true frequency of storms for their community and use this information when making protection decisions.

On the contrary, “boundedly rational” decision makers do not consider all information when making a choice. Instead, they only consider information they deem important, meaning salient, available, or explicitly part of their decision criteria. For instance, the US Army Corps of Engineers does not consider the economic value of wetlands when evaluating a project because wetlands are not explicitly part of their criteria. Additionally, boundedly rational decision makers have a poor understanding of low probability events. For this research, a boundedly rational agents do not properly estimate the risk of storm events in their community. Instead, they utilize simple heuristics when evaluating the risk to their property.

The model can test both of these rationality assumptions. The implications of these assumptions on storm perception are described in the next section. Rationality assumptions can also be changed to evaluate protection decisions, described in

Section 3.8.

### 3.4.1 Perception of storm events

The main decision makers perceive storm risk differently in the model. Coastal managers have expert knowledge of storm frequency and storm risk. They use this rational perception when making coastal protection choices, as described in Section 3.8.

Investors and residents have a “boundedly rational” perception of storm risk. Their perception of storm frequency changes every time a storm strikes. The model formulation is grounded in the “availability heuristic” (Tversky and Kahneman, 1974), as discussed in Section 2.3.

Investors estimate storm frequency by considering storm events they can recall in recent memory. The model refers to this timeframe as their “assessment window” and counts the number of storm occurrences within a defined time horizon. Contrary to the assumption regarding coastal managers, investors do not know the true frequency of storms and do not consider the long-term historical frequency of storm events when evaluating risk, instead utilizing only their recent memory.

Perceived storm frequency is modeled as two parallel stocks representing the number of storm events and the window of consideration (Figure 3-6). *Perceived Frequency of Storms* is the stock of storms, *Total Number of Storms*, divided by the stock of observation years *Years of Storm Observation* (Equation 3.15).

$$E(Freq_t) = \frac{\# Storms_t}{\# Obs Years_t} \quad (3.15)$$

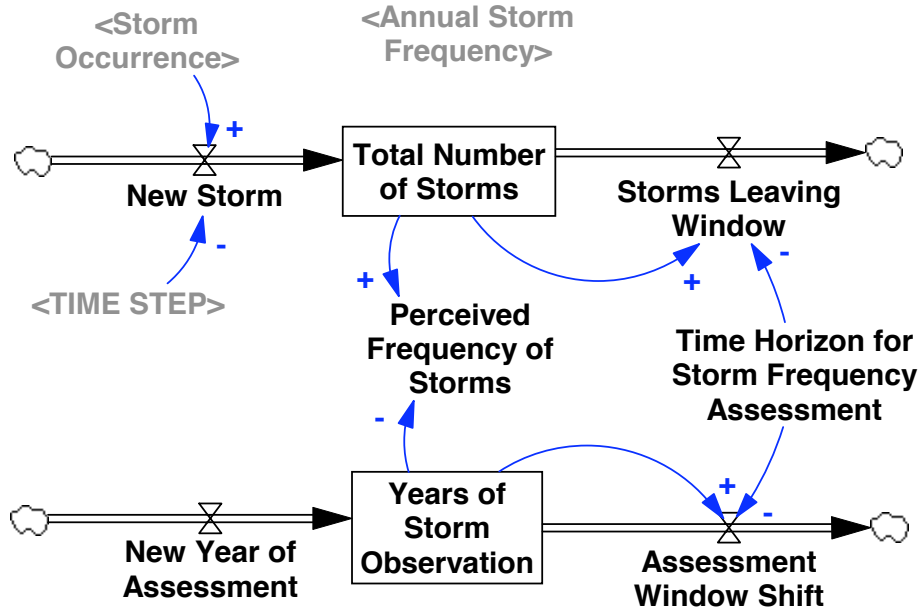


Figure 3-6: Perceived storm frequency model structure.

where

$E(Freq_t)$  is the *Perceived Frequency of Storms* (1/year)

$\# Storms_t$  is the *Total Number of Storms* (dmnl)

$\# Obs Years_t$  is the *Years of Storm Observation* (years)

The *Total Number of Storms* stock is the number of recent storms. The inflow *New Storm* increments the stock when a storm strikes. The storm count is decremented by the outflow *Storms Leaving Window* during the simulation.

$$\# Storms_T = \int_{t_0}^T (Storms_{new,t} - Storms_{old,t})dt + k_f * \tau_f \quad (3.16)$$

where

$\# Storms_t$  is the *Total Number of Storms* (storms)

$Storms_{new,t}$  is the *New Storm inflow* (storms/year)

$Storms_{old,t}$  is the *Storms Leaving Window* outflow (storms/year)

$k_f$  is the actual *Annual Storm Frequency* (1/year)

$\tau_f$  is the *Time Horizon for Storm Frequency Assessment* (years)

The initial perceived frequency of storms ( $k_f$ ) is the true storm frequency. The true frequency is determined by Emanuel's storm model, as described in Section 3.3. Initializing perceived frequency of storms to the true frequency is an optimistic assumption because investors do not have expert knowledge of storm risk. Over time, the perceived storm frequency changes as new storms occur and older storm events are forgotten.

The outflow *Storms Leaving Window* is the stock of storm occurrences divided by the *Time Horizon for Storm Frequency Assessment*, or number of years in the window (Equation 3.17). The weight given to a storm decreases exponentially with a time constant of  $\tau_f$ .

$$Storms_{old,t} = \frac{\# Storms_t}{\tau_f} \quad (3.17)$$

where

$\tau_f$  is the *Time Horizon for Storm Frequency Assessment* (years)

The number of observation years has similar structure to the stock of storm occurrences. The number of observation years is incremented and decremented each year. The stock is initialized to the *Time Horizon for Storm Frequency Assessment* and remains constant for most simulations. The number of observation years is mod-



eled explicitly, as opposed to using a constant, to test different assumptions of storm frequency updating. It can be considered a constant for the scenarios in this dissertation.

$$\# \text{ Obs Years}_T = \int_{t_0}^T (\text{New Year}_t - \text{WindowShift}_t) dt + \tau_f \quad (3.18)$$

$$\text{WindowShift}_t = \frac{\# \text{ Obs Years}_t}{\tau_f} \quad (3.19)$$

where

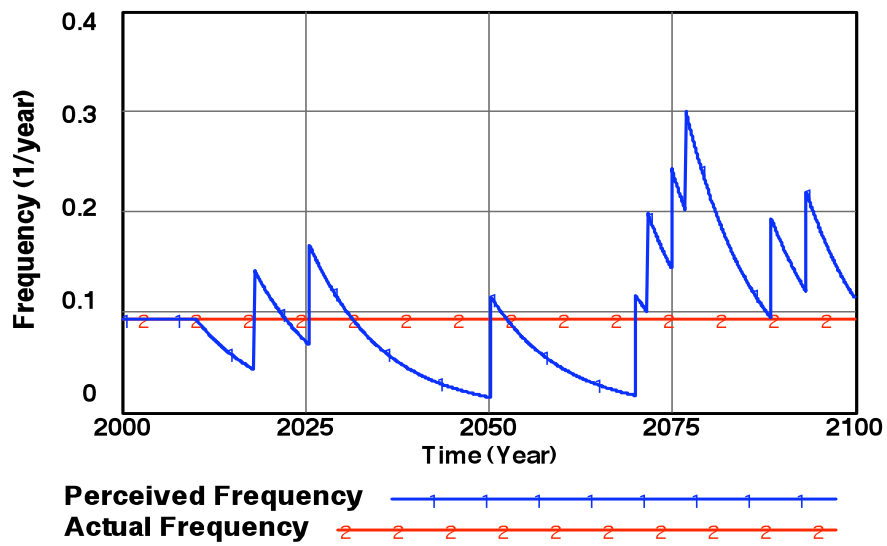
*New Year<sub>t</sub>* is the *New Year of Assessment* inflow

*WindowShift<sub>t</sub>* is the *Assessment Window Shift* outflow

*Time Horizon for Storm Frequency Assessment* is initialized at four years, an estimate from flooding studies (Birkland, 1997) and news reports (Cave and Almanzar, 2008). Investors and property owners behave as if they have a relatively short assessment window.

A partial model test illustrates the dynamics of storm frequency structure. *Perceived Frequency of Storms* fluctuates near the *Actual Storm Frequency* in simulations with stochastic storm arrivals (Figure 3-7). It rises above the actual frequency after a storm, then falls gradually between storms, often falling below the actual frequency over time.

The default model parameters for storm perception represent a boundedly rational agent; However, the model can be parameterized to test a community with rational investors. Rational investors would consider all historical data. To represent these conditions, the time horizon to assess storm frequency  $\tau_f$  is set to infinity. The result is that the actual storm frequency is the perceived storm frequency for the entire simulation.



**Figure 3-7:** Example of perceived storm frequency behavior for a series of storms, compared to the constant actual frequency.

### 3.5 Economy

The economic component of the model produces economic output, GDP, of the community. Output is a Cobb-Douglas function of capital and labor, the two factors of production considered (Equation 3.20).

$$Y_t = Y_0 a \left( \left( \frac{K_{f,t}}{K_0} \right)^{\alpha_k} \left( \frac{L_t}{L_0} \right)^{\alpha_l} \right) \quad (3.20)$$

where

$Y_t$  is the *Gross Output* (output units)

$Y_0$  is the *Initial Gross Output* (output units)

$K_{f,t}$  is *Total Undamaged Capital* (capital units)

$L_t$  is the *Employed Labor* (full-time equivalent workers)

$K_0, L_0$  are initial levels of capital and labor

$a$  is *Total Factor Productivity* (dmnl)

$\alpha_k$  is the share of capital (dmnl)

$\alpha_l$  is the share of labor (dmnl)

I assume constant returns to scale, so  $\alpha_k = 1 - \alpha_l$ . The parameter  $a$  is a scalar for total factor productivity, often interpreted as technological change. Labor and capital amounts are normalized by their current values, *Initial Employment* ( $L_0$ ) and *Initial Capital Stock* ( $K_0$ ).

Cobb-Douglas functions are considered appropriate for national-scale economic models. At the national-scale, it is reasonable to assume a constant ratio of labor and capital, given a diverse economy. The FRACC model is a meso-scale regional model, representing a county's economic system. While still covering a large geographic area, the assumption of constant factor shares may not hold. The Cobb-Douglas function was used for simplicity, but more general constant elasticity of substitution (CES) production functions could be used, which may be more appropriate for a sub-national

scale. In particular, if the model were run for a city or specific flood plain, a different production function should be used. The use of different production functions is left for future work.

Capital in the community can either be undamaged or damaged. Undamaged capital is the capital that is unaffected by prior storms, and produces economic output. Damaged capital is assumed not to be productive and produces no economic output. Employed labor is the actual number of employed laborers, which can be constrained by the number of job opportunities or the number of people in the community. Undamaged capital and employed labor are defined in more detail in Sections 3.5.1 and 3.5.4, respectively. Two key economic feedbacks adjust the factors of production according to their relative marginal products. These feedbacks are detailed in the Capital Adjustment (Section 3.5.2) and Labor Adjustment (Section 3.5.4) sections below.

### 3.5.1 Capital

The capital stock accumulates new capital investment less capital depreciation. The formation is similar to standard capital accumulation formulations presented in Blanchard (1997) (Equation 3.21).

$$K_T = \int_{t_0}^T (I_t - \delta K_t) dt + K_{t_0} \quad (3.21)$$

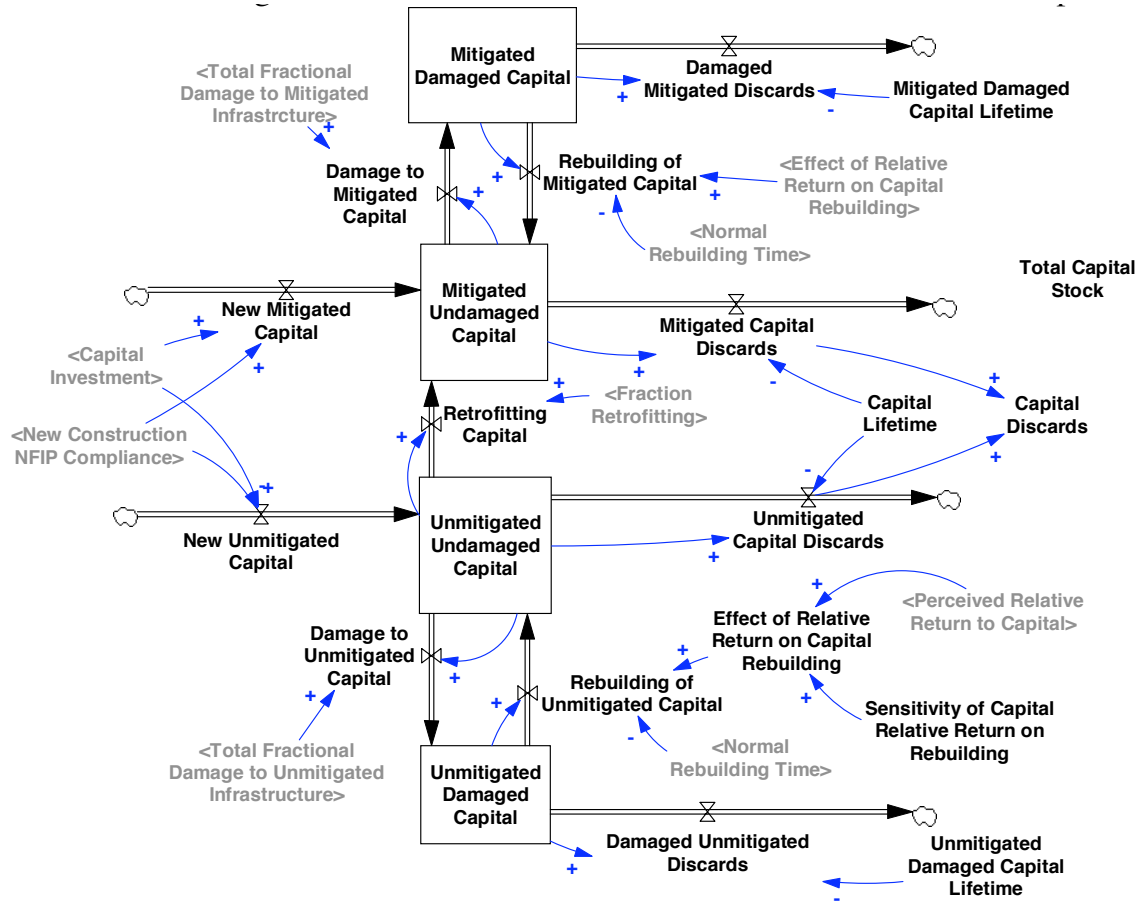
where

$K_T$  is the capital stock (capital units)

$I_t$  is capital investment (capital units/year)

$\delta$  is the fractional depreciation rate (1/year)

$K_0$  is the initial capital stock (capital units)



**Figure 3-8:** Four categories of capital in the community and the flows of investment, damage, rebuilding, and depreciation.

As mentioned above, the capital infrastructure in the FRACC model is divided between “undamaged” and “damaged” capital stocks. These two categories are divided again into “mitigated” and “unmitigated,” yielding four different categories: *Mitigated Undamaged Capital*, *Unmitigated Undamaged Capital*, *Mitigated Damaged Capital*, and *Unmitigated Damaged Capital* (Figure 3-8). All four categories are measured in “capital units,” defined to be one dollar’s worth of infrastructure.

The difference between the categories depends on whether the capital was damaged by a storm or RSLR, and whether the capital is mitigated according to National Flood Insurance Program (NFIP) building standards. The capital damage functions and the decision rule regarding mitigation are described in Sections 3.9 and 3.10.2, respectively.

All four categories of capital have a depreciation term, though the time constants for damaged capital are shorter than the 30 year lifetime of undamaged capital. *Mitigated Damaged Capital* depreciates faster than both stocks of undamaged capital, but slower than *Unmitigated Damaged Capital*. After a storm, damaged capital is discarded more quickly than undamaged capital, making room for new capital infrastructure. Mitigated capital, though, is less likely to be demolished quickly as owners wait for insurance settlements and disaster relief. Fieldwork in New Orleans confirms the difference in depreciation time constants. After Hurricane Katrina, the city of New Orleans demolished many damaged properties. Three years after the event, some of the remaining unoccupied damaged properties are waiting on insurance claims or assistance from FEMA before reconstruction can begin. Some mitigated properties had legal issues delaying their relief claims. For example, approximately 20,000 New Orleans residents had issues with property titles and are having trouble receiving federal disaster aid (DeBerry, 2008; Ydstie, 2008).

The following set of equations describes the structure of the capital component:

$$K_{total} = K_t^{mu} + K_t^{uu} + K_t^{md} + K_t^{ud} \quad (3.22)$$

$$K_T^{mu} = \int_{t_0}^T (I_t^{mu} - \delta_{mu}K_t^{mu} + R_t^{md} + T_t - D_t^{mu})dt + K_{t_0}^{mu} \quad (3.23)$$

$$K_T^{uu} = \int_{t_0}^T (I_t^{uu} - \delta_{uu}K_t^{uu} + R_t^{ud} - T_t - D_t^{uu})dt + K_{t_0}^{uu} \quad (3.24)$$

$$K_T^{md} = \int_{t_0}^T (-\delta_{md}K_t^{md} + D_t^{mu} - R_t^{md})dt + K_{t_0}^{md} \quad (3.25)$$

$$K_T^{ud} = \int_{t_0}^T (-\delta_{ud}K_t^{ud} + D_t^{uu} - R_t^{ud})dt + K_{t_0}^{ud} \quad (3.26)$$

where

superscripts  $mu$ ,  $uu$ ,  $md$ ,  $ud$  are for the four capital categories

$I_t$  is *Capital Investment* (capital units/year)

$D_t$  are the damage flows (capital units/year)

$R_t$  are rebuilding flows (capital units/year)

$T_t$  is *Retrofitting Capital* flow (capital units/year)

The  $D_t$  terms are damage flows from undamaged to damaged categories. Damage may occur when a storm strikes or when a protection structure breaches (Section 3.9). When damaged capital is repaired, the capital may move back to the appropriate undamaged stock at the rate  $R_t$ . *Retrofitting Capital* is the process of making current infrastructure more flood resilient, which is further described in Section 3.10.2.

New capital investment creates undamaged capital stock in the community. Total new *Capital Investment* ( $I_t$ ) is divided between the undamaged categories according to the current fraction of structures that are compliant with NFIP mitigation standards. The *New Construction NFIP Compliance* is an exogenous parameter described in Section 3.10.2.

$$I_t^{mu} = F_t^M I_t \quad (3.27)$$

$$I_t^{uu} = (1 - F_t^M) I_t \quad (3.28)$$

where

$I_t^{mu}$  is *New Mitigated Construction* (capital units/year)

$I_t^{uu}$  is *New Unmitigated Construction* (capital units/year)

$F_t^M$  is *New Construction NFIP Compliance* (dmnl)

*Unmitigated Undamaged Capital* may be retrofitted and become *Mitigated Undamaged Capital*. The flow of *Retrofitting Capital* is determined by the amount of *Unmitigated Undamaged Capital* and the average level of compliance with NFIP building standards (Equation 3.29). If compliance were to increase, due to increased enforcement or some other means, the rate of retrofitting after a storm would increase.

$$T_t = F_t^R K_t^{uu} \quad (3.29)$$

where

$F_t^R$  is *Fraction Retrofitting* (1/year)

Storm events require four additional terms to be included in the capital stock equations: two flows for damage and two flows for rebuilding. Undamaged capital may become damaged during a storm and is moved to a damaged stock. Once damaged, the capital may be rebuilt and become undamaged again. The damage and rebuilding flows exist for both mitigated and unmitigated capital.

For example, when a storm occurs, *Mitigated Undamaged Capital* may be flooded (Section 3.9) and become *Mitigated Damaged Capital*. Over time, the *Mitigated Damaged Capital* is either depreciated or rebuilt.

$$D_t^{mu} = f^{sm} K_t^{mu} \quad (3.30)$$

$$D_t^{uu} = f^{su} K_t^{uu} \quad (3.31)$$



where

$D_t^{mu}$  is the *Damage to Mitigated Capital* flow (capital units/year)

$D_t^{uu}$  is the *Damage to Unmitigated Capital* flow (capital units/year)

$f^{sm}$  is the *Total Fractional Damage to Mitigated Infrastructure* (1/year)

$f^{su}$  is the *Total Fractional Damage to Unmitigated Infrastructure* (1/year)

Capital is rebuilt according to the *Perceived Relative Return to Capital*, described further in Section 3.5.2. Capital is rebuilt faster when investors expect a high return on their investment. If they do not expect a strong return, capital is rebuilt more slowly or not at all.

$$R_t^{md} = \frac{K_t^{md}}{\tau_R} \xi_{rrk}^k \quad (3.32)$$

$$R_t^{ud} = \frac{K_t^{ud}}{\tau_R} \xi_{rrk}^k \quad (3.33)$$

where

$R_t^{md}$  is the *Rebuilding of Mitigated Capital* flow (capital units/year)

$R_t^{ud}$  is the *Rebuilding of Unmitigated Capital* flow (capital units/year)

$\tau_R$  is the *Normal Rebuilding Time* (years)

$\xi_{rrk}^k$  is the *Effect of Relative Return on Capital Rebuilding* (dmnl)

The depreciation factors  $\delta$  are the inverse of the lifetime of their capital stock category. The lifetimes of both undamaged categories are the same. Damaged capital stocks have a shorter lifetime because non-functioning capital is more likely to be abandoned and/or discarded.

$$\delta^{mu} = \delta^{uu} = \frac{1}{\tau_{mu}} = \frac{1}{\tau_{uu}} = \frac{1}{30} \quad (3.34)$$

$$\delta^{md} = \frac{1}{\tau_{md}} = \frac{1}{5} \quad (3.35)$$

$$\delta^{ud} = \frac{1}{\tau_{ud}} = \frac{1}{2} \quad (3.36)$$

where

$\delta^*$  are the depreciation factors (1/years)

$\tau_{mu}, \tau_{uu}$  are both the undamaged *Capital Lifetime* (years)

$\tau_{md}$  is the *Mitigated Damaged Capital Lifetime* (years)

$\tau_{ud}$  is the *Unmitigated Damaged Capital Lifetime* (years)

### 3.5.2 Capital adjustment

In the FRACC model economic capital is assumed to adjust to the profit maximizing level over a period of time. The lagged adjustment assumption contrasts to an equilibrium assumption of many economic models, in which capital is at the optimal level at all times. In the FRACC model, there is an optimal level of capital, called *Indicated Capital*, for the current economic conditions at any given moment. At that moment, the actual level of capital might not equal the indicated amount. Over time (i.e., with a lag) changes in investment adjust the current amount of capital to the indicated amount.

The FRACC model's lagged capital formulation is based on studies that examine economic capital investment. These studies show that capital adjustment lags stem from delays in perceiving the optimal amount and delays in acquiring new capital (Jorgenson et al., 1970; Mass, 1975; Senge, 1978). Models incorporating these dynamics have been used to study a variety of topics, including national macroeconomic trends (Forrester, 1977) and energy markets (Sterman, 1981; Fiddaman, 1997,

2002).

In FRACC, *Capital Investment* responds to five different adjustment processes (Figure 3-9). The formulation allows for perception delays and capital acquisition delays. Additionally, the formulation includes an adjustment for land availability. The five adjustment mechanism are:

1. Capital depreciation
2. Land availability
3. Long-run growth expectations
4. Relative return to capital
5. Aggregate demand

### Capital depreciation

Gross capital investment is the sum of capital depreciation and the net change of capital given the other four adjustments. Depreciated capital is replaced under the assumption that investors replace discarded and worn out capital if other conditions are favorable.

$$I_T^{tot} = I_t^{net} + \delta_{mu}K_t^{mu} + \delta_{uu}K_t^{uu} + \delta_{md}K_t^{md} + \delta_{ud}K_t^{ud} \quad (3.37)$$

where

$I_T^{tot}$  is the total *Capital Investment* (capital units)

$I_t^{net}$  is *Indicated Net Change in Capital* (capital units/year)

$K_t^{xx}$  are the four capital categories (capital units)

$\delta_{xx}$  are the depreciation factors (1/year)

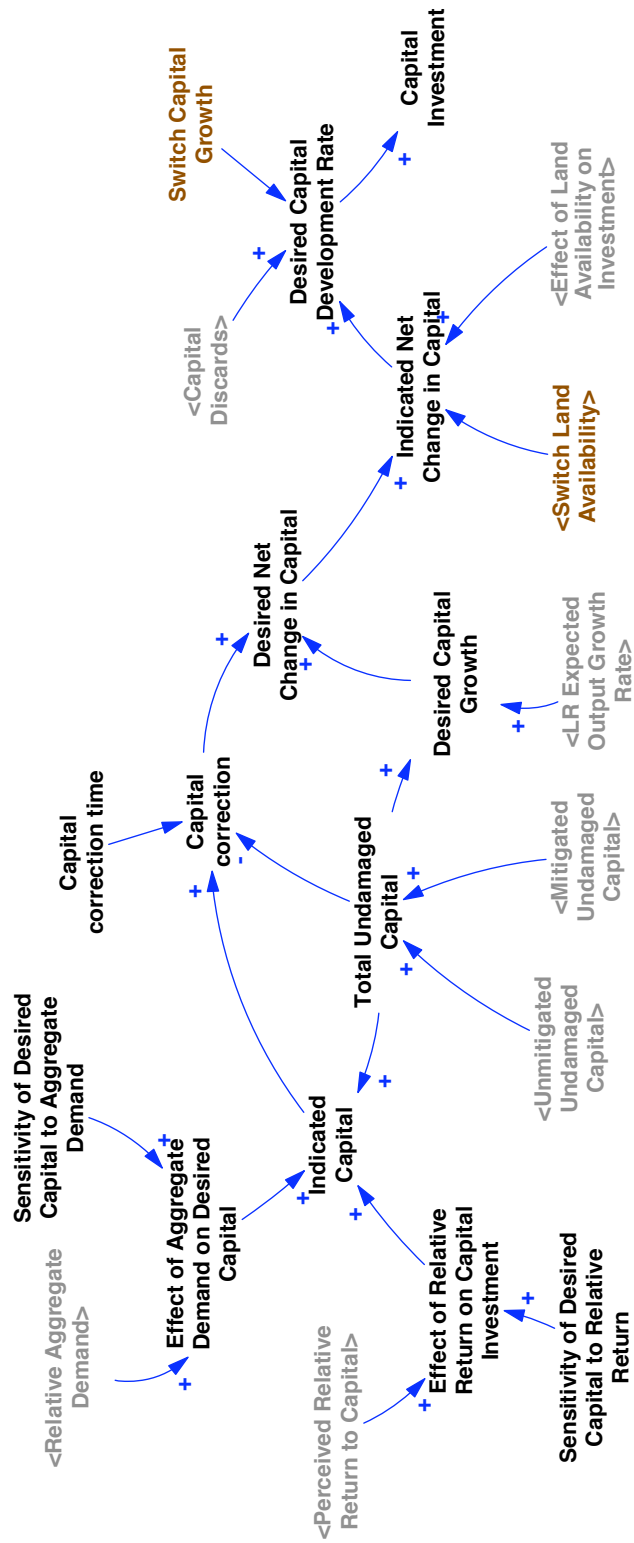


Figure 3-9: Adjustment mechanisms for new capital investment.

## Land availability

The total amount of dry land available is a constraint on economic growth. Economic growth increases the capital and housing density in the community. As the density increases, investment and construction becomes more difficult. If the community is densely developed, old capital must be removed before new capital can be constructed, slowing the overall rate of capital investment.

The *Indicated Net Change in Capital* ( $I_t^{net}$ ) factors in the land constraint adjustment, called the *Effect of Land Availability on Construction*. Land availability is assumed to affect total capital investment, adjusting the total amount of new investment indicated by the remaining capital adjustment mechanisms. The land effect is only a constraint for positive capital adjustments. If the net effect of the other three adjustments (below) is negative, then the land effect is not binding

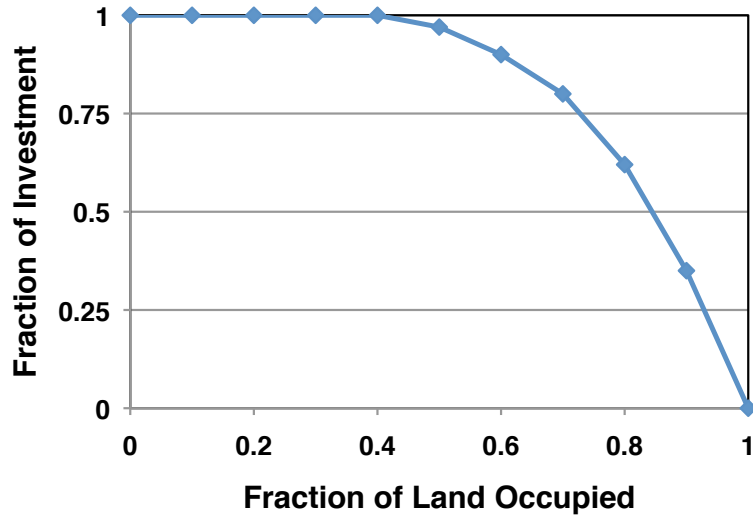
$$I_t^{net} = \begin{cases} I_t^{dnet} & \text{if } I_t^{dnet} < 0 \\ I_t^{dnet} \xi_{land}^k & \text{if } I_t^{dnet} \geq 0 \end{cases} \quad (3.38)$$

where

$I_t^{dnet}$  is *Desired Net Change in Capital* (capital units/year)

$\xi_{land}^k$  is the *Effect of Land Availability on Construction* (dmnl)

The *Effect of Land Availability on Investment* is a function shown in Figure 3-10. When the density of capital is low, the multiplier is 1, meaning that land has no effect on net investment. As the density of capital increases, development becomes more difficult in the community, which represents the land scarcity effect on investment.



**Figure 3-10:** Table function for *Effect of Land Availability on Investment*. As fraction of land developed increases, investment in new infrastructure decreases.

### Long-run growth expectations

The desired level of capital investment is adjusted for long-run expectations of economic growth. Investors increase or decrease new investment based on recent economic trends. *Desired Net Change in Capital* is the indicated amount of capital investment adjusted for long-run growth in the community.

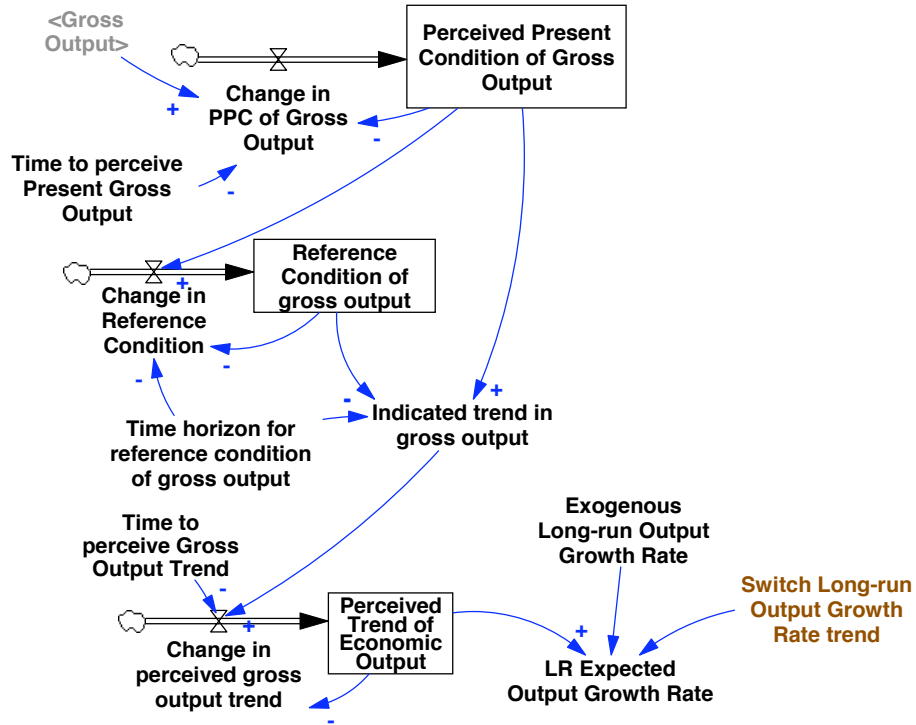
$$I_t^{dnet} = I_t^{grow} + I_t^{corr} \quad (3.39)$$

where

$I_t^{grow}$  is *Desired Capital Growth* (capital units/year)

$I_t^{corr}$  is *Capital Correction* (capital units/year)

The *Desired Capital Growth* term corrects for a steady-state error of capital if the community's economy is growing. If capital investment were not adjusted for the long-term growth rate, a community with a constantly growing economy would never achieve the indicated level of capital. *Desired Capital Growth* corrects potential



**Figure 3-11:** TREND function formulation used to estimate future economic output.

steady-state error by calculating the long-run growth rate using a standard TREND function (Sterman, 2000). The TREND function calculates the fractional growth rate of GDP using recent GDP values and some perception lags (Figure 3-11).

$$I_t^{grow} = g_t^y K_t^{tu} \quad (3.40)$$

$$g_t^y = TREND(Y_t) \quad (3.41)$$

where

$g_t^y$  is the *LR Expected Output Growth Rate* (1/year)

$K_t^{tu}$  is *Total Undamaged Capital* (capital units)

$Y_t$  is *Gross Output* (output units)

## Capital correction

The long-run growth trend is an additional adjustment to the *Capital Correction*—new investment to close the gap between the indicated and actual levels of capital. To close the gap, the difference between the indicated  $K_t^*$  and the actual  $K_t^{tu}$  is calculated (where  $K_t^{tu}$  is all undamaged capital). The difference cannot be added immediately because of construction and capital chain delays. The time lag for capital adjustment  $\lambda_{kadj}$  is four years, averaging construction and other typical delays (Senge, 1978).

$$I_t^{corr} = \frac{K_t^* - K_t^{tu}}{\lambda_{kadj}} \quad (3.42)$$

$$K_t^{tu} = K_t^{uu} + K_t^{mu} \quad (3.43)$$

$$\lambda_{kadj} = 4 \quad (3.44)$$

where

$K_t^*$  is the level of *Indicated Capital* (capital units)

$K_t^{tu}$  is *Total Undamaged Capital* (capital units)

## Indicated capital

The *Indicated Capital* stock in the community ( $K_t^*$ ) is determined by the two remaining capital adjustments: aggregate demand and relative return to capital. The indicated amount of capital reflects the current economic conditions (i.e., “indicated” by current economic conditions). Indicated capital is not the solution of an equilibrium optimization. As people demand more or less economic output, the indicated level of capital increases or decreases accordingly. Similarly, if the relative return to capital investment increases, the indicated amount of capital will increase as investors capture the higher level of return.



In the model, the indicated capital level is determined by scaling the current level of capital by multipliers for aggregate demand and relative return to capital. When people demand the current amount of economic output, the aggregate demand multiplier is 1, meaning the indicated capital level is the current level. Similarly, if the relative return to capital ratio is 1, then the relative return multiplier is 1. If aggregate demand or relative return changes, the indicated level of capital changes relative to the current level of capital.

$$K_t^* = \xi_{rrk}^k \xi_{ad}^k K_t^{tu} \quad (3.45)$$

where

$\xi_{rrk}^k$  is the *Effect of Relative Return on Capital Investment* (dmnl)

$\xi_{ad}^k$  is the *Effect of Aggregate Demand on Capital Investment* (dmnl)

### Relative return to capital

Investors are assumed to increase their investments when they expect a positive rate of return, and vice versa. Investor behavior is parameterized in the *Effect of Relative Return on Capital Investment* ( $\xi_{rrk}^k$ ), a function of the *Perceived Relative Capital Return* ( $RR_k^p$ ) and a sensitivity exponent ( $\sigma_{rrk}$ ).

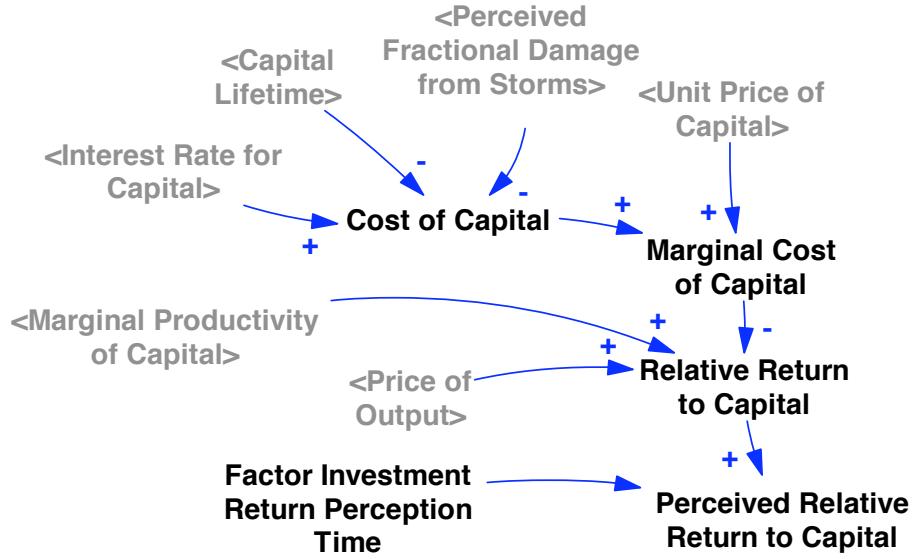
$$\xi_{rrk}^k = (RR_k^p)^{\sigma_{rrk}} \quad (3.46)$$

$$\sigma_{rrk} = 0.5 \quad (3.47)$$

where

$RR_k^p$  is the *Perceived Relative Capital Return* (dmnl)

$\sigma_{rrk}$  is the *Sensitivity of Desired Capital to Relative Return* (dmnl)



**Figure 3-12:** Perceived relative return to capital, including marginal costs and returns.

The *Perceived Relative Capital Return* represents how investors process return information. Investors can not base their investment decisions on the immediate returns to capital but instead use several of the past reporting periods. Past reporting periods are used because instant return information is often unavailable. Instead, return information is aggregated and reported after some time period (e.g., monthly, quarterly). The model smoothes relative return data over two years, meaning that investors average the returns to capital based on the past two years' *Relative Return to Capital* ( $RR_k$ ) (Figure 3-12).

$$RR_k^p = SMOOTHI(RR_k, \tau_{rrk}) \quad (3.48)$$

$$\tau_{rrk} = 2 \quad (3.49)$$

where

$RR_k$  is the *Relative Return to Capital* (dmnl)

$\tau_{rrk}$  is the *Factor Investment Return Perception Time* (years)

The actual *Relative Return to Capital* is the ratio of the *Marginal Productivity of Capital* to the *Marginal Cost of Capital*. The investor expects a positive return on investment when marginal productivity is greater than marginal cost, and vice versa. When they are equal, the current level of capital is sufficient. When costs are greater than productivity, capital infrastructure is overbuilt and the indicated level of capital is lower than the current level.

$$RR_k = \frac{P_y MP_k}{MC_k} \quad (3.50)$$

where

$MP_k$  is the *Marginal Productivity of Capital* ((unit/year)/capital unit)

$MC_k$  is the *Marginal Cost of Capital* (\$/year)/capital unit)

$P_y$  is the *Price of Output* (\$/unit)

The marginal productivity of capital is the increase in gross output per unit of additional capital. It is the derivative of the Cobb-Douglas production function (Equation 3.20) with respect to capital.

$$MP_{k,t} = \frac{\alpha_k Y_t}{K_{f,t}} \quad (3.51)$$

The *Marginal Cost of Capital* is the product of the *Unit Price of Capital* and the full *Cost of Capital*. The unit price of capital is assumed to be constant and does not include a scarcity effect for inputs. Capital construction markets could be included in future work.

$$MC_k = FC_k P_k \quad (3.52)$$

$$P_k = 1 \quad (3.53)$$

where

$FC_k$  is the full *Cost of Capital* (1/year)

$P_k$  is the *Unit Price of Capital* (\$/capital unit)

*Cost of Capital* is fractional cost of owning a unit of capital. Costs are incurred through capital depreciation and financing. The cost of capital is the expected *Capital Lifetime* ( $\tau_k$ ) plus the *Interest Rate for Capital* loans. Additionally, investors take their *Perceived Fractional Damage from Storms* into account. Damage from storms lowers the lifetime of capital, reducing the time investors can gain a return on their investment. Shorter capital lifetime effectively increases the cost of capital, and is included in the *Cost of Capital*.

$$FC_k = r_k + \frac{1}{\tau_k} + \hat{d} \quad (3.54)$$

where

$r_k$  is the *Interest Rate for Capital* (1/year)

$\tau_k$  is the *Capital Lifetime* (years)

$\hat{d}$  is the *Perceived Fractional Damage from Storms* (1/year)

The *Interest Rate for Capital* is the financing cost of capital. It is the sum of a risk-free rate plus the risk premium for capital investments, which are assumed to be held constant at 3 percent and 2 percent respectively. Interest rates are exogenous to

the model.

$$r_k = r_{rf} + r_{kp} \tag{3.55}$$

where

$r_{rf}$  is the risk free interest rate (1/year)

$r_{kp}$  is the risk premium for capital units (1/year)

As described in Section 3.4, investors' perception of storm frequency changes depending on the arrival of storm events. Perceived storm frequency affects capital investment by changing investors' analysis of the marginal cost of infrastructure. Investors estimate damage from storms and flooding utilizing their own understanding of the frequency of the events. Their perceived storm frequency is used in the estimate of the fractional damage to capital.

Expected damage is calculated by summing the product of the probability of a storm category, the fractional damage of a storm category, and the perceived frequency of storms. The result is the expected fraction of capital that will be damaged based on the perceived frequency and expected severity of storms. The expected fraction of damage from storms is:

$$\hat{d} = E(Freq) \sum_i P_i d_i^t \tag{3.56}$$

where

$i$  is the index for storm category (1, 2, 3,...)

$P_i$  is the probability of a storm category (dmnl)

$E(Freq)$  is the *Perceived Frequency of Storms* (1/year)

$d_i^t$  is fractional damage for a storm category (dmnl)

The probability of a storm category is calculated from the actual distribution of storms intensities. Storm intensity distribution are described in Section 3.3. The method for calculating fractional damage for a particular storm category is described below (Section 3.9).

### **Aggregate demand**

The second effect determining the *Indicated Capital* stock is the *Effect of Aggregate Demand on Capital Investment*. The aggregate demand feedback is a function of the aggregate output demanded by the community because of consumer expectations, consumer savings, insurance claims, government expenditures, and external trade. The aggregate demand capital adjustment mechanism represents the processes of internal consumer spending and government activity in the community. The *Effect of Aggregate Demand on Capital Investment* is determined by the *Relative Aggregate Demand*. *Relative Aggregate Demand* is the ratio of the expected aggregate demand, *Desired Gross Output*, to the current demand, *Gross Output*. A sensitivity parameter controls the strength of the of the effect.

When *Desired Gross Output* exceeds current *Gross Output*, then the indicated level of capital increases. The opposite is also true, with the indicated level of capital lowering if current economic output is greater than demand for output.

$$\xi_{ad}^k = RAD^{\sigma_{ad}} \quad (3.57)$$

$$RAD = \frac{Y^*}{Y} \quad (3.58)$$

where

$\xi_{ad}^k$  is the *Effect of Aggregate Demand on Capital Investment* (dmnl)

$RAD$  is the *Relative Aggregate Demand* (dmnl)

$\sigma_{ad}$  is the *Sensitivity of Desired Capital to Aggregate Demand* (dmnl)

$Y^*$  is the *Desired Gross Output* (units/year)

$Y$  is the current *Gross Output* (output units)

*Desired Gross Output* is the desired level of economic output to satisfy all the demand for goods and services. Desired output is the sum of government expenditures, insurance claim payments received, consumer consumption, consumer savings, and external demand. Each of these sources creates demand for economic output, increasing the desired amount of economic activity in the community.

$$Y^* = C^* + S^* + V + G + T \quad (3.59)$$

where

$C^*$  is *Desired Consumption* (output units/year)

$S^*$  is *Desired Savings* (output units/year)

$V$  is *Insurance Claims Paid* (output units/year)

$G$  is *Desired Government Services* (output units/year)

$T$  is *External Demand* (output units/year)

Consumers divide their income between *Desired Consumption* and *Desired Investment*. The amount they consume is determined by the *Marginal Propensity to Consume*, a fraction of their income they are likely to spend. The remainder is saved. Savings stay in the community for investment, creating additional aggregate demand.

$$C^* = \psi_c i^e N \quad (3.60)$$

$$S^* = (1 - \psi_c) i^e N \quad (3.61)$$

where

$\psi_c$  is the *Marginal Propensity to Consume* (dmnl)

$i^e$  is *Expected Income per Capita* ((output units/person)/year)

$N$  is *Population* (persons)

*External Demand*,  $T$ , is a constant for external demand that has been initialized to zero, which assumes there is no significant amount of external sources generating consumption locally.

Total consumer demand—savings and consumption—depends on expectations of future GDP per capita, *Expected Income per Capita*. Consumers demand more more if they expect incomes to rise and slow spending if GDP per capita does not rise as quickly. *Expected Income per Capita* is a function of the actual *Output per Capita*. As *Output per Capita* changes, consumers adjust their spending habits, but not instantaneously. Research shows that people become habituated to the their new income level after about two years (e.g., Layard, 2006). To capture the habituation behavior, *Expected Income per Capita* ( $i^e$ ) is modeled by a first order exponential smooth with a two year time constant  $\tau_{ei}$ .



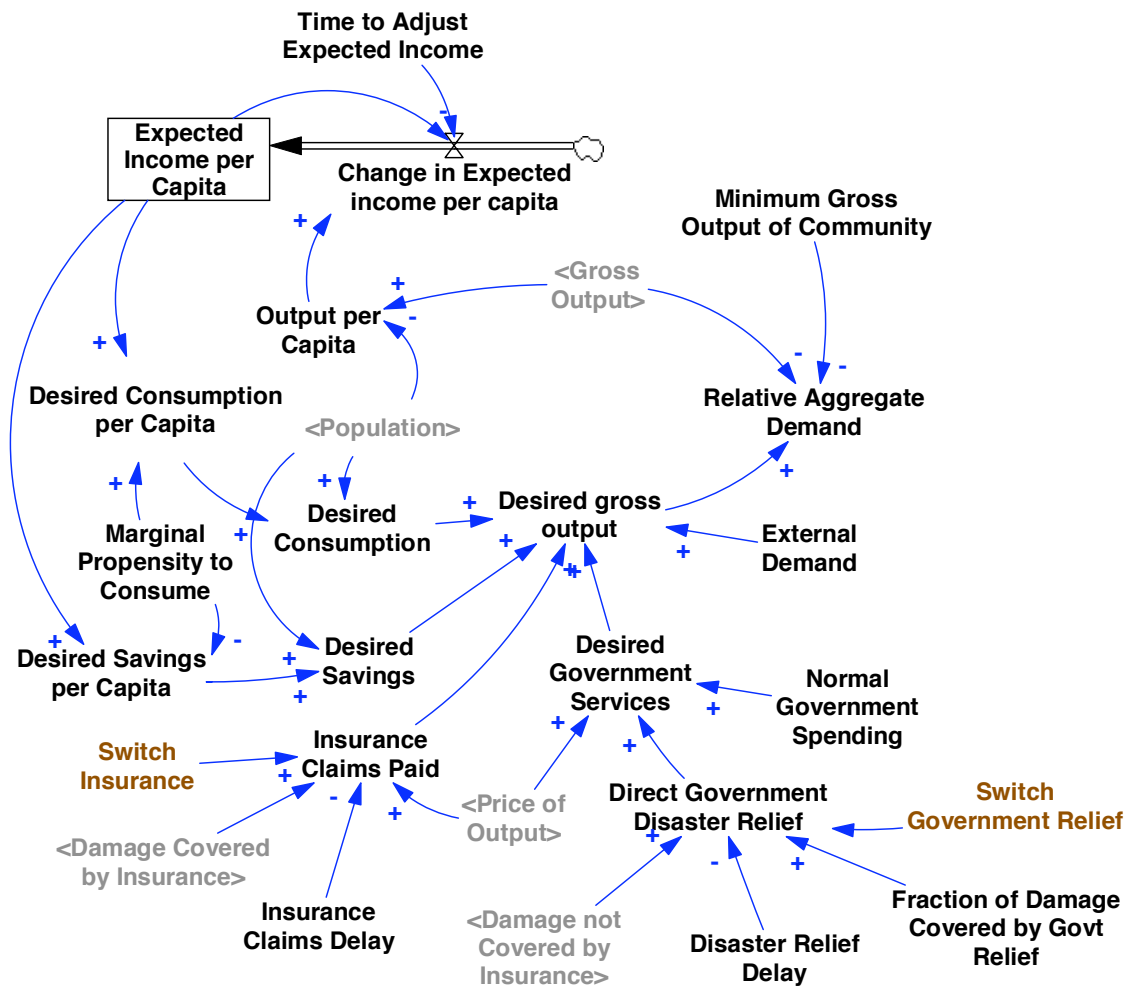


Figure 3-13: Expected aggregate demand adjustment and total aggregate demand for economic output.

$$i^e = \frac{(Y/N) - i^e}{\tau_{ei}} \quad (3.62)$$

where

$Y/N$  is *Output per Capita* ((output units/person)/year)

$\tau_{ei}$  is *Time to Adjust Expected Income* (years)

*Insurance Claims Paid* is a function of the storm damage to community. The value of the payments from flood and wind insurance is describe in Section 3.10.1. Payments are modeled with a lag to represent the time required to file a claim and to receive payment. A third-order delay (Sterman, 2000) is used with two year time delay.

$$V = DELAY3(D^{ins})P_y, \lambda_{ins} \quad (3.63)$$

where

$D^{ins}$  is the *Damage Covered by Insurance* (\$/year)

$\lambda_{ins}$  is the *Insurance Claims Delay* (years)

*Desired Government Services* are the government expenditures in the community. I assume that consumer taxes are offset by government spending, keeping aggregate demand at the pre-tax level. The current formulation does not explicitly represent taxes and assumes that taxes are included in consumer consumption, therefore *Normal Government Spending* is zero. If the government were spending more than their tax revenue, *Normal Government Spending* amount would be positive, increasing aggregate demand. *Desired Government Services* may also include disaster relief,

allowing government to induce economic investment.

$$G = G_d + G_0 \tag{3.64}$$

where

$G_d$  is *Direct Government Disaster Relief* (\$/year)

$G_0$  is *Normal Government Spending* (\$/year)

In times of disaster, such as after a storm, the government may provide disaster relief to the community. The model includes *Direct Government Disaster Relief* to help with reconstruction and to spur economic growth. The government covers a fraction of the storm damage that is not covered by private insurance. Disaster relief does not come immediately upon authorization from Congress and/or FEMA. There are delays with the distribution of funds, including setting up the field offices, filing claims, validating claims, and issuing payment. To capture the delays, the flow of disaster relief is a third-order delay with a time constant of five years. The bulk of relief comes within two years after the storm with a tail of money for several years afterwards. Government disaster relief is activated by default.

$$G_d = DELAY3(D^{nins} F_{cov}, \lambda_{gd}) \tag{3.65}$$

where

$D^{nins}$  is the *Damage not Covered by Insurance* (\$/year)

$F_{cov}$  is the *Fraction of Damage Covered by Govt Relief* (dmnl)

$\lambda_{gd}$  is the *Disaster Relief Delay* (years)

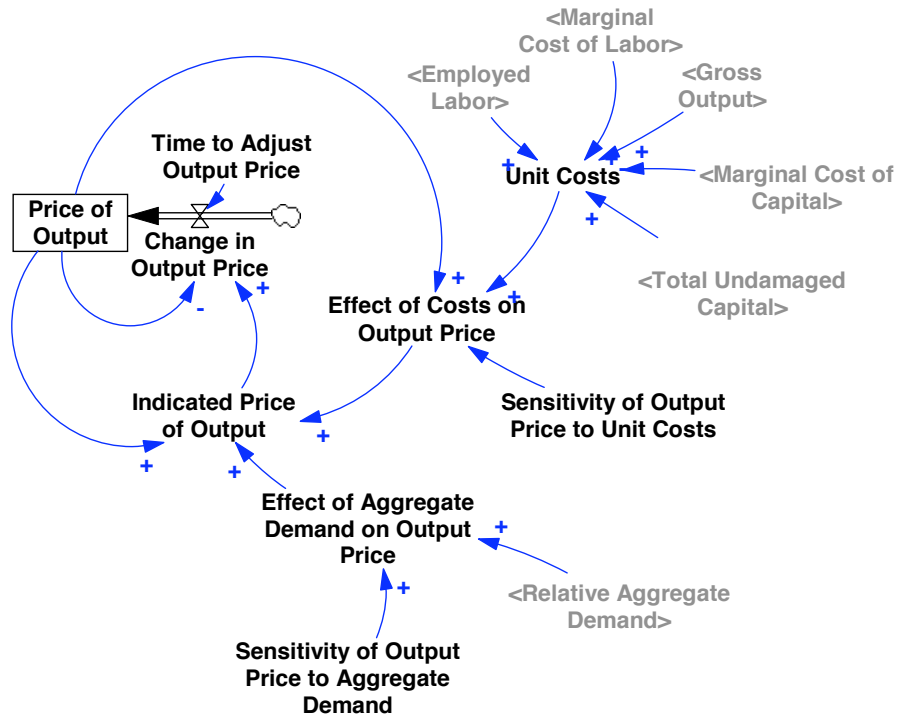


Figure 3-14: Adjustment mechanism for the price of output.

### 3.5.3 Price of output

According to economic theory, the price of a good in a competitive market should reflect the demand for the good and the supply of the good, which depends on the production cost. The price of output  $P_y$  is formulated to include these two feedbacks. As the cost of producing the good rises, the price also rises. Similarly, as demand increases, the price rises and vice versa. The market doesn't set price instantaneously, instead adjusting the price to current market conditions over time.

Equations 3.66-3.71 detail the price adjustment mechanism. The *Price of Output* adjusts to the *Indicated Price of Output* with an adjustment time, *Time to Adjust Output Price* (Figure 3-14).

$$P_y = \int_{t_0}^T \left( \frac{P_y^* - P_y}{\tau_{padj}} \right) dt + P_{y,t_0} \quad (3.66)$$

$$\tau_{padj} = 1 \quad (3.67)$$

$$P_{y,0} = 1 \quad (3.68)$$

where

$P_y$  is the *Price of Output* (\$/output unit)

$P_y^*$  is the *Indicated Price of Output* (\$/output unit)

$\tau_{padj}$  is the *Time to Adjust Output Price* (years)

$P_{y,0}$  is the initial price of output (\$/output unit)

The *Indicated Price of Output* is the price of output that is appropriate for the current economic conditions. The indicated price includes the feedback for aggregate demand and the feedback for unit production costs. The *Indicated Price of Output* is the current price adjusted for the effects of these two feedbacks. The *Effect of Aggregate Demand on Output Price* is a function of *Relative Aggregate Demand* (Equation 3.58, described above). The second effect, *Effect of Costs on Output Price*, is a function of *Unit Costs*, the costs of producing a unit of output.

$$P_y^* = P_y \xi_{ad}^P \xi_C^P \quad (3.69)$$

$$\xi_{ad}^P = RAD^{\sigma_{ad,p}} \quad (3.70)$$

$$\xi_C^P = 1 + \sigma_{c,p} \left( \frac{C_{unit}}{P_{y,t}} - 1 \right) \quad (3.71)$$

where

$\xi_{ad}^P$  is the *Effect of Aggregate Demand on Output Price* (dmnl)

$RAD$  is the *Relative Aggregate Demand* (dmnl)

$\sigma_{ad,p}$  is the *Sensitivity of Output Price to Aggregate Demand* (dmnl)

$\xi_C^P$  is the *Effect of Costs on Output Price* (dmnl)

$\sigma_{c,p}$  is the *Sensitivity of Output Price to Unit Costs* (dmnl)

$C_{unit}$  is the *Unit Costs* (\$/output unit)

If relative aggregate demand is greater than one, meaning that demand for output is greater than current economic output, then there is a positive pressure on output price. The indicated price increases and the actual *Price of Output* adjusts with a delay.

The unit cost of output is the cost of producing a unit of gross output. Unit cost is calculated by summing the total cost of the factors of production and dividing by total gross output (Equation 3.72).

$$C_{unit} = \frac{MC_l L + MC_k K}{Y} \quad (3.72)$$

The price of output is used in the relative return to capital formulation. As the output price rises, the relative return of producing another unit of output also increases, causing an increase in capital investment, all else being equal (Equation 3.50).

### 3.5.4 Labor

Labor in the model is represented as the number of employed people working in the community. The formulation differs from many macroeconomic models that use population as proxy for labor. In the FRACC model, population is used to calculate the potential labor force, those employed or seeking employment. Labor does not

equal the labor force because people seeking work might not find a job. Jobs, positions filled by the labor force, are modeled as a separate process in the community and are adjusted according to the relative return to labor and demand for output. In the end, the labor variable used in the main production function is the lesser of either the labor force or the number of jobs (Equation 3.73). The labor sector of the model is shown in Figure 3-15. Jobs, labor force, and employed labor are measured in units of full-time equivalent (FTE) workers.

$$L_t = \text{MIN}(J_t, LF_t) \quad (3.73)$$

where

$L_t$  is *Employed Labor* (FTE)

$J_t$  is *Jobs* (FTE)

$LF_t$  is *Labor Force* (FTE)

The labor force is assumed to be a constant fraction of the community's population (defined in Section 3.7). The fraction of people seeking employment depends on the number of adults in the community and the percentage of adults that usually look for work. I assume that the fraction of adults (those over 18 years old) is constant. Additionally, the percentage of adults seeking work is also constant. These are simplifications that could be relaxed in future work. In the end, *Labor Force* is the total population of the community multiplied by the fraction over 18 and the fraction of adults seeking work. The variables are community specific and defined in Chapter 4.

$$LF_t = F_{lf}F_{wa}N_t \quad (3.74)$$

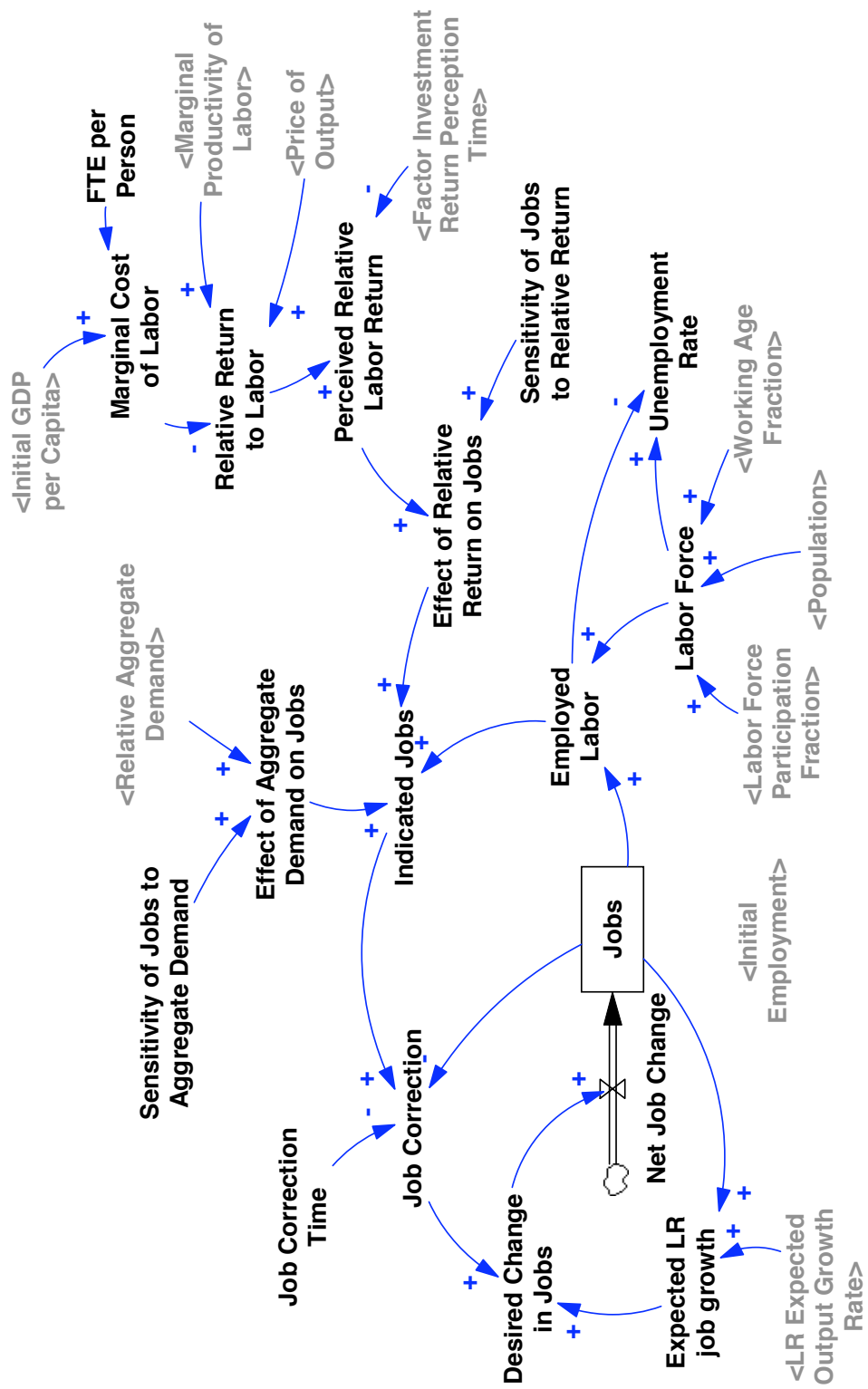


Figure 3-15: Adjustment mechanisms for jobs, labor, and employment.



where

$N_t$  is the *Population* (persons)

$F_{lf}$  is the *Labor Force Participation Fraction* (FTE/person)

$F_{wa}$  is the *Working Age Fraction* (dmnl)

The people in the labor force fill open jobs in the community. The number of jobs varies depending on the economic conditions. Jobs respond to three different adjustment mechanisms:

1. Long-run economic growth
2. Relative return to labor
3. Aggregate demand for output

### **Long-run economic growth**

Similar to the capital adjustment process, the number of *Jobs* is adjusted for long-run economic expectations. If the economy is growing, employers create more jobs because of the expected increase in economic production. In an economic downturn, employers expected negative long-run growth and reduce the number of available jobs.

In light of long-run growth trends, employers decide the *Net Job Change* by adding the *Expected LR Job Growth* to *Job Correction*, the adjustment for the difference between the indicated and the current level of jobs. The long-run growth adjustment serves the same purpose as the long-run growth term in the capital adjustment cycle—to ensure there will not be a steady-state error in a community with constant growth.

$$J_T = \int_{t_0}^T (\tilde{J}_t) dt + J_{t_0} \quad (3.75)$$

$$\tilde{J}_t = \widehat{J}_t + \hat{J}_t \quad (3.76)$$

$$\widehat{J}_t = g_t^y J_t \quad (3.77)$$

where

$\tilde{J}_t$  is the *Net Job Change* (FTE/year)

$J_0$  is the initial number of jobs (FTE)

$\widehat{J}_t$  is the *Expected LR Job Growth* (FTE/year)

$\hat{J}_t$  is the *Job Correction* (FTE/year)

Employers determine the *Job Correction* adjustment value by estimating the *Indicated Jobs* level and subtracting the current number of jobs. Expanding their employment involves a hiring search and job training, and is not instantaneous. To reflect this, the difference between indicated and current jobs is divided by a time constant needed to add jobs to the community, *Job Correction Time*.

$$\hat{J}_t = \frac{J^* - J}{\tau_{adj}} \quad (3.78)$$

where

$J^*$  is the *Indicated Jobs* (FTE)

$\tau_{adj}$  is the *Job Correction Time* (years)

## Indicated jobs

The indicated number of jobs in the community is ideal level of *Jobs* given the economic conditions in the community. Employers decided the *Indicated Jobs* by

adjusting their current workforce by their estimates for future aggregate demand and relative return to labor.

$$J_t^* = \xi_{ad}^J \xi_{rrl}^J L_t \quad (3.79)$$

where

$\xi_{ad}^J$  is the *Effect of Aggregate Demand on Jobs* (dmnl)

$\xi_{rrl}^J$  is the *Effect of Relative Return on Jobs* (dmnl)

### Relative return to labor

If it is profitable for employers to add workers, they will increase the number of jobs in the community. In the model, profitability is characterized by the ratio of the marginal return to labor to the marginal cost of labor, called the *Relative Return to Labor*. When the relative return to labor is greater than one, creating jobs will yield a positive return. When the marginal cost of labor (the wage) is equal to the marginal return to labor, the relative return is 1. The *Effect of the Relative Return on Jobs* would also be 1, meaning the current level of employed laborers was sufficient. The system would be in equilibrium with respect to the relative return to labor. When the ratio is less than one the number of jobs in the community will be reduced, all else being equal.

$$\xi_{rrl}^J = (RR_j^p)^{\sigma_{rr,j}} \quad (3.80)$$

$$\sigma_{rr,j} = 0.75 \quad (3.81)$$

where

$RR_j^p$  is the *Perceived Relative Return to Labor* (dmnl)

$\sigma_{rr,j}$  is the *Sensitivity of Jobs to Relative Return* (dmnl)

The *Effect of Relative Return on Jobs* is a function of the *Perceived Relative Labor Return*, not the actual *Relative Return on Labor*. The formulation represents how investors process returns data and use it to make investment decisions. Investors tend to make decisions based on recent trends rather than instantaneous economic data. Labor returns data is smoothed over a time constant, *Factor Investment Return Perception Time*.

$$RR_j^p = SMOOTHI(RR_j, \tau_{rrl}, 1) \quad (3.82)$$

$$\tau_{rrl} = 2 \quad (3.83)$$

where

$RR_j$  is the *Relative Return to Labor* (dmnl)

$\tau_{rrl}$  is the *Factor Investment Return Perception Time* (years)

As mentioned above, the current *Relative Return to Labor* is the ratio of the *Marginal Productivity of Labor* to the *Marginal Cost of Labor*. The marginal productivity of labor is the derivative of the production function (Equation 3.20) with respect to employed labor. The marginal cost of labor is the initial per capita GDP for the community. The constant cost of labor is a simplification that could be relaxed in future work to reflect labor market adjustments, which may be important after a storm.

$$RR_j = \frac{P_y MP_l}{MC_l} \quad (3.84)$$

$$MP_{l,t} = \frac{\alpha_l Y_t}{L_t} \quad (3.85)$$

$$MC_l = w_0 \quad (3.86)$$

where

$MP_l$  is the *Marginal Productivity of Labor* ((output units/year)/FTE)

$MC_l$  is the *Marginal Cost of Labor* (\$/year)/FTE)

$k_{j,fte}$  is the full-time equivalency per person (FTE/person)

### Aggregate demand for output

The *Effect of Aggregate Demand on Jobs* utilizes the same *Relative Aggregate Demand* variable described in the capital adjustment section above (Section 3.5.2). If the expected aggregate demand is equal to the current level of output (i.e., relative aggregate demand equals one), the system is considered in equilibrium—no additional jobs are required. When demand is greater than the current economic output, the *Effect of Aggregate Demand on Jobs* increases the indicated number of jobs creating a gap with the current number of jobs.

$$\xi_{ad}^J = RAD^{\sigma_{ad,j}} \quad (3.87)$$

where

$\xi_{ad}^J$  is the *Effect of Aggregate Demand on Jobs* (dmnl)

$RAD$  is the *Relative Aggregate Demand* (dmnl)

$\sigma_{ad,j}$  is the *Sensitivity of Jobs to Aggregate Demand* (dmnl)

## 3.6 Housing Stock

The housing sector of the model represents homes and apartments where people live. It is modeled explicitly because of the specific importance of housing in the community dynamic—no one would live in the community if they did not have a home to live in. Housing is a determinate of the community’s population (Section 3.7) and ultimately the labor force.

Housing has a parallel structure to the capital in the community (Figure 3-16; see Section 3.5.1). Housing is categorized in two dimensions: mitigated or unmitigated, undamaged or damaged. “Undamaged” means that the housing is livable and able to provide a home to residents. Housing damaged by storms is moved into the “damaged” category. Housing stock is measured in square meters, representing the area of living space for community residents.

The four housing categories have flows of investment, depreciation, retrofitting, and damage. The following set of equations describes the structure of the housing component:

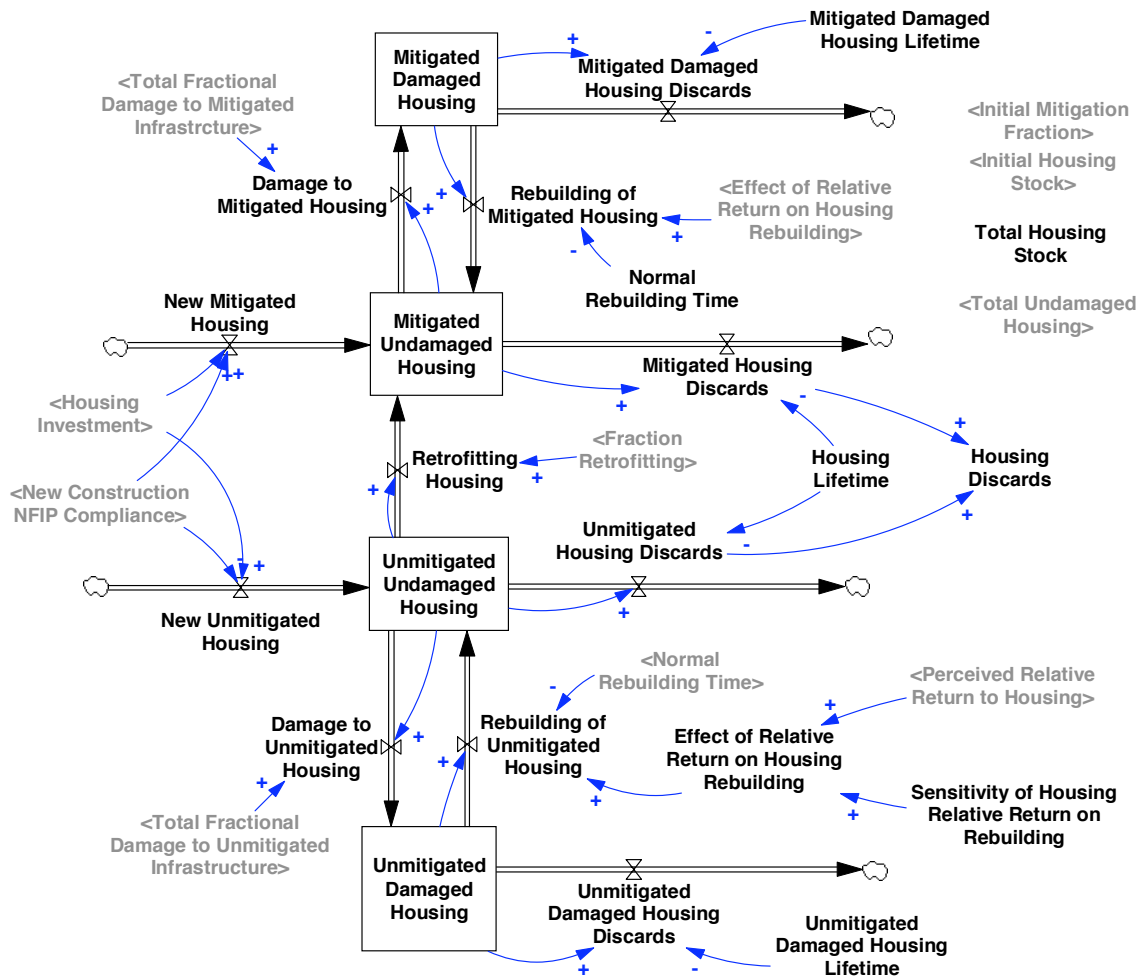
$$H_t = H_t^{mu} + H_t^{uu} + H_t^{md} + H_t^{ud} \quad (3.88)$$

$$H_T^{mu} = \int_{t_0}^T (I_t^{mu} - \delta_{mu}H_t^{mu} + R_t^{md} + T_t - D_t^{mu})dt + H_{t_0}^{mu} \quad (3.89)$$

$$H_T^{uu} = \int_{t_0}^T (I_t^{uu} - \delta_{uu}H_t^{uu} + R_t^{ud} - T_t - D_t^{uu})dt + H_{t_0}^{uu} \quad (3.90)$$

$$H_T^{md} = \int_{t_0}^T (-\delta_{md}H_t^{md} + D_t^{mu} - R_t^{md})dt + H_{t_0}^{md} \quad (3.91)$$

$$H_T^{ud} = \int_{t_0}^T (-\delta_{ud}H_t^{ud} + D_t^{uu} - R_t^{ud})dt + H_{t_0}^{ud} \quad (3.92)$$



**Figure 3-16:** Four categories of housing in the community and the flows of investment and depreciation.

New housing investment creates undamaged housing stock. Total new housing investment  $I_t^{tot}$  is divided between the undamaged categories according the current fraction of people choosing to mitigate the property's flood risk and build according to NFIP standards (Section 3.10.2).

$$I_t^{mu} = F_t^M I_t^{tot} \quad (3.93)$$

$$I_t^{uu} = (1 - F_t^M) I_t^{tot} \quad (3.94)$$

where

$I_t^{mu}$  is the *Building of Mitigated Housing* (sq. meters/year)

$I_t^{uu}$  is the *Building of Unmitigated Housing* (sq. meters/year)

$I_t^{tot}$  is the total *Housing Investment* (sq. meters/year)

$F_t^M$  is *New Construction NFIP Compliance* (dmnl)

*Unmitigated Undamaged Housing* may be retrofitted to become *Mitigated Undamaged Housing*. Retrofitting likely occurs after a flood event when property owners apply for disaster assistance and/or witness flood damage in their community. The retrofitting flow resides between the two undamaged stocks. The retrofitting rate is determined by the mitigation component described below (Section 3.10.2).

$$T_t = F_t^R H_T^{uu} \quad (3.95)$$

where

$F_t^R$  is *Fraction Retrofitting* (1/year)

When a storm occurs in the model, undamaged housing may become damaged. Storm events require four additional terms to be included in the housing sector: two



flows of damage and two flows for rebuilding. Once damaged, owners of the housing may rebuild, moving the housing stock from the damaged back to the undamaged category. The damage and rebuilding flows exist for both mitigated and unmitigated housing. For example, when a storm occurs, mitigated housing may be damaged (Section 3.9) and moved into the mitigated damaged category. Over time, the damaged housing is either depreciated or is rebuilt.

$$D_t^{mu} = f^{sm} H_t^{mu} \quad (3.96)$$

$$D_t^{uu} = f^{su} H_t^{uu} \quad (3.97)$$

where

$D_t^{mu}$  is the *Damage to Mitigated Housing* flow (sq. meters/year)

$D_t^{uu}$  is the *Damage to Unmitigated Housing* flow (sq. meters/year)

$f^{sm}$  is the *Total Fractional Damage to Mitigated Infrastructure* (1/year)

$f^{su}$  is the *Total Fractional Damage to Unmitigated Infrastructure* (1/year)

Housing is rebuilt according to the *Effect of Relative Return on Housing Rebuilding* ( $\xi_{rrh}^H$ ). Investors are more likely to rebuild housing if there is a stronger return on their investment. If the income from housing is greater than the construction costs, housing will be rebuilt more quickly. The equation for the *Relative Return to Housing* is described in Section 3.6.1. The strength of relative return on investor behavior is parameterized in the *Effect of Relative Return on Housing Building*, which is a function of the relative return ratio and a sensitivity parameter.

$$R_t^{md} = \frac{H_t^{md}}{\tau_R} \xi_{rrh}^H \quad (3.98)$$

$$R_t^{ud} = \frac{H_t^{ud}}{\tau_R} \xi_{rrh}^H \quad (3.99)$$

where

$R_t^{md}$  is the *Rebuilding of Mitigated Housing* flow (sq. meters/year)

$R_t^{ud}$  is the *Rebuilding of Unmitigated Housing* flow (sq. meters/year)

$\tau_R$  is the *Normal Rebuilding Time* (years)

$\xi_{rrk}^k$  is the *Effect of Relative Return on Housing Rebuilding* (dmnl)

The depreciation factors  $\delta$  are the inverse of the lifetime of their housing stock category. The lifetimes for both undamaged categories are assumed to be the same. The lifetime of mitigated damaged housing is approximated at five years. If the housing is not repaired during this time then it is likely that it has been discarded or abandoned. Unmitigated damaged housing has a shorter lifetime.

$$\delta_{mu} = \delta_{uu} = \frac{1}{\tau_{mu}} = \frac{1}{\tau_{uu}} = \frac{1}{30} \quad (3.100)$$

$$\delta_{md} = \frac{1}{\tau_{md}} = \frac{1}{5} \quad (3.101)$$

$$\delta_{ud} = \frac{1}{\tau_{ud}} = \frac{1}{2} \quad (3.102)$$

where

$\tau_{mu}, \tau_{uu}$  are both the undamaged *Housing Lifetime* (years)

$\tau_{md}$  is the *Mitigated Damaged Housing Lifetime* (years)

$\tau_{ud}$  is the *Unmitigated Damaged Housing Lifetime* (years)

### 3.6.1 Housing adjustment

The adjustment mechanism for the housing sector is similar to the capital adjustment mechanism described above (Section 3.5.2). Like the capital adjustment process, housing investment is a factor of five different mechanisms:

1. Housing depreciation
2. Land availability
3. Long-run growth expectations
4. Aggregate demand
5. Relative return to housing

The first two mechanisms, housing depreciation and land availability, are the same as the capital processes. The last three mechanisms are similar in structure but use different parameters as inputs. The long-run growth adjustment is based on the trend of population, as opposed to the growth trend of economic output. Aggregate demand for housing is determined by the population of the community and the average area of living space required per person. Aggregate demand is the total demand for living space in the community. Relative return to housing, the final adjustment, uses the rental price of housing instead of the marginal productivity of capital, representing the return on an investment.

### **Housing depreciation**

Figure 3-17 shows the structure that calculates *Housing Investment*. The final amount of housing investment is determined by the five processes. Working backwards, investment is the sum of *Housing Discards* (i.e., depreciated housing) and *Indicated Net Change in Housing*, a variable representing the other four adjustments. Depreciated housing is added separately because a property owners are assumed to maintain their homes, performing regular upkeep. The assumption means the housing sector will have a constant supply of housing in a community with constant population. If investment did not include the amount of depreciated housing, then housing stock could not stay at an equilibrium point (if the rest of the model were in steady-state).

$$I_T^{tot} = h_t^{net} + \delta_{mu}H_t^{mu} + \delta_{uu}H_t^{uu} + \delta_{md}H_t^{md} + \delta_{ud}H_t^{ud} \quad (3.103)$$

where

$I_T^{tot}$  is total *Housing Investment* (sq. meters/year)

$h_t^{net}$  is the *Indicated Net Change in Housing* (sq. meters/year)

$\delta$  terms are discards from the housing stocks (1/year)

### Land availability

The total amount of dry land available is a constraint on housing growth. Both capital and housing occupy a finite area of dry land in the community. As the density increases and unbuilt dry land declines, housing investment and construction becomes more difficult. If the community is densely developed, old capital or housing must be removed before new housing can be constructed, slowing the overall rate of housing investment.

Land availability adjusts the overall rate of housing investment. That is, the *Indicated Net Change in Housing* variable is the adjustments for long-run growth, aggregate demand, and relative return adjusted by the current available unoccupied land area. The density of housing influences the total amount of new investment, as described in the capital adjustment section and depicted in Figure 3-10.

$$h_t^{net} = \begin{cases} h_t^{dnet} & \text{if } h_t^{dnet} < 0 \\ h_t^{dnet} \xi_{land}^H & \text{if } h_t^{dnet} \geq 0 \end{cases} \quad (3.104)$$

where

$h_t^{dnet}$  is the *Desired Net Change in Housing* (sq. meters/year)

$\xi_{land}^H$  is the *Effect of Land Availability on Housing* (dmnl)

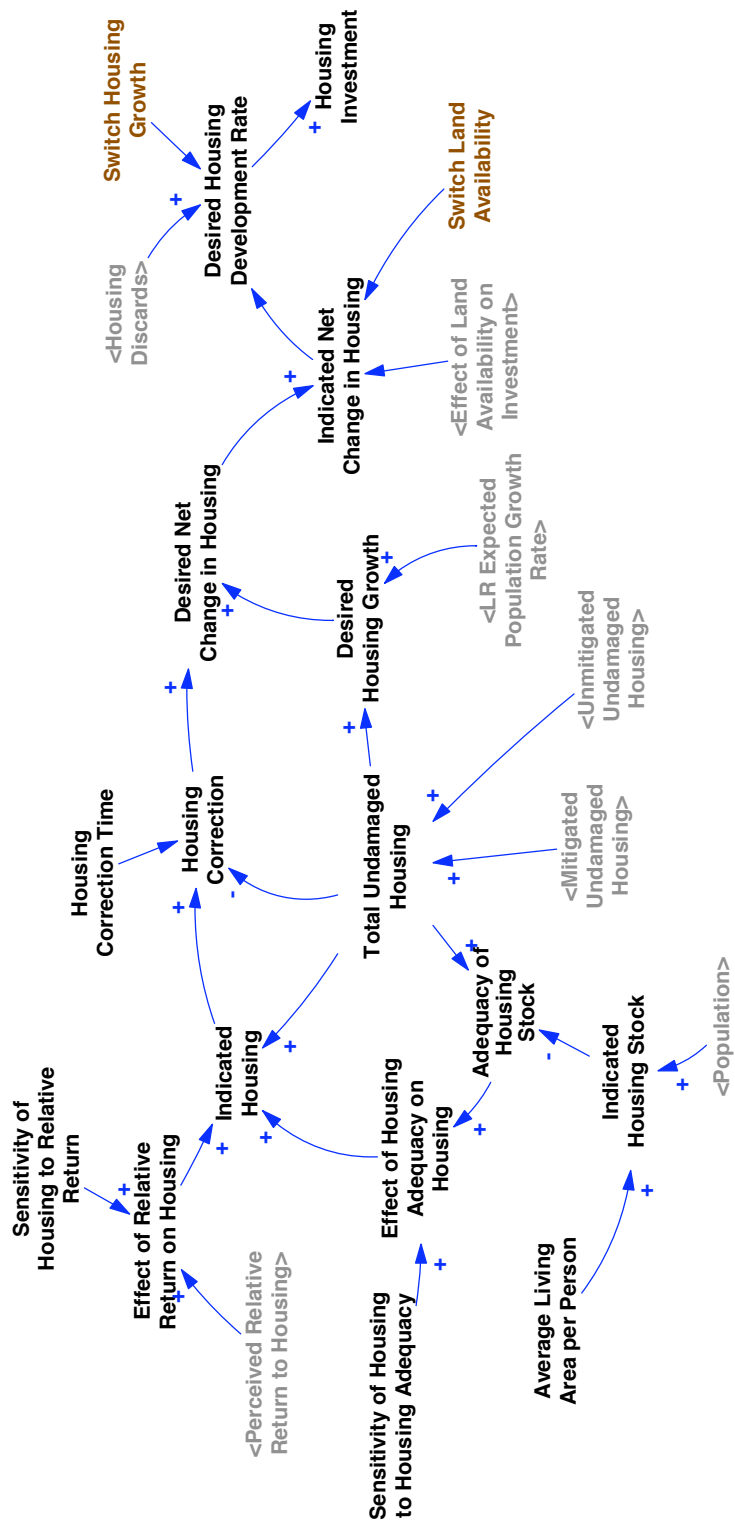


Figure 3-17: Adjustment mechanisms for new housing investment.

## Long-run growth expectations

Housing investors use their expectations of population growth when deciding how much to invest. If the population has a positive growth trend, investors will anticipate growth and invest in more housing. If the opposite is true and the community experiences a declining population, investors will invest less in new construction than they otherwise would have. The long-run growth adjustment for housing is based on recent trends in the community's population.

The long-run growth adjustment variable is called *Desired Housing Growth*. The term corrects for a steady-state error of housing if there were constant population growth in the community.

$$h_t^{dnet} = h_t^{corr} + h_t^{grow} \quad (3.105)$$

where

$h_t^{corr}$  is the *Housing Correction* (sq. meters/year)

$h_t^{grow}$  is the *Desired Housing Growth* (sq. meters/year)

Investors make housing decisions based recent population trends, not the current instantaneous growth rate. The long-run population growth rate is calculated using a standard TREND function (Serman, 2000). The TREND function calculates the fractional growth rate of population using recent population values and some perception lags (Figure 3-18).

$$h_t^{grow} = TREND(N_t)H_t^{tu} \quad (3.106)$$

where

$N_t$  is the *Community Population* (persons)

$H_t^{tu}$  is the *Total Undamaged Housing* (sq. meters)

### Housing correction

The long-run growth adjustment is added to an adjustment that corrects for the gap between the indicated and the actual levels of housing. The *Housing Correction* parameter is the difference between the *Indicated Housing* and the *Total Undamaged Housing*. The difference is not closed immediately because of delays in housing adjustments. The time lag for housing adjustments  $\lambda_{hadj}$  is set to four years, averaging construction and other delays (Senge, 1978).

$$h_t^{corr} = \frac{H_t^* - H_t^{tf}}{\lambda_{hadj}} \quad (3.107)$$

$$H_t^{tf} = H_t^{uu} + H_t^{mu} \quad (3.108)$$

where

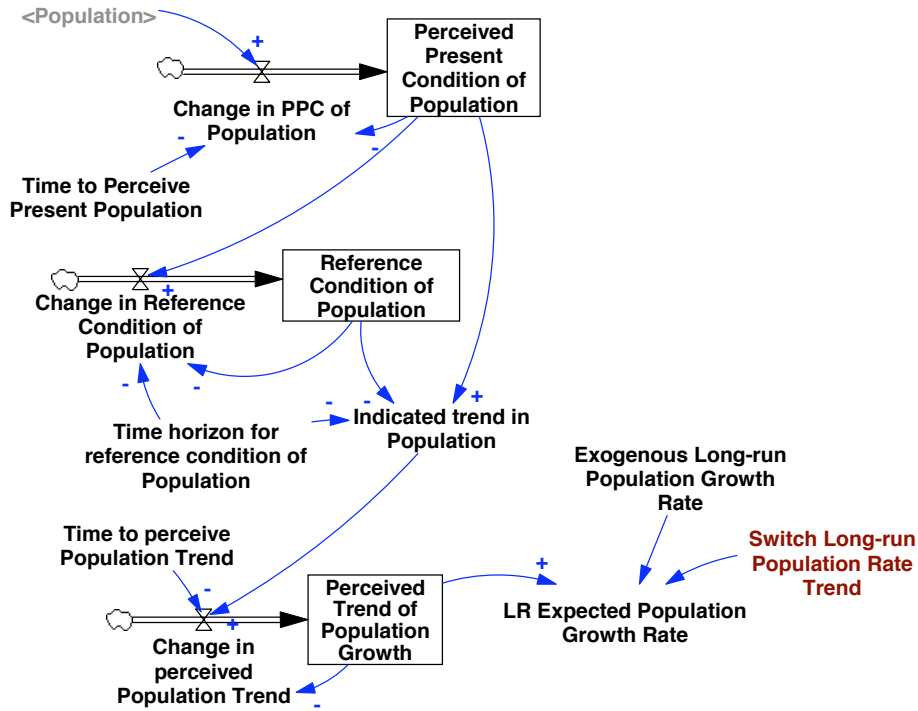
$H_t^*$  is the *Indicated Housing* (sq. meters)

$H_{tu}$  is the *Total Undamaged Housing* (sq. meters)

$\lambda_{hadj}$  is the *Housing Correction Time* (years)

### Indicated housing

Investors determine the indicated level of housing in the community by evaluating the aggregate demand for housing and the relative return to housing investment. These two adjustment mechanisms scale the current level of available housing to determine the *Indicated Housing*. Both adjustment effects represent the amount of change relative to the present level of housing that would be indicated by the current



**Figure 3-18:** TREND function formulation used to estimate the future population.

population and economic conditions.

$$H_{adj}^* = \xi_{rrh}^H \xi_{ad}^H H_t^{tf} \tag{3.109}$$

where

$\xi_{rrh}^H$  is the *Effect of Relative Return on Housing* (dmnl)

$\xi_{ad}^H$  is the *Effect of Housing Adequacy on Housing* (dmnl)

### Aggregate demand for housing

The aggregate demand feedback represents the demand for housing space given the community’s current population. As population grows, more housing is demanded to provide adequate living space. I assume the average amount of space desired by an individual remains constant throughout the simulation. The structure is shown in



the lower-left corner of Figure 3-17. The housing needs of the community (population times the average amount of space per person) are compared with the current housing stock. If the ratio of current living space to required space is low, then investors build more housing. If the current amount of housing exceeds the desired amount, then investors adjust the indicated level of housing downward, all else being equal.

$$\xi_{ad}^H = RAD^{-\sigma_{id,h}} \quad (3.110)$$

where

$\xi_{ad}^H$  is the *Effect of Housing Adequacy on Housing* (dmnl)

$RAD$  is the *Adequacy of Housing Stock* (dmnl)

$\sigma_{id,h}$  is the *Sensitivity of Housing to Housing Adequacy* (dmnl)

### Relative return to housing

Investors choose to build housing because they want a return on their investments. The *Effect of Relative Return on Housing* represents how the expected return to housing changes the indicated level of housing in community.

Similar to the capital adjustment mechanism, the relative return effect is a function of the *Perceived Relative Return to Housing*. Investors do not invest on the actual current rate of return, but instead on their perception of recent housing returns. Specifically, *Perceived Relative Return to Housing* is an exponentially weighted moving average (i.e., smooth) of the most recent two years of actual relative housing returns. Investors make their decisions based on their understanding of how the market has performed over the past two years.

$$\xi_{rrh}^H = (RR_h^p)^{\sigma_{rrh}} \quad (3.111)$$

$$RR_h^p = \text{SMOOTH}(RR_h, \tau_{rrh}) \quad (3.112)$$

where

$RR_h^p$  is the *Perceived Relative Return to Housing* (dmnl)

$\sigma_{rrh}$  is the *Sensitivity of Housing to Relative Return* (dmnl)

$\tau_{rrh}$  is the *Factor Investment Return Perception Time* (years)

The actual relative return is a ratio of the marginal return on housing (i.e., the rental value of a unit of housing) relative to the marginal cost of housing. The ratio easily compares the conditions for an investor. When the ratio is greater than one, the investor will make money, and vice versa.

$$RR_h = \frac{MR_h}{MC_h} \quad (3.113)$$

where

$MR_h$  is the *Average Rent* ((\$/sq. meter)/year)

$MC_h$  is the *Marginal Cost of Housing* ((\$/sq. meter)/year)

The marginal costs of housing incorporate the typical lifetime of housing and the financing costs of constructing new housing. Financing costs, the effective interest rate on housing construction, directly impact the attractiveness of housing investment. The lifetime of housing determines the rate of depreciation of a housing asset. Additionally, investors take the *Perceived Fractional Damage from Storms* into account (Equation 3.56). Damage from storms can lower the average lifetime of housing if the housing is ruined before it has fully depreciated. A shorter lifetime reduces the

time investors can gain a return on their investment, effectively increases the cost of housing.

$$MC_h = FC_H P_h \quad (3.114)$$

$$FC_h = r_h + \frac{1}{\tau_h} + \hat{d} \quad (3.115)$$

where

$FC_H$  is the *Cost of Housing* (1/year)

$P_h$  is the *Marginal Cost of Housing Construction* (\$/sq. meter)

$r_h$  is the *Interest Rate for Housing* (1/year)

$\hat{d}$  is the *Perceived Fractional Damage from Storms* (1/year)

$\tau_h$  is the *Housing Lifetime* (years)

The interest rate for housing construction is the sum of a risk-free rate plus the risk premium for the housing sector, which are both assumed to be held constant.

$$r_h = r_{rf} + r_{hp} \quad (3.116)$$

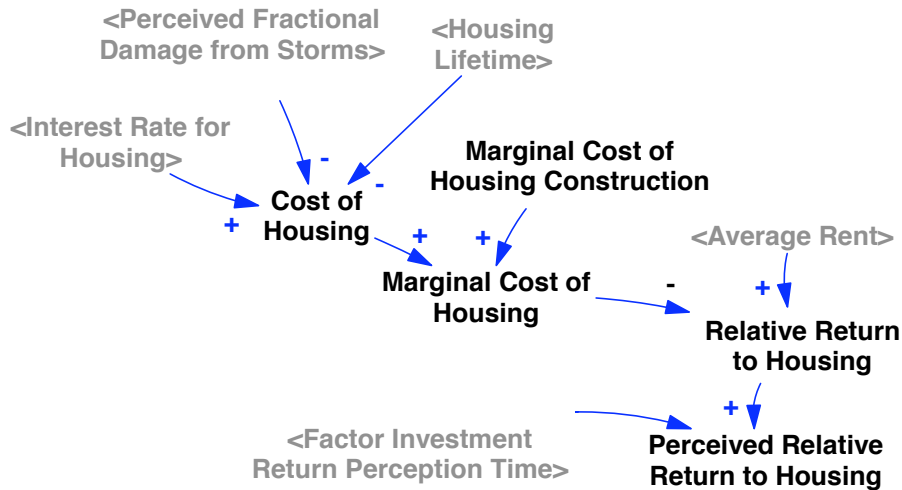
where

$r_{rf}$  is the risk-free interest rate (1/year)

$r_{hp}$  is the housing-premium interest rate (1/year)

### 3.6.2 Rental price adjustment

The rental price of housing changes based on the supply and demand for housing in the community. If there is excess housing in the community, the rental price falls.



**Figure 3-19:** Perceived relative return on investment into the housing sector.

If there is not enough housing in the community, the rental price rises. Housing rent changes the relative return on investment for housing in the community through the “relative return” adjustment mechanism described above. For example, as rent rises the relative return to housing also rises, increasing investment into new housing infrastructure.

There is also another rent adjustment mechanism—the relative cost of new housing. If the cost of constructing housing is more than the rent, then the rent adjusts upward. The relative cost mechanism represents developers passing on the costs of construction to consumers through the rental price.

The structure of the rent adjustment mechanism is similar to the structure of the price of output adjustment (Section 3.5.3). The *Adequacy of Housing Stock* is the same as described above, where the ratio of the current housing area is divided by the desired housing area. The *Marginal Cost of Housing* includes the interest rates for housing, the actual housing lifetime, and an adjustment of housing lifetime for the perceived storm damage. There are two sensitivity parameters to control the strength of the two adjustment mechanisms (Equations 3.117-3.120).

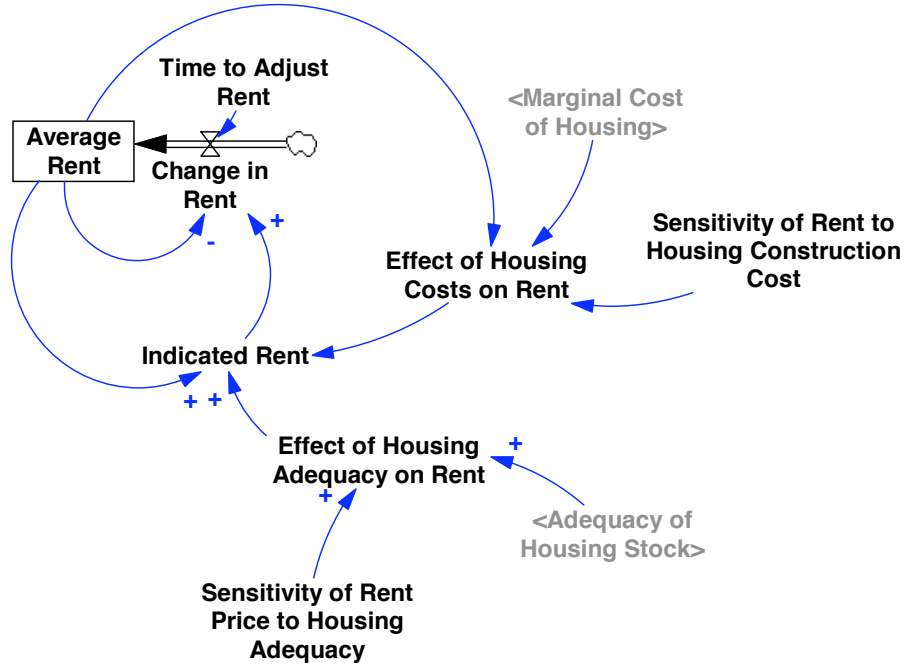


Figure 3-20: Rental price adjustment mechanism.

$$MR_{h,T} = \int_{t_0}^T \left( \frac{MR_{h,t}^* - MR_{h,t}}{\tau_{hadj}} \right) dt + MR_{h,t_0} \quad (3.117)$$

$$MR_{h,t}^* = MR_{h,t} \xi_{ad}^H \xi_C^H \quad (3.118)$$

$$\xi_{ad}^H = RAD^{-\sigma_{id,h}} \quad (3.119)$$

$$\xi_C^H = \frac{MR_h}{MC_h} \quad (3.120)$$

where

$MR_{h,T}$  is the *Average Rent* ((\$/sq. meter)/year)

$MR_{h,t}^*$  is the *Indicated Rent* ((\$/sq. meter)/year)

$\tau_{hadj}$  is the *Time to Adjust Rent* (years)

$MR_{h,t_0}$  is the initial rent ((\$/sq. meter)/year)

$\xi_{ad}^H$  is the *Effect of Housing Adequacy on Rent* (dmnl)

$\xi_C^H$  is the *Effect of Housing Costs on Rent* (dmnl)

## 3.7 Population

Unlike many previous coastal adaptation studies, the FRACC model represents the community's population endogenously. The size of the community depends on the attractiveness of the community, based on jobs and housing, the state of the community's infrastructure (Forrester, 1969), and its response to storm events.

Population is represented with two stocks: The *Community Population* living in the community and the *Evacuee Population* that evacuates during a storm. The total population of the community that would "call the community home" is the sum of these two stocks. An important distinction between the two stock is that the *Labor Force* is a fraction of only the *Community Population*, not the *Evacuee Population*.

The *Community Population* is the integral of the net flow of births, deaths, immigration, and emigration. Emigration and immigration do not include the people evacuated and returning due to storms. Instead, people evacuating and their subsequent return are distinct events from normal migration (Figure 3-21).

$$N_T = \int_{t_0}^T (r_b N_t + r_d N_t + r_i N_t - r_e N_t - E_t + R_t) dt + N_{t_0} \quad (3.121)$$

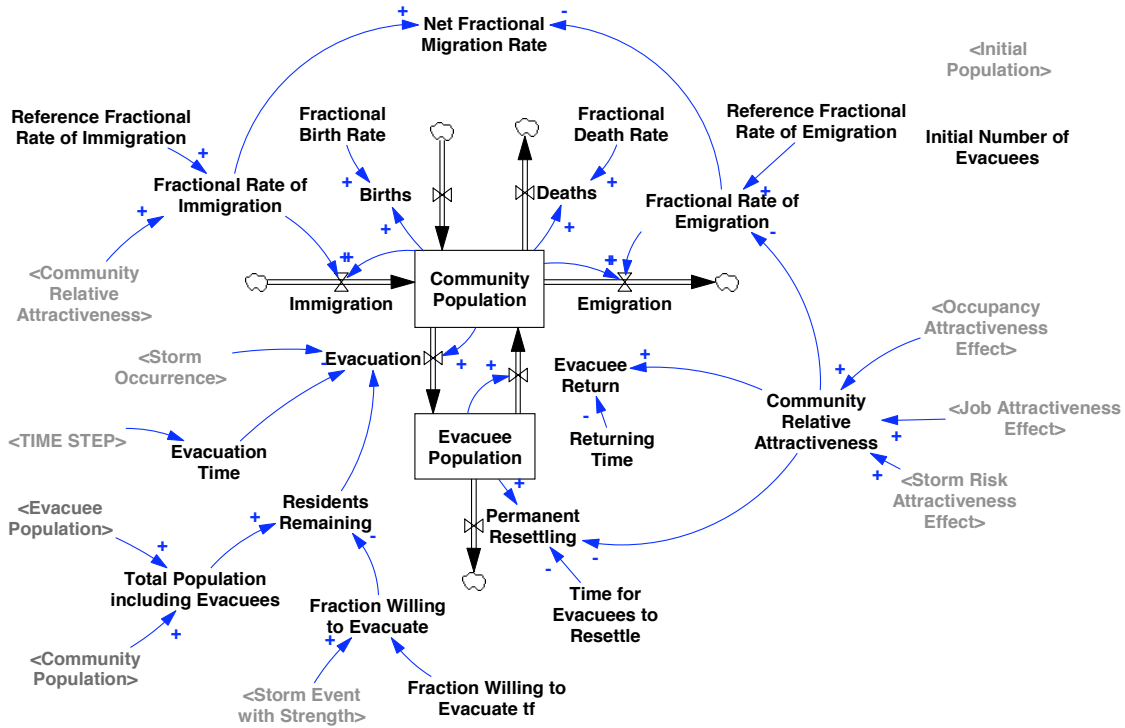


Figure 3-21: Endogenous population model including storm evacuations.

where

$N_T$  is the *Community Population* (persons)

$r_b$  is the rate of *Fractional Birth Rate* (1/year)

$r_d$  is the rate of *Fractional Death Rate* (1/year)

$r_i$  is the rate of *Fractional Rate of Immigration* (1/year)

$r_e$  is the rate of *Fractional Rate of Emigration* (1/year)

$E_t$  is the rate of *Evacuation* (persons/year)

$R_t$  is the rate of *Evacuee Return* (persons/year)

$N_0$  is the *Initial Population* (persons)

### 3.7.1 Births and deaths

*Births* and *Deaths* in the community are proportional to the current *Community Population*. The fractional rates of births and deaths are initialized to the national rates for the United States. Trends in fertility (e.g., smaller family sizes) and life expectancy are not included in the model. The fractional birth and death rates are constant. The flows of *Births* and *Deaths* are defined as:

$$\text{Births} = r_b N_t \quad (3.122)$$

$$\text{Deaths} = r_d N_t \quad (3.123)$$

where

$r_b$  is the rate of *Fractional Birth Rate* (1/year)

$r_d$  is the rate of *Fractional Death Rate* (1/year)

### 3.7.2 Immigration and emigration

*Immigration* and *Emigration* are the flows of people moving into and out of the community. Both flows are also proportional to the *Community Population*. The formulation is consistent with literature concluding large cities tend to attract more people and the distribution of cities follows a power law (Gabaix, 1999). The *Reference Fractional Rate of Immigration* and the *Reference Fractional Rate of Emigration* are the exogenous rates for the community adjusted by the *Community Relative Attractiveness* variable.



$$Immigration = r_i N_t \quad (3.124)$$

$$Emigration = r_e N_t \quad (3.125)$$

$$r_i = r_{i,0} \Phi \quad (3.126)$$

$$r_e = r_{e,0} \Phi \quad (3.127)$$

where

$r_i$  is the rate of *Fractional Rate of Immigration* (1/year)

$r_e$  is the rate of *Fractional Rate of Emigration* (1/year)

$r_{i,0}$  is the rate of *Reference Fractional Rate of Immigration* (1/year)

$r_{e,0}$  is the rate of *Reference Fractional Rate of Emigration* (1/year)

$\Phi$  is the *Community Relative Attractiveness* (dmnl)

The exogenous fractional immigration and emigration rates are both initialized the same. The community initially grows because of births and deaths, and the net effect of migration is zero.

### 3.7.3 Community attractiveness feedbacks

The quality of life in the community changes over time. For instance, property could be destroyed, jobs lost, and investment might grow or decline. Three different “community attractiveness” feedbacks represent the dynamics of community conditions: housing, jobs, and storm risk. Each of the three community attractiveness formulations assume that cities and towns outside the community of study (i.e., the remainder of the US) have a constant attractiveness. Changes to attractiveness are relative to the constant national average.

Community attractiveness  $\Phi$  is the product of the three different attractiveness effects:

$$\Phi = \xi_{housing} \xi_{jobs} \xi_{storms} \quad (3.128)$$

### Housing attractiveness

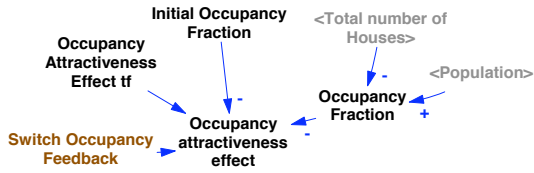
Housing conditions are an important consideration for people when choosing a town or city in which to live. Space and available housing can be an important incentive for people to relocate or live in a community. If there is inadequate housing supply, housing prices are relatively more expensive than communities with sufficient supply. To capture this feedback, the model uses occupancy density as proxy for housing conditions. Occupancy density is the average number of people living in a house (Equation 3.129). As the community attracts more people, occupancy density increases if housing supply does not similarly increase. The community becomes more crowded and less attractive relative to other communities.

$$F^{occ} = \frac{N}{\# \text{ of Houses}} \quad (3.129)$$

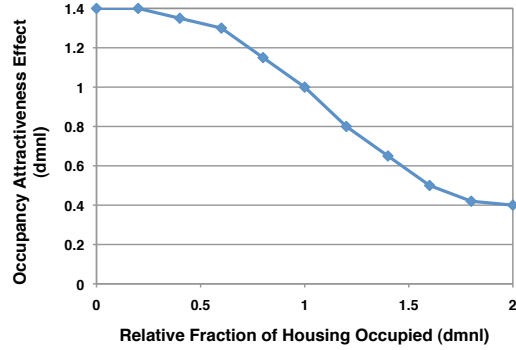
Residents feel a community is crowded if the occupancy density is higher than the initial value. The initial occupancy density is calculated using US Census data about the number of houses in the community and community's population. I assume that housing was in equilibrium at the time of the census. Housing attractive is a function of the ratio of current occupancy density to the initial occupancy density.

$$\xi_{housing} = LOOKUP\left(\frac{F^{occ}}{F_0^{occ}}\right) \quad (3.130)$$

Residents are indifferent toward the community if the ratio of current to initial occupancy density is 1. If the ratio is less than one, residents find the community more attractive because the current housing stock is less crowded than it was initially.



**Figure 3-22:** Community attractiveness based on occupancy fraction.



**Figure 3-23:** Function relating occupancy fraction to community attractiveness. As occupancy increases, attractiveness decreases. Crowded communities are less attractive.

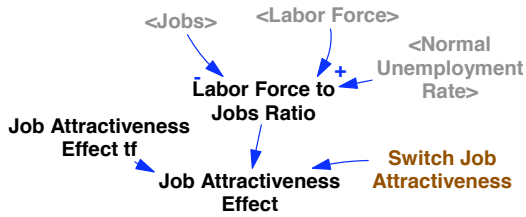
The opposite is true if the ratio is greater than one. The effect saturates at either extreme (Figure 3-22).

### Job attractiveness

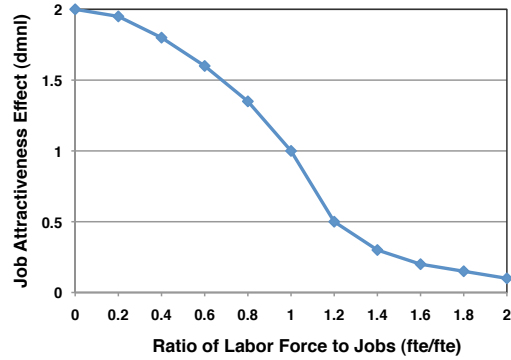
Plentiful jobs can attract people to communities and secure employment conditions can retain current residents. On the contrary, if the community has relatively fewer employment opportunities, people are less likely to move to or stay in the community.

Residents decide job attractiveness of a community by how easy it is to get a job. A Labor Force to Jobs ratio estimates the employment opportunities in the community. The ratio includes the total number of people who should be employed under ideal economic conditions, compared to the number of jobs in the community. Under normal economic conditions not everyone in a community is employed. The Labor Force is adjusted to account for a Normal Unemployment Rate, the rate of unemployment that is considered “full employment.” The final equation for the jobs ratio is:

$$Labor\ to\ Jobs\ Ratio = \frac{(1 - Norm\ Unemployment\ Rate)LF}{J} \quad (3.131)$$



**Figure 3-24:** Community attractiveness based on employment opportunities.



**Figure 3-25:** Table function relating employment to community attractiveness. Job scarcity decreases community attractiveness.

People’s reaction to job availability is a function of the labor-to-jobs ratio (Equation 3.132). If the number of job seekers equals the number of jobs, there is no effect on community attractiveness (Figure 3-25). When the ratio is less than one, there are more jobs in the community than people seeking work and residents find the community is more attractive. The opposite is true if the ratio is greater than one. The slope of the function is steeper around one, which assumes that people are sensitive to employment opportunities.

$$\xi_{jobs} = LOOKUP(Labor\ to\ Jobs\ Ratio) \tag{3.132}$$

### Perceived storm risk and attractiveness

If storm risk in a community increases, people are less likely to find the community attractive to live in. In the FRACC model, storm attractiveness is a function of residents’ *Relative Expected Damage from Storms*. Residents estimate the expected storm damage using their perception of storm frequency, and their estimate is the basis of how attractive they find the community with respect to storms.

Residents' estimate of storm risk is relative to the actual risk of damage. The *Relative Expected Damage from Storms* is the expected fractional damage (Equation 3.56) normalized by the reference fractional damage. The two fractional damage is calculated similarly, except the expected fractional damage value utilizes the *Perceived Frequency of Storms*, and reference fractional damage utilizes the community's actual annual storm frequency, as calculated by the GFDL model for the present climate, described in Section 3.3. The GFDL model was chosen as the reference model, simply as a basis for comparison.

$$\xi_{storms} = LOOKUP\left(\frac{\hat{d}}{d^r}\right) \quad (3.133)$$

where

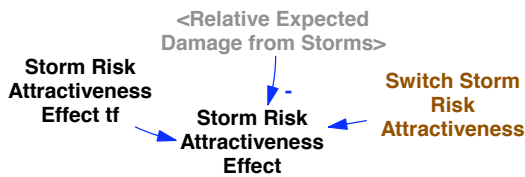
$\hat{d}$  is the perceived expected fractional damage (1/year)

$d^r$  is the reference fractional damage (1/year)

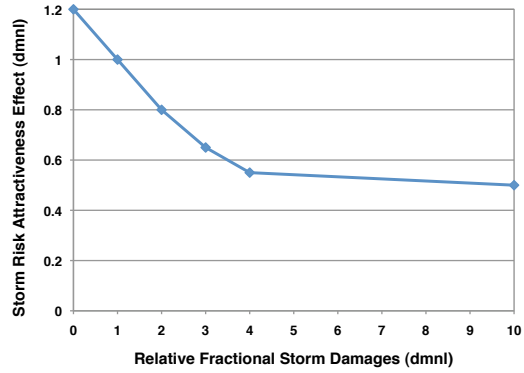
Residents' perception of storm attractiveness is a function of relative expected damage (Figure 3-27). Exactly how a community's attractiveness changes is poorly constrained by data, but is assumed to decrease as perceived storm damage increases. Residents are indifferent to the community when the ratio of damage is 1. As the ratio increases, meaning perceived damage is greater than actual damage, residents find the community less attractive. The effect saturates as damage rises significantly, because people tend to have difficulty distinguishing extreme levels of risk.

### 3.7.4 Evacuation and return

A portion of the community's population evacuates when a storm threatens. The evacuation temporarily reduces the number of residents living in the community and creates a population of *Evacuees* living in other communities. *Evacuees* choose to either return to their homes or settle outside the community, starting a new life



**Figure 3-26:** Community attractiveness based on storm perception.



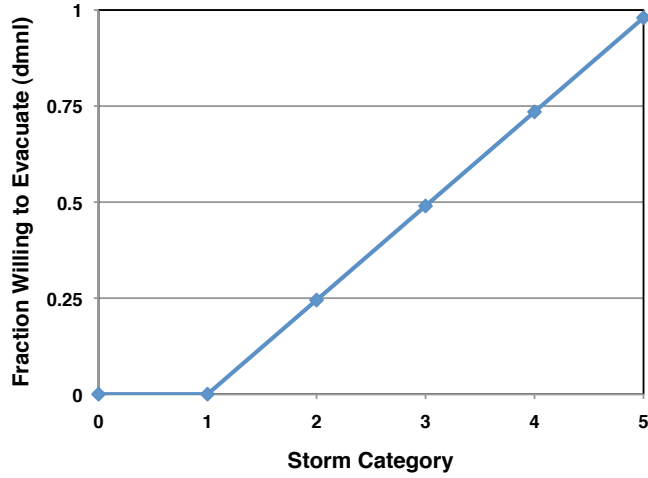
**Figure 3-27:** Table function relating perceived relative storm damage to community attractiveness.

there. The choice to return is a function of the community’s relative attractiveness.

Residents only evacuate if a storm is going to strike their community. Near-misses, or storms that approach but ultimately do not strike the community, do not cause evacuation. The exclusion of near-misses is a simplifying assumption of the FRACC model. Near-misses and the corresponding “false alarms” occur in many communities and the disruption caused by near-misses should be considered in future work.

The number of people willing to leave the community depends on the severity of the storm. For example, if a Category 5 storm strikes the community, I assume that 98 percent of the community is required and willing to evacuate. The remaining percentage of people are assumed to choose to stay or are unable to leave their homes no matter the storm intensity. If another Category 5 storm strikes the community immediately after the first storm, there will still be 2 percent of the residents remaining in the city. The formulation also means that if a Category 2 storm were to strike immediately after a Category 5 storm, no additional residents would be evacuated because those who have the disposition to leave for a Category 2 would have already left during the Category 5 evacuation.

The evacuation model structure is shown in the lower left portion of Figure 3-21. The total population at the time of a storm, *Total Population including Evacuees*, is



**Figure 3-28:** Lookup table for Fraction Willing to Evacuate from the community based on storm category.

determined by summing of the *Community Population* (those remaining after a storm) and the *Evacuees*. The total population is then multiplied by the *Fraction Willing to Evacuate*. The *Fraction Willing to Evacuate* is a function of storm intensity. The table function is shown in Figure 3-28.

$$Evacuation_t = E_t = \Psi_t \frac{MAX(0, N_t - N_t^R)}{\tau_e} \quad (3.134)$$

where

$E_t$  is the rate of *Evacuation* (persons/year)

$N_t$  is the *Community Population* (persons)

$N_t^R$  is the *Residents Remaining* (persons)

$\Psi$  is the *Storm Occurrence* (binary 0,1)

$\tau_e$  is the *Evacuation Time* (years)

The *Evacuation Time* is set to the time step of numerical integration, which means evacuation occurs immediately in the event of a storm.

The stock of *Evacuees* is the integral of three different flows of people: *Evacuation*, *Evacuee Return*, and *Permanent Resettling*. *Evacuation* is the inflow of evacuees into the stock. Evacuees have the choice to return back to the community or to resettle outside of the community. Both flows are proportional to the *Evacuee Population*. The time constant for returning to the community is smaller than the time constant for resettling. The result is that most people choose to return to their original homes. That said, the rate of return includes an adjustment for *Community Relative Attractiveness*. The attractiveness adjustment includes the “occupancy attractiveness” component that is important after a storm event. Evacuees would like to return to their homes if they are able but, if their house is damaged, then the attractiveness of returning to the community is lower. In the model formulation, they delay their choice to return giving them more time to consider permanent resettlement. At the extreme, if all homes were destroyed by the a storm and never rebuilt, all evacuees would ultimately decide to permanently resettle elsewhere.

$$D_T = \int_{t_0}^T (E_t - R_t - PR_t)dt + D_{t_0} \quad (3.135)$$

$$R_t = \Phi \frac{D_t}{\tau_r} \quad (3.136)$$

$$PR_t = \frac{1}{\Phi} \frac{D_t}{\tau_{pr}} \quad (3.137)$$



where

$D_t$  is the stock of *Evacuee Population* (persons)

$R_t$  is the rate of *Evacuee Return* (persons/year)

$PR_t$  is the rate of *Permanent Resettling* (persons/year)

$\Phi$  is the *Community Relative Attractiveness* (dmnl)

$D_0$  is the initial evacuee population (persons)

$\tau_r$  is the *Returning Time* (years)

$\tau_{pr}$  is the *Time for Evacuees to Resettle* (years)

### 3.8 Public Coastal Adaptation

To protect against storm surge and the rising sea, communities may choose to construct public adaptation structures, which provides flood protection to the entire community. The FRACC model represents two different forms of public adaptation: levees and beach nourishment. Each of these methods provide a barrier against storm surge and RSLR. The cost structure is different for levees and beach nourishment, each having different costs for construction and maintenance. There are other public adaptation options, such as seawalls, but this model includes only levees and beach nourishment because they are representative of the other engineering options and they are used in many different regions of the world.

The following section describes how residents and investors perceive public protection projects. Section 3.8.2 details the coastal managers' decision process, which is then followed by a description of their benefit-cost decision rule. The next sections discuss levee construction and the associated costs, followed by sections on beach nourishment construction and costs.

### **3.8.1 Perception of public adaptation**

Decision makers in the FRACC model perceive that levees and beach nourishment provide 100 percent protection to property in the community. That is, they perceive that the expected damage due to an event below the design specification (i.e., storm category) of the public adaptation is zero. If public adaptation were designed for a Category 3 storm, then capital infrastructure is perceived to be completely protected against flooding from Category 1, Category 2, and Category 3 storms. The public still considers the risk of wind damage from those categories of storms.

News reports and interviews support this perception (Webber and Fisher, 2008; Mattingly, 2008; White, 2009). City leaders and the US Army Corps of Engineers have historically not communicated risk very clearly (Axtman, 2009). After a recent flood, one resident said that the town was told, “The levees are good. You can go ahead and build (Webber and Fisher, 2008).” The levees in the community were evaluated to protect against the 100-year flood, which made flood insurance optional for many residents, according to NFIP guidelines. Residents appear to not have understood the risk of lower-probability events. In the model, residents are assumed to have a poor understanding of their exposure and believe that levees provide full protection to their design. Optimistically, residents do evaluate risk for events beyond the public protections’ design standards.

### **3.8.2 Coastal managers’ protection choice**

Coastal managers decide the amount, or height, of public adaptation that will be built. The “agent” in the model represents the professional state and local officials who regularly talk with scientists, the US Army Corps of Engineers (USACE), US Geological Service, National Ocean and Atmospheric Administration (NOAA), and other professionals. Through these contacts, coastal managers are assumed to have a strong understanding of climate science and the different means of coastal protection.

Even with a strong understanding of climate science, the decisions made by coastal managers are not purely science-based. In the US, for instance, many public adaptation projects are constructed in cooperation with the USACE. There are many reasons for local agencies to work with the USACE. The USACE has the expertise for many of the construction projects in-house. Additionally, the federal government covers over half of the initial construction costs if communities work with USACE. The USACE has a set of guidelines for its projects that are frequently adopted for coastal adaptation projects.

The FRACC model has been constructed using these USACE guidelines to better represent the real-world decision making process. The USACE uses a benefit/cost analysis (BCA) framework to evaluate a project. The National Economic Development report, part of the USACE process, summarizes a project's BCA. The USACE accounts for the national economic effects that the public adaptation project would have. The main economic factor for most projects is flood damage to property and infrastructure. Additional economic factors of the BCA may include the value of a large port (flow of goods), the use value of beaches, and the value of tourism. For many projects, the potential to prevent infrastructure damage is key, so it is the primary decision factor in the model (USACE, 2000; Thomson, 2009).

Interestingly, wetlands are not part of the normal economic benefit/cost process of the USACE. Wetlands and other environmental considerations are included in a sister analysis called the National Ecosystem Restoration (NER) report. NER reports discuss environmental impacts but do not assign economic values to ecosystem services (Axtman, 2009). The separation of wetland values means that the decision-rule used in previous studies (e.g., Fankhauser, 1995) might be economically optimal but does not reflect current decision processes.

The coastal managers' decision rule is:

$$H^* = \begin{cases} H_{cm} & \text{if } B_p^d > C_p^d \\ 0 & \text{if } B_p^d \leq C_p^d \end{cases} \quad (3.138)$$

where

$H^*$  is desired height of public protection (meters)

$H_{cm}$  is the coastal managers' calculated protection height (meters)

$B_p^d$  is the discounted benefit of public adaptation (\$)

$C_p^d$  is the discounted cost of public adaptation (\$)

The USACE uses economic discounting to evaluate the benefit and cost streams (Powers, 2003; USACE, 2000). The continuous time formulation used in the model is:

$$B_p^d = \frac{B_p}{r_d} \quad (3.139)$$

$$C_p^d = \frac{C_p}{r_d} \quad (3.140)$$

where

$B_p$  is the benefits of public adaptation (\$)/year

$C_p$  is the cost of public adaptation (\$/year)

$r_d$  is the discount rate (1/year)

The public adaptation benefits calculation is described in the next section and the cost of levees and beach nourishment are in more detail in Section 3.8.6 and Section 3.8.8, respectively.

### 3.8.3 Estimating the benefits of public adaptation

Coastal managers estimate the benefits of public adaptation by calculating both the value of land that would be permanently inundated by RSLR and the value of avoided storm damage. Both valuations require knowing the value of the infrastructure in the community.

The value of land depends on the value of the capital and housing in the community. A unit of capital is valued by its annual economic output. Housing is valued according to the stream of rents. In the end, the total value of dry land is:

$$V_{dl} = H_{tu}MR_h + K_{tu}MP_kP_y \quad (3.141)$$

where

$V_{dl}$  value of dry land (\$/year)

$H_{tu}$  is the *Total Undamaged Housing* (sq. meters)

$MR_h$  is the *Average Rent* (\$/sq. meter)

$K_{tu}$  is the *Total Undamaged Capital* (capital units)

$MP_k$  is the *Marginal Productivity of Capital* ((output units/capital unit)/year)

$P_y$  is the *Price of Output* (\$/unit)

The value of infrastructure in the community is used to estimate damage prevented by public adaptation. Storm damage is calculated using the value of dry land and the expected fractional damage with and without protection. The storm damage benefit of public adaptation is the difference between these two.

The value of dry land is estimated from the area of land that would be inundated without protection. The area is assumed to be completely protected from RSLR if the height of the public adaptation structure is greater than the RSLR height. The

prevented loss is the fraction of the community's land threatened by RSLR multiplied by the value of dry land.

$$B_p = (d_{np} - d_p)V_{dl}\tau_{dl} + \frac{A_{rslr}}{A_0}V_{dl} \quad (3.142)$$

where

$B_p$  is the benefits of public protection (\$/year)

$d_{np}$  is the estimated fractional damage with no protection (1/year)

$d_p$  is the estimated fractional damage with protection (1/year)

$\tau_{dl}$  is the time horizon for valuing annual avoided damage (years)

$A_{rslr}$  area inundated by RSLR (sq. km)

$A_0$  is the total initial area of the community (sq. km)

### 3.8.4 Public adaptation height

The height of an adaptation structure is required to estimate the costs of either a levee or beach nourishment project. The desired height of public adaptation structures is calculated by the coastal managers. The coastal managers are optimistically assumed to have perfect foresight regarding RSLR over the planning horizon of the project. The height is calculated to be the estimated height of the sea at the end of their planning horizon, plus an additional factor to protect against storm surge. By default, the planning horizon is 50 years, so they project the sea level height 50 years out from the present time of the simulation. Their projection is either linear or quadratic, based on the SLR scenario chosen. Coastal managers use the current SLR scenario (i.e., mathematical fit) to project RSLR past 2100 if an adaptation project requires an estimate. The additional storm surge factor is equal to the surge estimate for the project's design storm. By default, the coastal managers use a Category 2 design storm, so the additional height is 2.13 m (Table 3.3). A Category 2 storm

was chosen because it is in between normal tidal and wind surge and the Category 3 protection of New Orleans, before Hurricane Katrina. Tidal and surge conditions depend on the location and, as such, the design storm could be adjusted by additional engineering detail.

The height estimate that includes RSLR and surge is adjusted by an additional term: RSLR pre-project. The term is the height of the sea when public adaptation is first constructed. It is assumed that public adaptation is built at the current shoreline, not the shorelines at the beginning of the simulation. If coastal protection is not built until 2050, then the sea level in 2050 is the height relative to the base of the coastal protection.

$$H_{cm} = H_{rslr}^* + H_{surge}^* - H_{rslr, c} \quad (3.143)$$

where

$H_{cm}$  is the coastal manager's calculated protection height (meters)

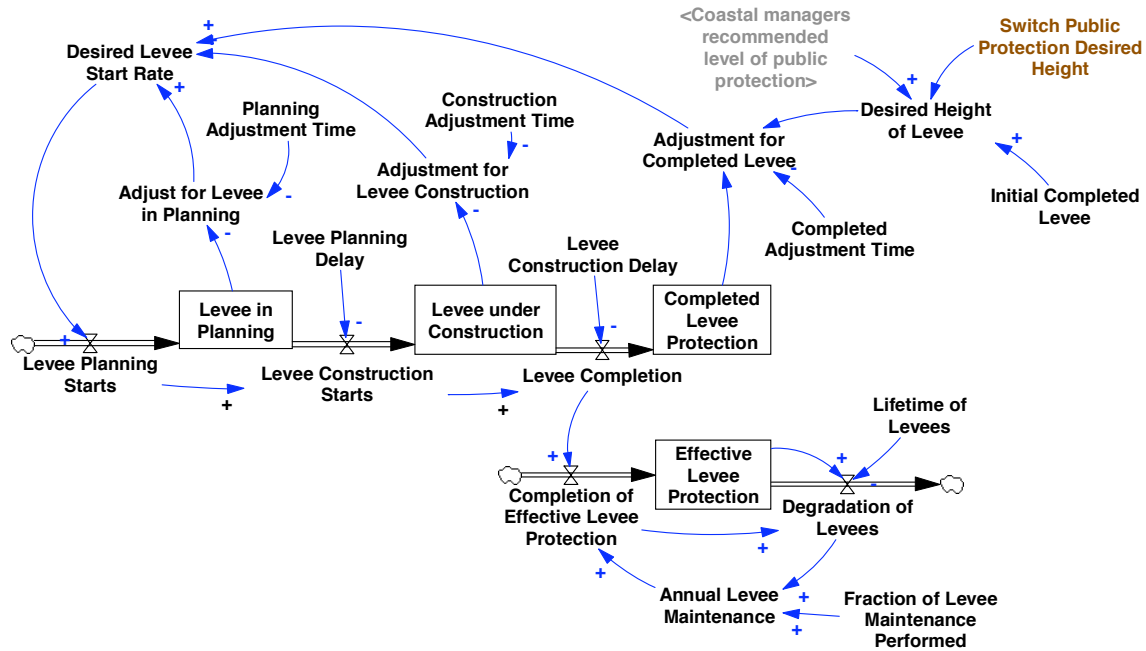
$H_{rslr}^*$  is the projected height of RSLR over the planning horizon (meters)

$H_{surge}^*$  is the additional height for storm surge (meters)

$H_{rslr, c}$  is the sea level at the time of construction (meters)

### 3.8.5 Levee construction

Levee construction is a process that takes several years to complete. The FRACC model represents construction as a staged process that includes planning and construction delays. The structure of the model follows the standard construction chain from Sterman (2000) and includes three different construction phases: planning, construction, and completion (Figure 3-29). Each of the phases is measured in units of levee height (i.e., meters).



**Figure 3-29:** Levee construction chain, including delays, and the levee effectiveness formulation.

This research modeled coastal defense construction projects more explicitly than previous research. The FRACC model relaxes the “brick by brick” of Fankhauser (1995). Construction occurs over a period of years instead of instantaneously. The level of protection Levee provided by the defense is realized as construction completes. The “brick by brick” assumption could be further relaxed by changing the cost structure of levees (and beach nourishment projects). The current formulation still assumes a linear cost function, described below.

The height of the levee is determined as described in Section 3.8.2. For a given levee height, new construction takes into account the current height of the levee and any construction that might already be underway. The formulation guarantees that the final height of the levee will be the desired height, even with lags in the system.

The height of the completed levee is a stock with only one inflow—completion of levee construction. This means that the height of the completed levee can only grow. A levee will not be demolished if the coastal manager’s analysis calls for a levee that



is shorter than the one already in place.

The two other structures in the construction chain represent two important phases of construction: the levee height that is being planned and the levee height that is under construction. Levees require several years to construct, and larger projects take over a decade to complete (Blakey and Whittington, 2001; Russo, 2009). The planning stage includes “feasibility” studies and government delays for authorization and funding. The construction phase includes all of the required time to transport soil and build the height of the levee to the final height. The time delays for these phases are taken from the US Army of Corps of Engineers projects guide (Blakey and Whittington, 2001), which states approximately 5 years for planning and initial engineering and a varying number of years for construction. These values are optimistic since they do not include project delays because of civil litigation. Many levee construction projects get tied up in environmental litigation because of their impact on wetlands and/or endangered species. These litigation delays can take many years. We can expect that levee projects initiated in response to RSLR may be more contentious and involve more litigation since they will involve building in already developed area along the current coastline, lengthening delays further.

The three levee construction stocks are mathematically defined as:

$$U_T = \int_{t_0}^T (r_{fin})dt + U_{t_0} \quad (3.144)$$

$$U_T^C = \int_{t_0}^T (r_{con} - r_{fin})dt + U_{t_0}^C \quad (3.145)$$

$$U_T^P = \int_{t_0}^T (r_{start} - r_{con})dt + U_{t_0}^P \quad (3.146)$$

where

$U_T$  is the *Completed Levee Protection* (meters)

$U_T^C$  is the *Levee under Construction* (meters)

$U_T^P$  is the *Levee in Planning* (meters)

$r_{start}$  is the rate of *Levee Planning Starts* (meters/year)

$r_{con}$  is the rate of *Levee Construction Starts* (meters/year)

$r_{fin}$  is the rate of *Levee Completion* (meters/year)

$U_0^C, U_0, U_0^P$  are initial values of the stocks (meters)

*Levee Construction Starts*, the flow from planning to construction, is a sixth-order delay of the *Levee Planning Starts*. Similarly, the flow from *Levee under Construction* to *Completed Levee Protection* is a sixth-order delay of *Levee Construction Starts*:

$$r_{start} = MAX(0, \hat{U}_t) \quad (3.147)$$

$$r_{con} = DELAY6(r_{start}, \tau_{plan}) \quad (3.148)$$

$$r_{fin} = DELAY6(r_{con}, \tau_{con}) \quad (3.149)$$

where

$\hat{U}_t$  is the *Desired Levee Start Rate* (meters/year)

$\tau_{plan}$  is the *Levee Planning Delay* (years)

$\tau_{con}$  is the *Levee Construction Delay* (years)

*Desired Levee Planning Starts* is the adjustment for the levee construction process so that the completed levee height equals the desired height. *Desired Levee Planning Starts* take the full construction chain into account. If only the height of the completed levee was compared to the desired height and the amount of levee in planning or under construction is ignored, then excess planning and construction would occur. The final

height of the levee would exceed the desired height. The *Desired Levee Start Rate* is the sum of the adjustments:

$$\hat{U}_t = A_{plan} + A_{con} + A_{fin} \quad (3.150)$$

$A_{plan}$  is the *Adjustment for Levee in Planning* (meters/year)

$A_{con}$  is the *Adjustment for Levee Construction* (meters/year)

$A_{fin}$  is the *Adjustment for Completed Levee* (meters/year)

The adjustments for each of the construction chain phases incorporate delays for recording progress and reporting the status of the stocks. These are considered to be minimal for levee construction projects as the USACE has regular reporting procedures for projects.

$$A_{plan} = \frac{-U_t^P}{\tau_{pa}} \quad (3.151)$$

$$A_{con} = \frac{-U_t^C}{\tau_{ca}} \quad (3.152)$$

$$A_{fin} = \frac{U_t^* - U_t}{\tau_{fa}} \quad (3.153)$$

where

$U_t, U_t^P, U_t^C$  are stocks in the levee construction chain (meters)

$U_t^*$  is the *Desired Height of Levee* (meters)

$\tau_{pa}$  is the *Planning Adjustment Time* (years)

$\tau_{ca}$  is the *Construction Adjustment Time* (years)

$\tau_{fa}$  is the *Completed Adjustment Time* (meters)

### 3.8.6 Levee costs

The actual cost of a levee is the sum of construction costs and maintenance costs. Construction costs occur as a levee project transitions from the planning to the construction phase. Annual maintenance costs occur indefinitely after the levee is completed. All of the cost estimates are averages for a unit of levee length and height (i.e., dollars per meter of height per kilometer of length). Levee construction costs are from the DIVA database (which uses Hoozemans et al. (1993) values) and maintenance costs were estimated from Okita and Prichard (2006). The cumulative levee costs are the sum of the annual expenditures on levee construction and maintenance (Equations 3.154-3.156).

$$C_{levee} = \int (C_{tm} + C_{tc}) \quad (3.154)$$

$$C_{tm} = r_m p_m l_{levee} \quad (3.155)$$

$$C_{tc} = r_c p_c l_{levee} \quad (3.156)$$

where

$C_{levee}$  is the *Cumulative Levee Expenditures* (\$)

$C_{tm}$  is the total cost of levee maintenance (\$/year)

$C_{tc}$  is the total cost of levee construction (\$/year)

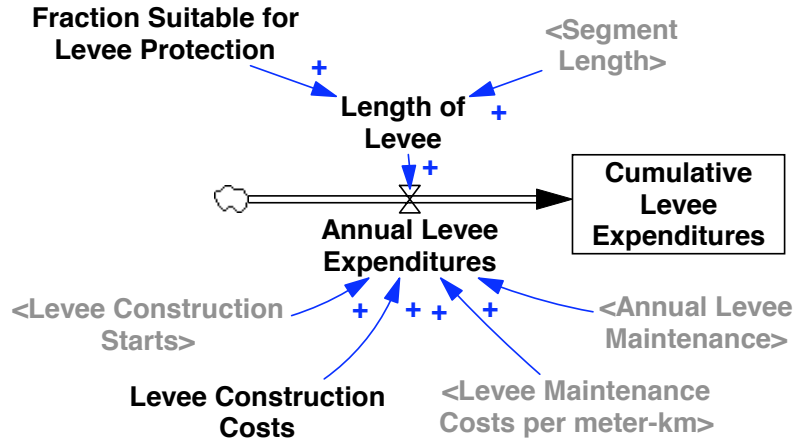
$r_m$  is the rate of *Annual Levee Maintenance* (meters/year)

$p_m$  is the *Levee Maintenance Costs* (\$/meter/km)

$r_c$  is the *Levee Construction Starts* (meters/year)

$p_c$  is the *Levee Construction Costs* (\$/meter/km)

$l_{levee}$  the length of the levee (km)



**Figure 3-30:** Levee cost calculations, both annual and cumulative.

Coastal managers discount construction costs when evaluating an adaptation project (Section 3.8.2). For a levee, the maintenance costs are discounted but the initial construction costs are not, a simplification.

$$C_{levee}^d = C_c^* + \frac{C_m^*}{r_d} \quad (3.157)$$

$$C_c^* = p_c l_{levee} H_{cm} \quad (3.158)$$

$$C_m^* = p_m l_{levee} \frac{H_{cm}}{\tau_{levee}} \quad (3.159)$$

where

$C_{levee}^d$  is the discount levee costs (\$)

$C_c^*$  is the estimate initial construction costs (\$)

$C_m^*$  is the estimate total maintenance costs (\$/year)

$r_d$  is the discount rate (1/year)

$H_{cm}$  is the height of levee (meters)

$\tau_{levee}$  is the lifetime of the levee (years)

### 3.8.7 Beach nourishment construction

Beach nourishment is another adaptation option for coastal managers. Many communities in the US have chosen beach nourishment instead of sea walls, levees, or other physical structures. One of the main advantages of beach nourishment is tourism. A well-executed beach nourishment project can improve the quality of a beach, which increases tourism, in addition to providing flood protection.

A beach nourishment adaptation project is represented by the volume of sand required for a particular level of protection. Sand volume is determined by the length of the coastline, the coastal managers' suggested height, and the distance to the depth of closure. Depth of closure is where shoreline erosion forces have a net zero effect, and the sea floor is relatively stable.

Figure 3-31 shows the model representation of the beach nourishment process. The beach nourishment construction chain is similar to the levee construction chain, including planning and construction delays. The desired volume of sand, for the level of protection recommended by coastal managers, is compared to the complete volume of beach nourishment, the third stock in the chain. New beach nourishment 'starts' correct the gap, taking into account the volume of sand already in planning and under construction.

Beach nourishment projects have shorter delays than levee projects. Constructing a beach nourishment project is typically quicker than a levee given appropriate local sand resources (Elko, 2009). Sand resources are assumed to be plentiful, an assumption that can be challenged in future work.

The beach nourishment construction change differs from the levee construction chain in one significant way: an outflow of erosion. Natural erosion processes are always at work on the coast, eroding most shorelines as a constant rate (e.g. O'Connell, 2003; Wiegel, 1992). Completed nourishment sand is eroded at a constant rate. Im-

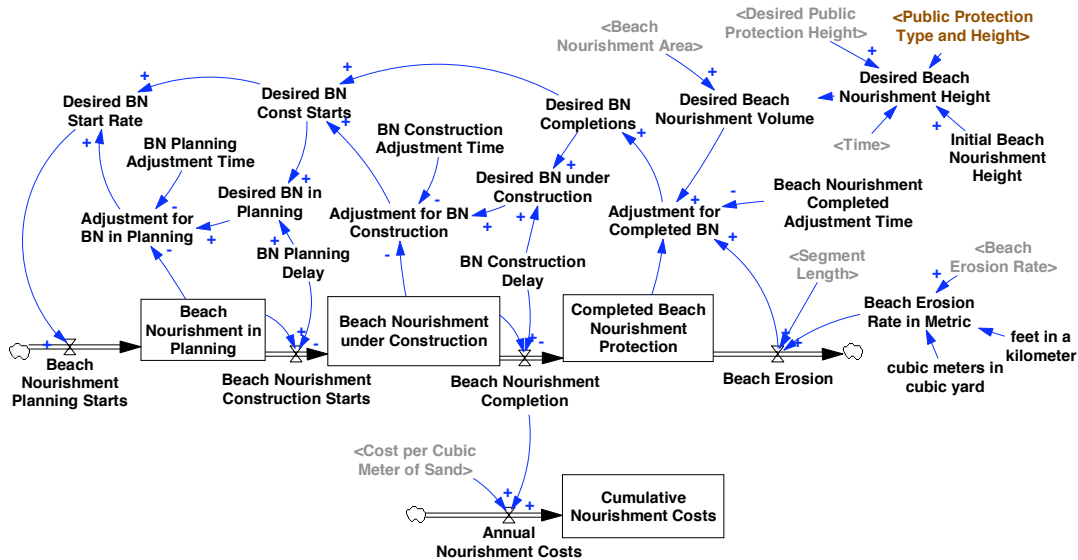


Figure 3-31: Beach nourishment construction, including delays and erosion.

portantly, the shoreline is assumed to be in equilibrium at the start of the simulation, meaning project starts equals the rate of erosion.

### 3.8.8 Beach nourishment costs

The costs of beach nourishment are dominated by the cost of sand. The FRACC model simplifies the cost structure of beach nourishment to be the cost of sand to maintain the desired height of protection. The annual cost of beach nourishment is the amount of *Beach Nourishment Completion* multiplied by the cost of sand per unit of volume. The cost of sand can vary greatly depending on off-shore sand resources. Estimates range from \$5–25 per cubic yard (Elko, 2009). For this research, a value of \$15 per cubic yard was used. There is great uncertainty in the cost of future sand resources, but a full sand resource analysis and model is beyond the scope of this work.

Coastal managers estimate the cost of beach nourishment calculating the volume of sand required for the desired level of protection. The initial amount of sand required for protection is this volume minus the volume already on the beach. They also estimate the total volume lost to erosion for the life of the project. The final discounted

cost of beach nourishment, used in the benefit-cost decision (Section 3.8.2), is the undiscounted cost of initial volume plus the discounted cost of future renourishment and maintenance.

$$C_{bn}^d = (V_f - V_0) * p_s + \frac{r_e p_s}{r_d} \quad (3.160)$$

where

$C_{bn}^d$  is the total discounted cost of beach nourishment (\$)

$V_f$  is the final volume require for the recommend level of protection (cubic meters)

$V_0$  is the initial volume of sand (cubic meters)

$p_s$  is the price of sand (\$/cubic meter)

$r_e$  is the rate of erosion (cubic meters/year)

$r_d$  is the discount rate (1/year)

### 3.8.9 Public adaptation maintenance and effectiveness

Most of the time, public adaptation defenses provide protection against storm surge and RSLR. Sometimes levees and protective dunes breach, causing flooding and substantial damage to infrastructure. The effectiveness of levees and beach nourishment projects is captured in the FRACC model.

Levees often fail because of a lack of upkeep and maintenance. To capture levee maintenance, *Effective Levee Height* is introduced to the model (Figure 3-29). The *Effective Levee Height* is a stock that has an inflow of levee construction and maintenance and an outflow of depreciation. The time constant of the outflow is long, reflecting the relatively long lifetime of levee structures. When a levee is constructed, the *Effective Levee Height* is the same as the actual physical height of the levee, *Completed Levee Protection*. Over time, the effective height falls while the actual levee remains at the original height. The difference between effective and actual height is



used to change the probability of levee breaching, discussed in the next section.

Regular maintenance prevents the effective height from falling. Maintenance includes assessing and performing the work required for optimal levee performance. The *Fraction of Levee Maintenance Performed* is a parameter of the model that can be changed to test different local scenarios. Often communities only perform part of the required maintenance because of budget constraints. The default value of *Fraction of the Levee Maintenance Performed* is set so a high percentage of maintenance is implemented, giving the community an optimistic assumption on their levee maintenance.

$$\text{Effective Levee Height} = \int (\text{Levee Work} - \text{Degradation}) + U_{t_0} \quad (3.161)$$

$$\text{Levee Work} = r_{fin} + r_{main} \quad (3.162)$$

$$\text{Degradation} = \text{DELAY3}(r_{fin}, \tau_{levee}) \quad (3.163)$$

$$r_{main} = k_{main}(\text{Degradation}) \quad (3.164)$$

where

$r_{fin}$  is the annual amount of new levee completed (meters/year)

$r_{main}$  is annual levee maintenance (meters/year)

$\tau_{levee}$  is lifetime of a levee (years)

$k_{main}$  is the fraction of required maintenance performed (dmnl)

Beach nourishment projects do not require the same type of maintenance that levees do. Instead of a large upfront cost and then smaller amounts of annual maintenance, beaches are “renourished” periodically for the life of a nourishment project. The renourishment expenditures are typically incurred every 6–10 years, but are site-specific and depend on the rate of erosion.

In the model, renourishment is captured by a continuous process of maintaining the desired protective height. If renourishment were to stop, erosion would degrade the effectiveness of beach protection.

### 3.8.10 Public adaptation breaching

Coastal defense breaching is a function of the water height relative to the effective height of the levee. Coastal defenses perform well if the height of the water is lower than the structure. When a levee or dune is overtopped, breaching is more likely to occur. Some overtopping is built into a structure by design, so breaching does not always occur. During periods of splashing and short periods of sustained overtopping, the coastal defense should still perform reasonably well, protecting the majority of property behind it. During periods of sustained overtopping, the defense may scour (i.e., construction materials may wash away) and become saturated. These conditions increase the probability of breaching.

To capture many of these performance dynamics, breaching is a probabilistic event which depends on the total height of the water and the effective height of the coastal defense (Figure 3-32). Using effective height, as opposed to actual height, captures the construction state of the levee or dune. If maintenance has been regularly performed, the structure is in a good state and will perform better against high water and storm surge.

The *Total Water Height* is the height of relative sea level plus the *Storm Surge Height*. Storm surge is calculated as a function of storm intensity, described in more detail in Section 3.3.3.

The probability of a breach is a function of water height relative to the structure's top (Equation 3.165). In the denominator, the difference between the *Effective Height of Public Protection*, *Total Water Height*, and a *Reference Protection Height* is multiplied by a sensitivity parameter. The sensitivity parameter controls the steepness of

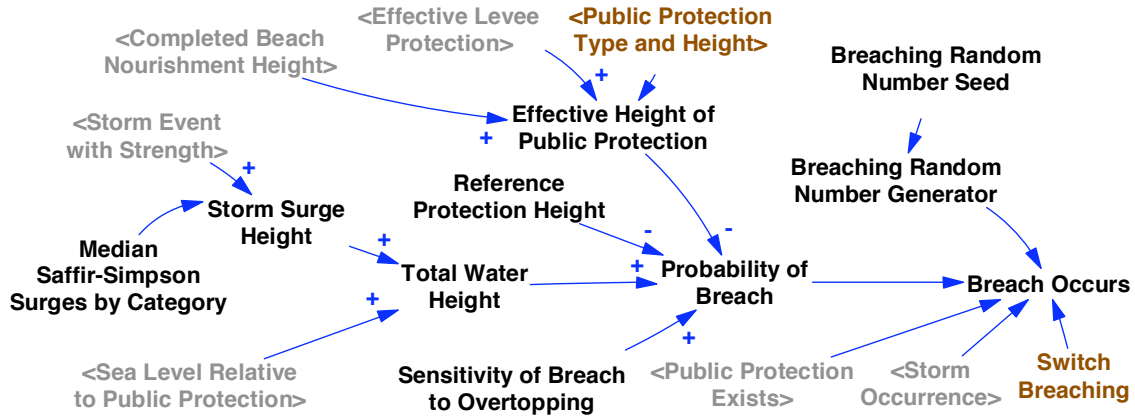


Figure 3-32: Levee and dune breaching, including the random number input.

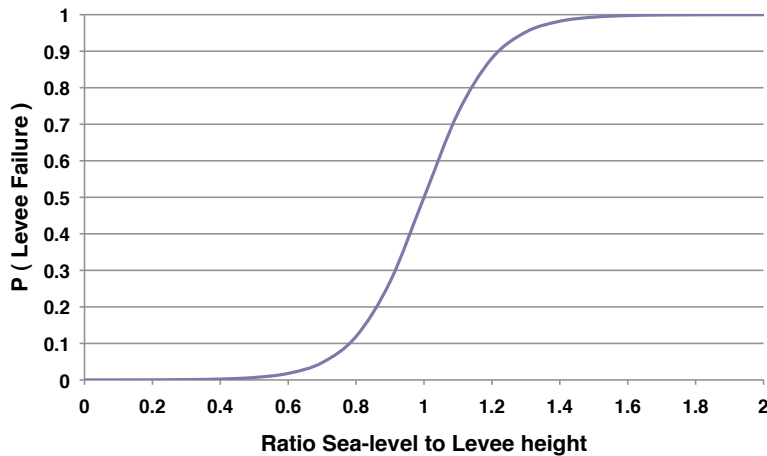


Figure 3-33: Fragility curve for levees and beach nourishment: probability of breach as a function of overtopping height.

the fragility curve, shown in Figure 3-33. The constant *Reference Protection Height* shifts the fragility curve horizontally, adjusting the mid-point of the fragility curve.

$$P(Breach) = \frac{1}{1 + e^{\sigma_{breach}(effective\ height - sea\ height - ref\ height)}} \quad (3.165)$$

### 3.9 Flooding and Damage Representation

Water can damage coastal properties in two main ways. First, storm surge can temporarily flood homes during a storm event. These waters eventually recede leav-

ing damaged capital and housing, but the inundated land will eventually dry out. Alternatively, long-term RSLR can slowly, but permanently, flood the land. The area covered by the higher ocean level will not dry out, but instead become more deeply submerged. This section describes how each of these flooding impacts are handled in the model.

### **3.9.1 Long-term RSLR damage**

Following the assumptions of Yohe et al. (1996), capital and housing are abandoned gradually with the slowly rising water level from RSLR. I assume that the property is abandoned at the end of its useful life, without any additional economic cost to the community. The assumption holds true as long as RSLR is slow relative to the lifetime of the infrastructure. It also depends on the coastal slope of the community, as a rapid rate of RSLR for an area with little elevation change would flood a very large area, probably before the capital was fully depreciated.

While RSLR does not damage capital directly, it does change the amount of available land for new housing and capital construction. RSLR causes long-term inundation of land that permanently reduces the amount of available dry land. In the FRACC model, as the sea level rises, land is lost and removed from the stock of available land for development. Houses and capital can no longer be built on the inundated land. Land availability is a constraint on new investment in the community (Sections 3.5.2 and 3.6.1) and ultimately affects economic growth in the community. The indirect RSLR effect reduces economic output in 2100 under all SLR scenarios, described further in Chapter 6.

Communities can protect against the loss of dry land due to RSLR. I assume levees provide 100 percent protection against RSLR (but not against storms). If the height of the ocean is lower than the height of the levee, the community is protected from the rising ocean. In this way, levees provide a benefit to the community against long-term SLR, increasing long-term economic growth, all else being equal.

### 3.9.2 Storm damage representation

Storm damage is divided into two components: water and wind. The components are treated independently, a simplifying assumption.

#### Water damage from storms

Water damage only occurs in portions of the community that are flooded. The coastal slope of the land and the total water height during a storm are used to calculate the area possibly flooded. Coastal slope is assumed to be constant. The total water height is the current relative sea level height plus the height of storm surge.

Flooding occurs because either no coastal protection exists or the coastal protection is overtopped or breached. In the case of no protection, all of the land below the total height of water is inundated. If the coastline is protected by a levee or beach nourishment, then flooding occurs when the total height of water exceeds the height of the protection. If the water exceeds the height of the protection, a breach of the protection may occur. If a breach occurs, then damage is the same as if no protection existed. If the protection does not fail, the overtopping water causes half of the possible flood damage. The damage function for overtopping could be changed in future research, if a better weir model of overtopping were available. In general the damage would be positively correlated with the total height of water.

$$d_{u,m}^w = \begin{cases} d_{u,m}^* & \text{if no protection} \\ d_{u,m}^* & \text{if breach} \\ 0.5d_{u,m}^* & \text{if overtopping} \\ 0 & \text{if } H_{water} < H_{protection} \end{cases} \quad (3.166)$$

where

subscripts  $u, m$  are for unmitigated and mitigated property

$d_{u,m}^w$  is the fractional damage because of water (dmnl)

$d_{u,m}^*$  is the potential fractional damage because of water (dmnl)

The fractional damage for mitigated and unmitigated properties differs because of their base floor elevation. Mitigated properties (Section 3.10.2) have a higher first floor, potentially lifting property and utilities above the water level. The fractional damage to a property is based on a depth-damage curve from Green et al. (1994). Green *et al.* compiled estimates of flood damage for several countries, and his estimate for the US is used for this research (Figure 3-34).

The height of water in a structure is the non-negative difference of the average water height in the community and the base floor elevation. The average water height is half of the total water height, given the linear assumptions of coastal slope. Therefore, the potential fractional damage from water is a function of the average water height, the base floor elevation, and the depth-damage relationship:

$$d_{u,m}^* = f(\text{MAX}(0, \text{Ave Water Height} - \text{BFE}_{u,m})) \quad (3.167)$$

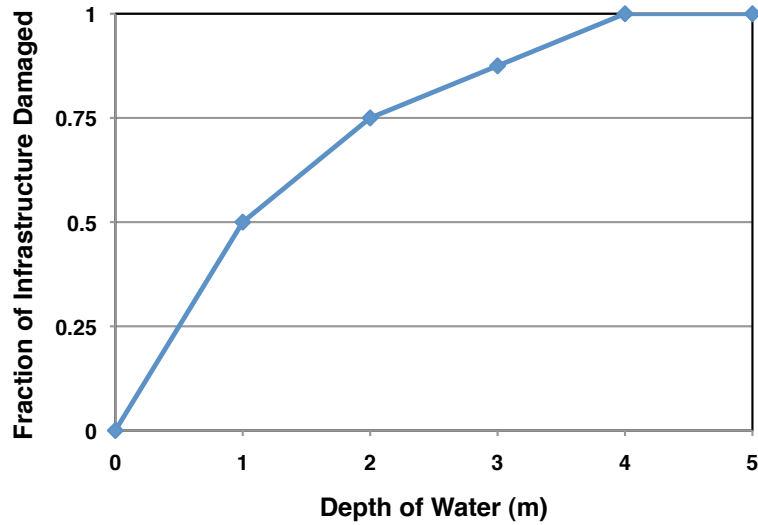
$$\text{Ave Water Height} = \frac{1}{2} H_{\text{water}} \quad (3.168)$$

where

$f$  is the depth-damage table function (dmnl)

*Ave Water Height* is the average water height in the community (meters)

*BFE* is the base floor elevation of the property (meters)



**Figure 3-34:** Water depth-damage function. Fractional damage as a function of water height above base floor elevation in meters. (Source: Green et al., 1994)

### Wind damage from storms

Unlike water damage, wind causes damage throughout the entire community. Wind damage is a cubic function of hurricane category (i.e., wind speed) (Iman et al., 2002a,b). The damage function is scaled such that the maximum storm strength, Category 5, will damage 50 percent of the property in the community. The exact percentage is hard to estimate from storm data, especially because of the aggregate nature of the model's capital sector.

$$d^{wind} = \frac{Storm\ Category^{\sigma_w}}{Maximum\ Wind\ Damage} \quad (3.169)$$

where

$d^{wind}$  is the fraction damage by wind (dmnl)

*Storm Category* is the category of storm (1, 2, ...) (dmnl)

$\sigma_w$  is the sensitivity of damage to wind (dmnl)

*Maximum Wind Damage* is for scaling the maximum fractional damage according to storm category (dmnl)

### Total storm damage

Total storm damage is the sum of water damage and wind damage. Water damage is scaled by the fraction of the community flooded. Not more than 100 percent of the community can be damaged by the combination of water and wind, so a MIN function is used to restrict the level of damage.

$$d_{u,m}^t = MIN(1, F_{flooded} D_{u,m}^w + D^{wind}) \quad (3.170)$$

where

$d_{u,m}^t$  is the total fractional damage by property category (dmnl)

$F_{flooded}$  is the fraction of community flooded (dmnl)

## 3.10 Private adaptation

Property owners can buy flood insurance coverage and/or physically mitigating the flood risk—forms of accommodation to climate change. The FRACC model includes two private adaptation options: flood insurance and risk mitigation by raising the building.



### 3.10.1 Insurance

Storm damage occurs because of water and wind. Typically in the United States, a property owner would need an insurance policy for each risk. Wind damage coverage is often included in home owners insurance while flood damage is covered by a specific flood insurance policy. I assume exogenous coverage for wind insurance, which is normally included in homeowners, renters, and commercial property insurance policies. These property insurance markets are not modeled explicitly.

Flood insurance is extended to most communities by FEMA through the National Flood Insurance Program (NFIP). A study of the NFIP have found that the average coverage is around 52 percent in Special Flood Hazard Areas, but good data are lacking (Dixon et al., 2006). The percentage of insurance coverage varies by geographic region (Chapter 4).

After a storm, insurance coverage typically rises because 1) enforcement is better, 2) flood risk becomes more salient, and/or 3) the NFIP requires flood insurance to receive federal disaster assistance (Sweeney, 2009; Zingarelli, 2009). The magnitude of increase in coverage is not well constrained by available data.

A stock structure was included in the model to represent flood insurance (Figure 3-35). The stock is the fraction of properties in the flood plain (i.e., likely to experience water damage) with flood insurance. The stock is initialized to the *Normal Fraction of Flood Insurance Coverage*, which varies by community as suggested by Dixon et al. (2006).

$$\text{Flood Ins Coverage} = \int (\text{New Coverage} - \text{Lapsed Coverage})dt + k_{nfip} \quad (3.171)$$

where

*Flood Ins Coverage* is the current *Flood Insurance Coverage*

*New Coverage* is the *Change in Flood Insurance Coverage*

*Lapsed Coverage* is the *Lapse of Insurance Coverage*

$k_{nfip}$  is the *Normal Fraction of Flood Insurance Coverage*

When a storm occurs, insurance coverage increases to the normal coverage plus half of the remaining fraction, and is defined exogenously by *Fractional Change of Coverage after Storm*. The maximum is not well defined by NFIP data, but Dixon et al. (2006) suggest that coverage is 50 percent more likely in communities that have recently experienced flooding.

$$New\ Coverage = \frac{\Psi}{k_{ts}}(Max\ Ins\ Coverage - Flood\ Ins\ Coverage) \quad (3.172)$$

$$Max\ Ins\ Coverage = k_{ds}(1 - k_{nfip}) + k_{nfip} \quad (3.173)$$

where

$\Psi$  is the *Storm Occurrence* (binary 0,1)

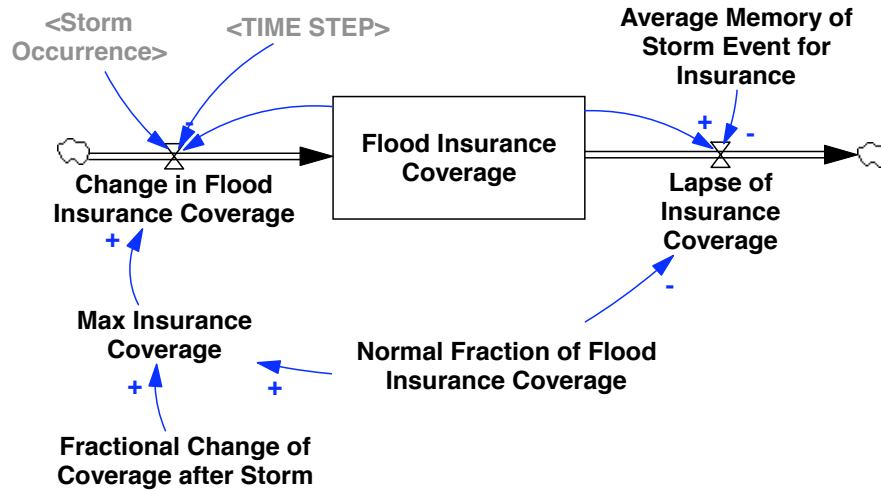
*Max Ins Coverage* is the *Max Insurance Coverage*

$k_{ds}$  is the *Fractional Change of Coverage after Storm*

$k_{ts}$  is the model time step

Coverage then slowly declines as policies lapse, representing people forgetting about flood risk and dropping out of the group policy requirement.

$$Lapsed\ Coverage = \frac{Flood\ Ins\ Coverage - k_{nfip}}{\tau_{ins}} \quad (3.174)$$



**Figure 3-35:** Adjustment mechanisms for flood insurance coverage.

where

$\tau_{ins}$  is the *Average Memory of Storm Event for Insurance*

The price of insurance is not modeled explicitly. Flood insurance appears to have a low price elasticity. The decision to purchase coverage is driven by the NFIP mandatory purchasing requirements for mortgages and disaster relief (Dixon et al., 2006).

The value of insurance payments after a storm is the sum of the wind payments and the water payments. Water insurance payments are the value of flood damage multiplied by the fraction of the community flood insurance coverage. Wind insurance payments are the value of wind damage to property multiplied by the exogenous percentage of wind coverage. Because wind damage is normally included in homeowners and renters insurance, this percentage is set to the average of homeowners and renter insurance coverage (69.5 percent from Insurance Research Council (2006)). These insurance settlements increase the aggregate demand in the community (Section 3.5.2).

### 3.10.2 Infrastructure mitigation

To qualify for national flood insurance, property owners in flood-prone areas need to design buildings in a way that physically mitigates the exposure to water damage. The construction standards are specified as part of the NFIP. Mitigated properties often have the first floor of living space and important utilities and appliances raised about a base flood elevation. The NFIP requires the base elevation to be above the 100-year flood event, which was an arbitrary decision made in the 1971 (Galloway et al., 2006).

The percentage of properties that are built in compliance with NFIP standards changes during the simulation. Initially, the fraction of mitigated properties depends on the age of the capital stock. Communities with older infrastructure are assumed to have a lower initial fraction of compliance because either the infrastructure was built prior to the NFIP program or enforcement was less strict. Mathis and Nicholson (2006) finds that enforcement has been strengthening over the last 15 years, but nationwide only 63 percent of new buildings are in full compliance. Additionally, Mathis and Nicholson (2006) finds that the fraction of recent compliance varies by region of the country.

The fraction of property that is mitigated in the community is initialized to a fraction of compliance that is weighted by the age of the community's infrastructure. Properties constructed recently (post-1990, to align with Mathis' data) are considered to comply at the community's fractional rate for new construction. Half of older properties are assumed to be built according to NFIP guidelines, a value that is hard to support with data (Sweeney, 2009; Zingarelli, 2009). After initialization, new construction is divided into mitigated and unmitigated categories according to the most recent fraction of compliance, (Mathis and Nicholson, 2006). The fraction of compliance for new construction, called *New Construction NFIP Compliance*, is constant for the simulation. Future work could relax this assumption, allowing for trends in compliance.

Besides new construction, the current fraction of mitigated structures in the community may increase because of retrofit properties. After a storm event, a fraction of the damaged infrastructure is assumed to be retrofitted in accordance with NFIP standards. Property owners may retrofit because they have experienced a flood, or observed their neighbors flooding, and/or they are required by FEMA to retrofit if they want to qualify for federal disaster assistance (Sweeney, 2009; Zingarelli, 2009). The *Fraction Retrofitting* is a function of the fraction of the community flooded and the *New Construction NFIP Compliance*. The fraction of retrofits is proportional to the area of the community that was flooded by the recent storm.

$$F_t^R = \Psi(F_t^M)(F_{flooded}) \quad (3.175)$$

where

$F_t^R$  is the *Fraction Retrofitting* (1/year)

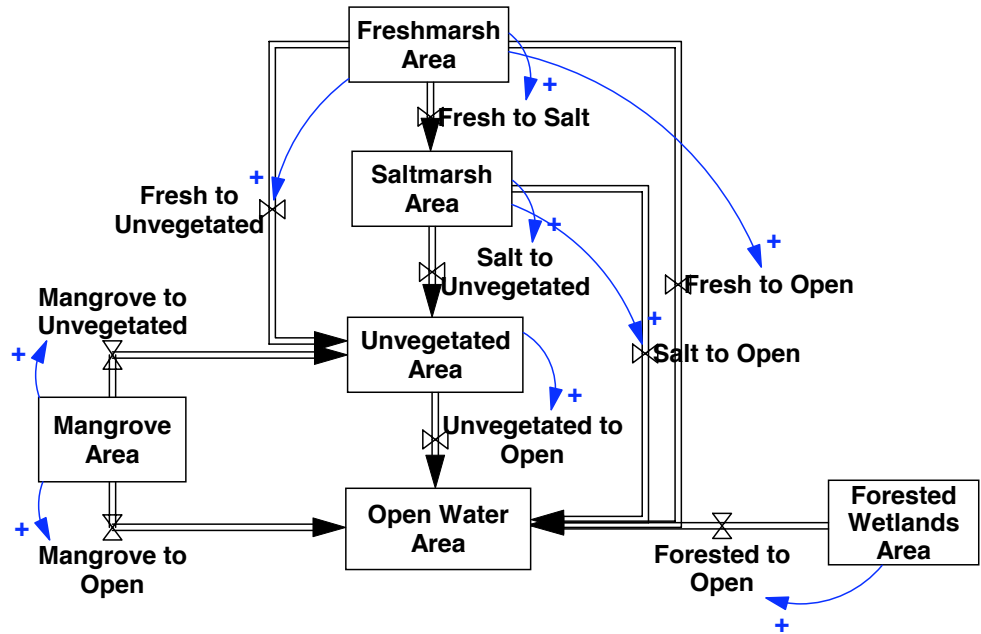
$\Psi$  is the *Storm Occurrence* (binary 0,1)

$F_t^M$  is *New Construction NFIP Compliance* (dmnl)

$F_{flooded}$  is the fraction of community flooded (dmnl)

### 3.11 Wetlands and RSLR Response

The FRACC model includes a wetland succession model. The model is the same wetlands model that is used in the DIVA model (McFadden et al., 2007; Vafeidis et al., 2008) described in the literature review. The DIVA model is written in the Java programming language. The wetland module code was converted to the Vensim modeling environment for this work, recreating the same model and wetland dynamics. The model of wetland succession is described succinctly here—further documentation is included with the DIVA model (DINAS-COAST Consortium, 2006).



**Figure 3-36:** Wetland succession between six different biome classifications.

The model categorizes wetland acreage into six different types based on their vegetation type and sensitivity to RSLR. Four biome types have vegetation: freshwater marsh, salt marsh, forested wetlands, and mangroves. These areas are considered separately because the biomes have different time constants for succession. Forested wetlands and mangroves change their biome type slowly, compared to salt and freshwater marshes. These lags are important in determining the transformation rate of the wetland system. The other two biome categories are water-dominated biomes. Unvegetated acreage is area that does not contain plants, is often flooded or wet, but is above the mean high water line. Open water is also unvegetated, but is below the mean high water line, so is on the verge of becoming permanently inundated (Table 2 in McFadden et al., 2007).

The other FRACC model components provide two inputs to the wetlands component: RSLR and the existence of a levee. Wetland succession is driven by RSLR. As water rises, wetland acreage changes from one biome category to another, following standard biome succession theory (Clements, 1916). The rate and amount of change was determined during the DIVA modeling process, which utilized several empirical

studies of wetland succession (e.g., Reyes et al., 2000). The acreage of each biome is a function of the biome's time constant for succession, the amount of RSLR, accommodation space for wetland migration, and environmental constants of the coastline. The environmental constants, like sediment supply, were taken from the DIVA database.

The presence of a levee affects the “accommodation space” space for wetland migration. Accommodation space is the acreage available for wetlands to migrate inward. The available area for migration is limited by a levee, which presents a barrier to further inland migration. Accommodation space due to coastal development has been parameterized in the DIVA database. The database value is adjusted when a levee is constructed to represent the reduction in accommodation space.

The wetlands component provides one output to the other components: total wetland acreage. Total acreage can be used by coastal managers in their benefit/cost analysis, described in Section 3.8.2, but is not currently activated by default because of US Army Corps of Engineers normal BCA methods (Section 2.5).

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# Chapter 4

## Case Study Communities

### 4.1 Introduction

Three different sites in the United States were chosen as case studies for this research. The three locations are coastal counties, including:

1. Cape Cod and the Islands, Massachusetts
2. Miami-Dade County, Florida
3. St. Mary Parish, Louisiana

These three communities were chosen because they represent different types of coastal development and ecosystems. Some communities may attempt to protect and accommodate, while other communities may choose to retreat from the coast.

The three dimensions differentiating the communities are urban density, area of wetlands, and the risk of tropical storms. Table 4.1 summarizes Cape Cod, Miami-Dade County, and St. Mary Parish qualitatively along these three dimensions. Table 4.2 presents important statistical data that differentiates the communities.

The United States was chosen because of data availability and familiarity with the laws and attitudes toward risk. I hope the insights from these three communities

| <b>Community</b> | <b>Urban Density</b> | <b>Area of Wetlands</b> | <b>Tropical Storm Risk</b> |
|------------------|----------------------|-------------------------|----------------------------|
| Cape Cod         | Low                  | Medium                  | Low                        |
| Miami-Dade       | High                 | High                    | High                       |
| St. Mary Parish  | Low                  | High                    | High                       |

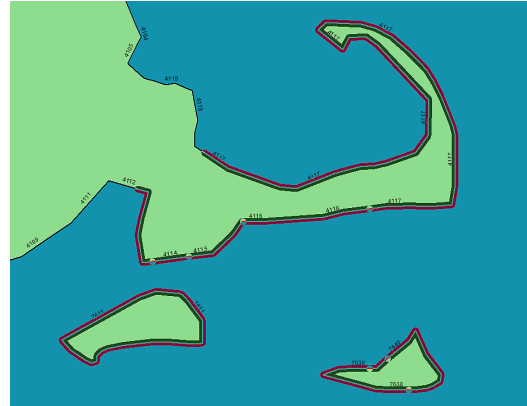
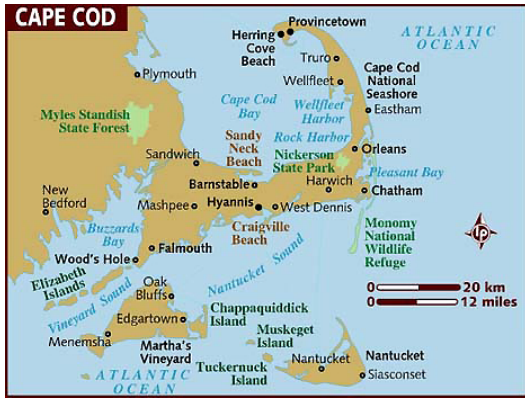
**Table 4.1:** Dimensions distinguishing qualitatively between community case studies.

will be applicable to other regions around the world, which is discussed further in Section 8.4.1.

The next sections introduce each of the three communities qualitatively. The demographics, industry, and natural ecosystems are described. The final section details how particular region-specific parameters were determined. Parameters such as wetland area, coastal uplift, and storms patterns are described.

| <b>Parameter</b>                   | <b>Community</b> | <b>Value</b> | <b>Units</b> |
|------------------------------------|------------------|--------------|--------------|
| Coastal slope                      | Cape Cod         | 0.181        | degrees      |
|                                    | Miami-Dade       | 0.052        |              |
|                                    | St. Mary Parish  | 0.062        |              |
| Rate of Subsidence                 | Cape Cod         | 0.7          | mm/year      |
|                                    | Miami-Dade       | 0.6          |              |
|                                    | St. Mary Parish  | 8.6          |              |
| Population                         | Cape Cod         | 246,737      | people       |
|                                    | Miami-Dade       | 2,402,210    |              |
|                                    | St. Mary Parish  | 53,500       |              |
| GDP per Capita                     | Cape Cod         | 25,619       | \$/person    |
|                                    | Miami-Dade       | 18,497       |              |
|                                    | St. Mary Parish  | 13,399       |              |
| Land Area                          | Cape Cod         | 1417         | sq. km       |
|                                    | Miami-Dade       | 5040         |              |
|                                    | St. Mary Parish  | 1587         |              |
| Wetland Area                       | Cape Cod         | 283          | sq. km       |
|                                    | Miami-Dade       | 3780         |              |
|                                    | St. Mary Parish  | 320          |              |
| Fraction Area<br>Developable       | Cape Cod         | 0.67         | fraction     |
|                                    | Miami-Dade       | 0.25         |              |
|                                    | St. Mary Parish  | 0.8          |              |
| Fraction Area<br>Already Developed | Cape Cod         | 0.5          | fraction     |
|                                    | Miami-Dade       | 0.6          |              |
|                                    | St. Mary Parish  | 0.2          |              |

**Table 4.2:** The important parameters for Cape Cod, Miami-Dade County, and St. Mary Parish.



**Figure 4-1:** Map of Cape Cod region. **Figure 4-2:** DIVA segments for Cape Cod.

## 4.2 Cape Cod

Cape Cod, Massachusetts, is a low-density area in the southeast corner of the state. For this research, “Cape Cod” includes the counties of Barnstable, Nantucket and Duke, commonly referred to as “Cape Cod and the Islands.” The research includes the islands of Nantucket and Martha’s Vineyard as part of the regional analysis.

Cape Cod is primarily a seasonal vacation destination. Many businesses are open for the summer tourist season and closed for the remainder of the year. There is little heavy industry in the region.

### 4.2.1 Land constraints and development

The Cape Cod region is surrounded by water except for a small connection to the mainland severed by a canal. This constrains growth of the region but also means that RSLR affects the Cape from all directions.

Nantucket and Martha’s Vineyard are islands. Both coastlines are home to cliffs and bluffs that are experiencing erosion problems. The islands each have several towns primarily located on the coasts. The land on the islands is expensive and homes are expensive relative to property values in other areas of the state and country. Nantucket has a reputation for hosting expensive real estate and having strict zoning and building ordinances.

Barnstable County, the county of Cape Cod proper, contains several parks that constrain land use and development. The Cape Cod National Seashore, a long stretch of coastline that is protected from any development, lies along the eastern edge. There are several additional county parks and paved recreation trails throughout the county that further constrain development.

Cape Cod has a higher ratio of coastline to land area because of the region's shape. The higher ratio exposes more of Cape Cod to SLR than the other two communities. Additionally, Cape Cod is the northern most community selected for this research. As such, the ocean waters are cooler and tropical storms are less frequent. Nor'easters pose an additional threat to the community, along with the infrequent tropical storm. Nor'easters are excluded from the FRACC model.

The population and capital density in the Cape Cod region is low. Many of the homes are clustered in coastal towns, with densities lower in the interior. Many homes in the region are second homes, used primarily in the summer months. Because the homes on Cape Cod are expensive, cumulative storm damage could be significant.

#### **4.2.2 Wetlands**

The Cape Cod region has a reasonably large area of wetlands. The wetlands are located in many areas of the region, with a significant fraction located on the northern edge of Barnstable County. Wetlands are important to Cape Cod's ecosystem, but have experienced pressure from coastal development. In response, Cape Cod instituted strict development guidelines regarding wetlands along with the existing federal and state regulations.

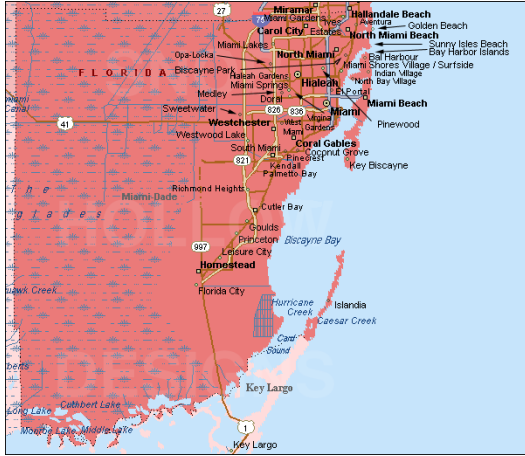
The low urban density and lack of coastal defense in the region provide the opportunity for wetlands to migrate inland. While roads and homes prevent wetland migration in some locations, in many areas the wetlands have a clear path to move further inland. This migration could help preserve wetland ecosystems, even if in the

face of future RSLR, but at the expense of existing homes.

### **4.2.3 Public adaptation decisions**

The Cape Cod economy depends on its natural beauty and its beaches to attract tourists. Due to these economic concerns, it is very likely that Cape Cod will not create any substantial coastal defenses. Levees, sea walls, and other physical structures would impact the natural views and decrease the attractiveness to tourists.

Cape Cod residents are protective of their way of life and the “feel” of their communities. Any coastal defense project would likely be challenged in the courts. Complaints would likely include adverse effects to property values and damage to ecosystems. On Nantucket Island, a recent small-scale privately-funded beach nourishment project was blocked by a community vote. The project was going to be privately funded by the immediate property owners and would have not required any public funds. Even so, the community voted against allowing the property owners to use public offshore land as a source of nourishment material. One key opponent group was comprised of local fisherman who worried about the impact to a nearby fishing area (Graziadei, 2008; Bransfield, 2008).



**Figure 4-3:** Map of Miami-Dade County.



**Figure 4-4:** DIVA segments near Miami-Dade County.

## 4.3 Miami-Dade County

Miami-Dade County has dense urban development and is home to many popular beaches. Miami Beach is world-famous and draws millions of tourists each year. Along with its beaches, the county contains part of the Everglades, the important wetland ecosystem in southern Florida. The Miami-Dade area faces a high risk of tropical storms, though it has skirted significant damage by recent storms, including Hurricane Andrew in 1992, which was not a direct hit.

### 4.3.1 Land constraints and development

Land in Miami-Dade County is constrained by the ocean to the East and South, and by the Everglades and other wetlands to the West. The wetlands, in particular, impede land development. While developers in the region feel that every acre of land could be developed (McCune, 2009), federal and local regulations prohibit development of wetlands. Additionally, western portions of the county are included in Everglades National Park, which removes the land from the possibility of development.

The county has two lines that restrict development. From the ocean moving westward, the first is the urban in-fill line that forces municipalities and unincorporated

land to build up rather than out. In this area, development typically involves replacing one- and two-story buildings with ten-story buildings, making the area more densely populated.

Further west, the capital development boundary demarcates the urban area from the “open space.” Area within the urban development boundary, which includes the urban in-fill area, can be developed into dense urban land. Open space is land that cannot be developed more densely than one house per five acres. Open space land includes agriculture, wetlands, and mining land.

Field interviews estimate that 15 percent of the land within the urban development boundary is undeveloped (McCune, 2009). The process of expanding the urban development boundary is long and time consuming. In recent decades, there has been strong resistance to expanding the boundary. The resistance is a noted change from the 1980s, which experienced rapid development with an ever-expanding urban development boundary. Now, the open space land includes allowances for limestone mining and agriculture. These two operations are significant sources of income for the region, with agriculture being the second largest revenue source, exceeded only by tourism. For the purposes of this research, a fixed urban boundary is assumed.

Miami-Dade County is the most developed of the three segments. The county includes both dense home and commercial capital along the coast, with the density decreasing as one moves westward, away from the coast. The coast and downtown Miami host denser housing developments, while the interior of the county has more single family homes (McCune, 2009; Schwarzreich, 2009).

### **4.3.2 Wetlands**

Miami-Dade County has a large area of wetlands that includes portions of the Florida Everglades. The wetlands are found predominately in the western and southern portions of the county. There is currently some room for the wetlands to migrate



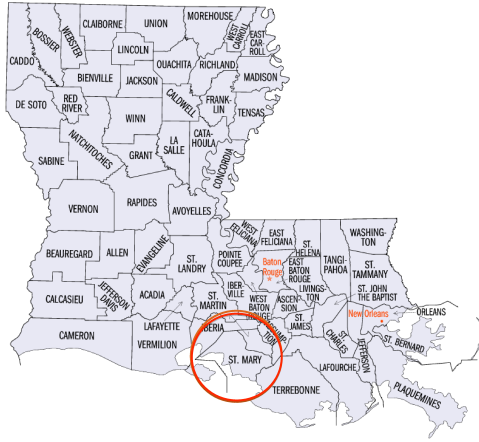
northward, into agricultural lands. Additionally, Florida and the federal government are implementing a large program to rehabilitate the Everglades. The restoration project aims to improve water flow and provide room for inland migration.

My research assumes that wetland area is equal to the county's total area minus the area that was designated "developable" through my fieldwork interviews (McCune, 2009). The calculated wetland area is used instead of the DIVA database values because it uses first-hand knowledge, which is more accurate. Also, the DIVA database does not explicitly describe how far inland the data represent, including the values for coastal wetlands. The data representation poses a problem for Miami-Dade County, whose coastline curves around the tip of Florida. Simply summing the wetland area from the associated DIVA segments might double-count some wetland acreage.

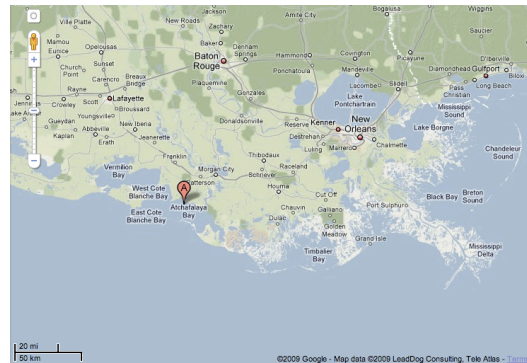
### **4.3.3 Public adaptation decisions**

Tourism and beaches are vital to Miami-Dade County's economy. Tourism is the largest sector of the county's economy. Beach nourishment during the 1980's is a primary reason for the recent decades of tourism and real estate growth.

Beach nourishment has been proven successful in the county and, therefore, I assume that local coastal managers will continue to use this method of coastal defense. Beach nourishment projects are expected to continue for the upcoming decades (Wiegel, 1992). However, the sand resources in southeast Florida are more limited than in other portions of the state, such as the West coast (Thomson, 2009). For this reason, it is likely that sand will be a constraining factor for future beach nourishment. Experts do not agree on how constraining the sand supply might be (Elko, 2009; Thomson, 2009), but generally agree that the county would continue to nourish the beaches until it was infeasible to continue doing so, either economically or technically.



**Figure 4-5:** Map of St. Mary Parish in Louisiana.



**Figure 4-6:** St. Mary Parish in southern Louisiana, near New Orleans and the Mississippi River delta.

## 4.4 St. Mary Parish

St. Mary Parish is a county (parish) on Louisiana’s Gulf coast. It is mainly oriented East-West, with a coastal southern boarder. Oil and gas exploration along its coastline provides for much of the region’s income, along with agriculture and shipping. Morgan City is a port city that provides services to many of the offshore drilling platforms and some cargo shipping.

### 4.4.1 Land constraints and development

St. Mary Parish is bounded by the Gulf of Mexico to the south and the Atchafalaya River basin to the north. The Atchafalaya River has provided the region with much of the rich sediment that supports the area’s agriculture and provides nutrients to the regions’ wetland vegetation. Some of the land in the parish is home to wild life refuges, including a sanctuary for black bears.

Approximately 80 percent of the land in St. Mary Parish is suitable for development. Some of the developable land is currently zoned as conservation land, but could be rezoned for housing and commercial development. Of the 80 percent that is developable, currently 20 percent has been developed, with the remaining land used

for agriculture and conservation (Fink, 2009).

Most of the dry land is found in the western half of the parish, farther from the coast. The land to the west is bordered by wetlands to the south. Approximately 40,000 acres of the dry land is used for sugar cane production. The dry land is not very high above sea level, and some ridges boasting housing developments are about 9 feet (2.74 m) above sea level (Fink, 2009).

There are two coastal towns that face the brunt of hurricane forces: Sale Point and Burns Point. These towns have been severely damaged in recent years by Hurricane Rita and Hurricane Gustav. FEMA requires the homes in these towns to build 14 feet (4.27 m) above sea-level (Fink, 2009).

#### **4.4.2 Wetlands**

Of the lower 48 states, Louisiana is home to approximately 25 percent of the total coastal wetland regions. Since 1900, Louisiana has undergone significant changes in its coastal wetland ecosystem. It is estimated that, in the 20th Century, over 800,000 acres of wetlands and barrier shoreline were lost (Barras et al., 2008). These losses are in part natural, but have also been accelerated because of human activity taking place upriver. In the Atchafalaya River basin, flood control projects have reduced the water and sediment flows that are vital to the wetlands' wellbeing.

St. Mary Parish has both coastal and freshwater wetlands. The area of wetlands in the parish was estimated by fieldwork interviews and checked against satellite photos. The wetland information in DIVA database could not be used because of poor geographical resolution. The final wetland area for the parish is the total parish area multiplied by the area that cannot be developed. The wetland biomes are proportional to the percentages in the DIVA database for the segment containing the parish.

### 4.4.3 Public adaptation decisions

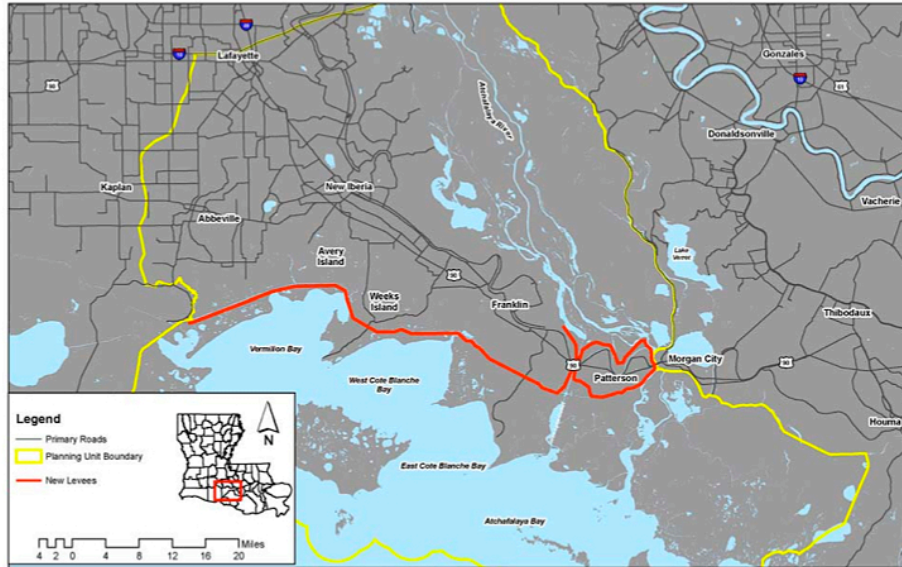
The coastline of St. Mary Parish largely consists of wetland regions. Within the wetlands is a sizable oil and gas drilling operation, including platforms and pipelines. The industrial infrastructure is vulnerable to storms, but typically is built to withstand wind and storm surge.

To protect their infrastructure, many towns in the region have already built levees, floodgates, and other flood control measures. For this research, I assume that these towns would continue constructing levees as their primary means of coastal defense. Beach nourishment does not make sense for the region because of the lack of beaches. Wetland restoration and sediment nourishment for wetlands may be an option in the future, but has not been extensively utilized and can only be done for a limited geographic area and over a long-time horizon (Axtman, 2009).

The US Army Corps of Engineers has developed several coastal defense options for the region as part of the Louisiana Coastal Protection and Restoration (LACPR) project. Several of the options include extensive levees running along rivers and parallel to the coastline (USACE, 2009b). Figure 4-7 is one proposed option. The plan includes a levee constructed inland from the coast along the Gulf Intracoastal Canal. The levee would prevent storm surge from moving farther inland. The levee would be constructed in the middle of the coastal wetlands and could have long-term consequences on the health of the ecosystem. The USACE is planning to offset acreage losses (USACE, 2009a).

## 4.5 Determining Initial Parameters

Data availability is a significant challenge to modeling climate change adaptation. The following initial parameters were collected from various data sources. Whenever possible, the same data source was used for all three regions, such as US Census Bureau data for population and housing.



**Figure 4-7:** One of the coastal defense options of the LACPR report. The red line is the proposed location of new levee protection. (Source: Figure 9-10 from USACE, 2009b)

I initially hoped to use the DIVA global coastal database for many of the following parameters (DINAS-COAST Consortium, 2006). While the DIVA database was useful, the data were too aggregated for the regional-scale analysis of this dissertation. The DIVA database contains many of the parameters below, so it may be possible to perform a global-scale adaptation study using the FRACC model in future work.

#### 4.5.1 Relative sea-level change

The rate of RSLR ( $r_{t,rslr}$  in Equation 3.9) is different for each geographic region covered in this dissertation. All three segments are subsiding, though they are doing so at different rates. Miami-Dade’s shoreline is subsiding the least at 0.6 mm/year. Cape Cod subsides 0.1 mm/year more than Miami-Dade, averaging 0.7 mm/year.

St. Mary Parish is subsiding significantly more per annum, at a rate of 8.6 mm/year. The difference is attributed to the loose alluvial soils deposited by the Atchafalaya and Mississippi rivers, which are slowly compacting. Additionally, some towns are pumping water out from behind levees, lowering water tables and increasing the rate

of subsidence.

The rates of subsidence ( $u$  in Equation 3.9) are based on Table 1 of Nicholls and Leatherman (1996). The rates represent the “Local Change” component of their US coastline study. The Local Change component is the observed sea-level change at the location minus a global sea-level rise component of 1.8 mm/year.

| Parameter          | Community       | Value | Units   | Source                         |
|--------------------|-----------------|-------|---------|--------------------------------|
| Rate of Subsidence | Cape Cod        | 0.7   | mm/year | Nicholls and Leatherman (1996) |
|                    | Miami-Dade      | 0.6   |         |                                |
|                    | St. Mary Parish | 8.6   |         |                                |

**Table 4.3:** Rate of subsidence for Cape Cod, Miami-Dade County, and St. Mary Parish.

#### 4.5.2 Coastal slope

A community’s coastal slope ( $\varphi$  in Equation 3.14), the rate land rises from the water, is assumed to be constant for the whole shoreline. The data comes from the global DIVA database. A community may have several coastal slope values in the database. The coastal slope value used in the FRACC model is the distance-weighted average of the DIVA database values. That is, the slope of the database segments that are contained in the community were weighted by their coastal length and then averaged. The DIVA database provides only one segment that contains St. Mary Parish’s coastline and surrounding areas. The coastal slope value for this DIVA segment was used without modification.

| Parameter     | Community       | Value | Units   | Source                        |
|---------------|-----------------|-------|---------|-------------------------------|
| Coastal slope | Cape Cod        | 0.181 | degrees | DINAS-COAST Consortium (2006) |
|               | Miami-Dade      | 0.052 |         |                               |
|               | St. Mary Parish | 0.062 |         |                               |

**Table 4.4:** The coastal slope for Cape Cod, Miami-Dade County, and St. Mary Parish.

### 4.5.3 Storm distributions

The FRACC model defines both storm frequency and intensity for its communities. These characteristics are outputs of Emanuel’s Coupled Hurricane Intensity Prediction System (CHIPS) model (Section 2.2; Emanuel et al., 2008). Emanuel ran the CHIPS model offline to generate storm parameters for the FRACC model.

Emanuel filtered storm tracks according to the geographic boundaries of the three case study communities, which I provided. The geographic filters were used to isolate the storms that passed near the communities. The hurricane model was run until 3000 storms passed through the area close to each of Cape Cod, St. Mary Parish, and Miami-Dade. For instance, the hurricane model seeded 22,819,000 storms for one of Miami-Dade’s data sets. Many of the storms dissipated quickly. Other storms made landfall but not in the Miami-Dade area. The CHIPS model continued to seed storms until 3000 storms passed near Miami-Dade. The same procedure was used for the other data sets.

The CHIPS model was constrained by the atmospheric and sea-surface temperature outputs of two different global circulation models (GCMs), each estimating the temperatures for two different global climates. The two GCMs were the ECHAM model and the GFDL2 model, chosen because they were used in the IPCC AR4. As part of the AR4 process, GCM results for the SRES scenarios were archived and made available to researchers. Emanuel downloaded these data sets to provide the CHIPS model with environmental conditions for Atlantic Ocean. Both the GFDL and ECHAM data sets provide atmospheric and sea-surface temperatures for the present climate (average climate from 1980–2000) and a future, warmer climate. The warmer climate scenario was the IPCC SRES A1B scenario. In the end, twelve different storm data sets were generated for this research: One data set per community per GCM per climate scenario. In figures, the data sets are label by combining the GCM and the century of a climate (e.g., “GFDL-20” is the GFDL model using the 20th century (1980–2000) climate average).

Emanuel produced an annual frequency and 3000 unique storm events for each of the twelve data sets. I analyzed the 3000 storms to verify they made landfall (see Appendix A). From the storms that made landfall, a distribution of storm intensities used in FRACC was generated. I classified tropical storms into Saffir-Simpson categories (Section 2.2) according to the maximum wind speed over the community. The result is a distribution of storms binned into “Category 1”, “Category 2”, etc.

### Storm arrivals

Storms arrive in the FRACC model according to a Poisson distribution. The Poisson distribution is a function of the mean frequency calculated by Emanuel (Equation 4.1). The output of the Poisson function is either zero or one, with a one indicating the arrival of the storm. The frequency of storm arrivals, provided by the CHIPS model, is shown in Table 4.5.

$$\textit{Storm Arrival} = \textit{POISSON}(k_f) \tag{4.1}$$

where

$$k_f \text{ is the actual } \textit{Annual Storm Frequency} \text{ (1/year)}$$

### Storm intensities

When a storm arrives, the intensity of the storm is randomly chosen from the appropriate distribution. Binning the storms that made landfall into the Saffir-Simpson scale categories generated storm intensity distributions. The distributions vary for a location depending on the GCM and climate scenario. Figure 4-8 illustrates the probabilities for the twelve storm data sets.

The distribution of storms were similar for Miami-Dade and St. Mary Parish, which are both located on the southern coast of the US. By comparison, Cape Cod



| Community         | GCM   | Storm Frequency |              |
|-------------------|-------|-----------------|--------------|
|                   |       | 20th Century    | 22nd Century |
| Cape Cod          | ECHAM | 0.0195          | 0.019        |
|                   | GFDL  | 0.0108          | 0.0343       |
| Miami-Dade County | ECHAM | 0.1087          | 0.0514       |
|                   | GFDL  | 0.0925          | 0.0851       |
| St. Mary Parish   | ECHAM | 0.0402          | 0.0441       |
|                   | GFDL  | 0.0399          | 0.0793       |

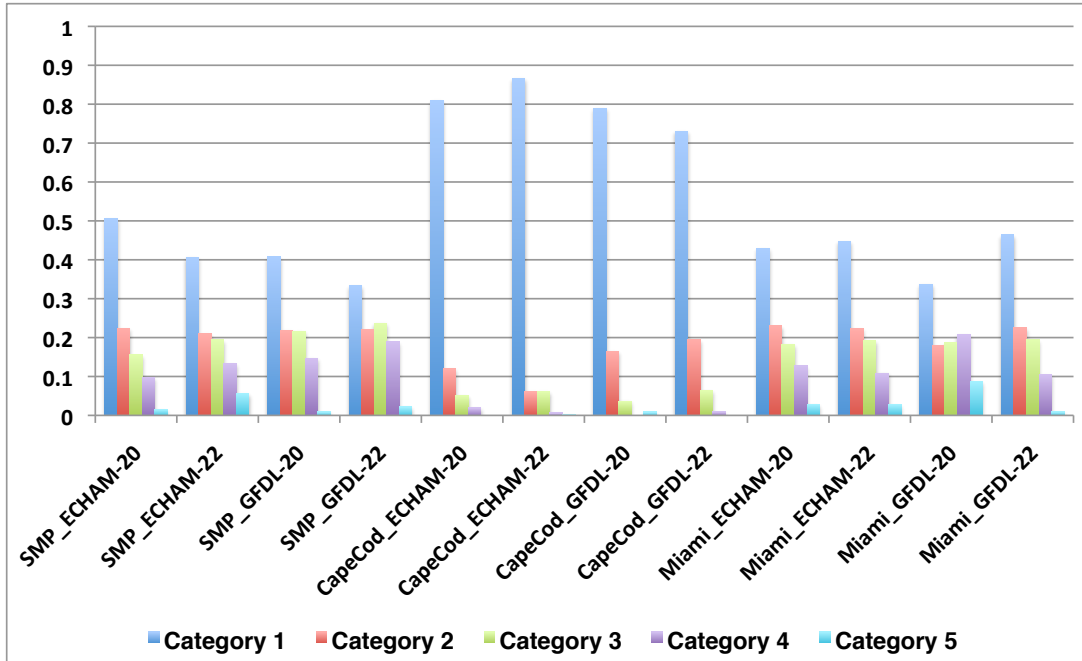
**Table 4.5:** Storm Frequencies by region, GCM, and climate conditions. Data generate by the CHIPS model. The storm frequency for the three communities for the present climate (20th Century; average climate from 1980-2000) and the A1B SRES scenario (22nd Century; average climate from 2180-2200). Measured in storms per year.

had more Category 1 storms and fewer Category 4 and 5 storms—practically none. Cape Cod’s distribution is reasonable because tropical storms lose energy as they travel from the warm equatorial waters up the east coast of the United States. The colder waters near Cape Cod do not supply the storm with sufficient energy and the storm dissipates. The four data sets for Cape Cod are grouped together in Figure 4-9, above the CDFs for the other locations.

The GCMs differed in their results for a given location and climate. Typically, the GFDL model had more intense storms for the current climate. Under a future A1B climate, both models changed their distributions of storms. The ECHAM model typically had more intense storms under a warmer climate while the GFDL model had fewer intense storms. The differences in outcomes are due to differences in ocean and atmospheric assumption of the two models, and beyond the scope of this dissertation.

#### 4.5.4 Economic parameters

The communities have different levels of economic activity. The following are some of the important economic parameters, including population, labor force participation, and land development patterns.



**Figure 4-8:** Probability of a category of storm for Miami-Dade, St. Mary Parish, and Cape Cod, for each of the four GCM parameter sets.

## Population

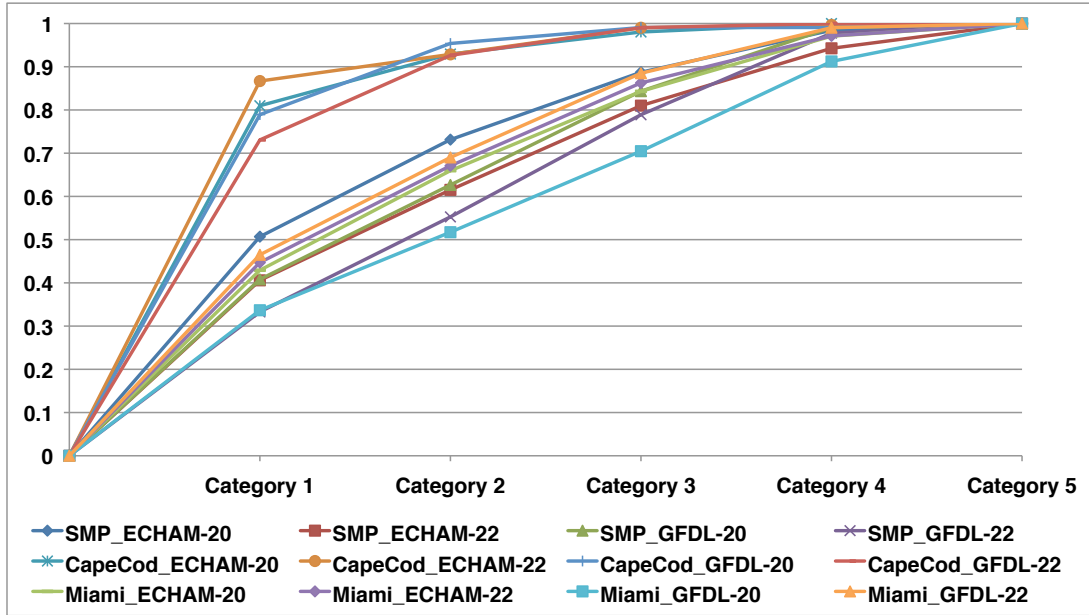
The simulation begins in 2000, so the community population values were initialized to the county populations of the 2000 US Census (Table 4.6). Cape Cod is the sum of Barnstable, Duke and Nantucket counties.

| Parameter          | Community       | Value     | Units  | Source                |
|--------------------|-----------------|-----------|--------|-----------------------|
| Initial population | Cape Cod        | 246,737   | people | US Census data (2000) |
|                    | Miami-Dade      | 2,402,210 |        |                       |
|                    | St. Mary Parish | 53,500    |        |                       |

**Table 4.6:** Initial population values for Cape Cod, Miami-Dade County, and St. Mary Parish.

## Labor force participation

The community's population in part determines the size of the labor force. The other main factor is the labor force participation fraction . The US Census provides two data points that were used to determine labor force participation. First, the US Census Bureau estimates a labor force participation rate for people 18 years or older



**Figure 4-9:** Cumulative density functions of storm intensities for Miami-Dade, St. Mary Parish, and Cape Cod, for each of the four GCM parameter sets.

( $F_{lf}$  in Equation 3.74). Second, the census provides data to estimate the population over 18 ( $F_{wa}$  in Equation 3.74).

| Parameter                        | Community       | Value | Units    | Source                |
|----------------------------------|-----------------|-------|----------|-----------------------|
| Fraction over 18yo Participating | Cape Cod        | 0.739 | fraction | US Census data (2006) |
|                                  | Miami-Dade      | 0.827 |          |                       |
|                                  | St. Mary Parish | 0.733 |          |                       |
| Fraction over 18yo               | Cape Cod        | 0.819 | fraction | US Census data (2000) |
|                                  | Miami-Dade      | 0.761 |          |                       |
|                                  | St. Mary Parish | 0.727 |          |                       |

**Table 4.7:** Labor force determinants for Cape Cod, Miami-Dade County, and St. Mary Parish.

### GDP per capita

The US census provides data regarding the per capita income for the communities. Cape Cod has the highest per capita income and St. Mary Parish has the lowest. Cape Cod's per capita income is the population-weighted average for the three counties. The data are summarized in Table 4.8.

The initial GDP per capita is also used to initialize the marginal cost of labor ( $MC_l$  in Equation 3.84). It is assumed that wages in the community are reflected in per capita GDP values. The assumption can be changed if better data were available.

| Parameter              | Community       | Value  | Units     | Source                |
|------------------------|-----------------|--------|-----------|-----------------------|
| Initial GDP per capita | Cape Cod        | 25,619 | \$/person | US Census data (2000) |
|                        | Miami-Dade      | 18,497 |           |                       |
|                        | St. Mary Parish | 13,399 |           |                       |

**Table 4.8:** Initial GDP per capita values for Cape Cod, Miami-Dade County, and St. Mary Parish.

#### 4.5.5 Land and development parameters

Each community is endowed with an area of land. A fraction of the land contains coastal wetlands, parks, or open space preserves that are assumed to be off-limits to development. Of the fraction of land that is available for development, a portion of it has already been developed at the beginning of the simulation. The parameters to determine the area of land in each of these categories are described below.

##### Total land area

The total area in a community ( $DL_{t_0}$ , Eq. 3.12) is the area of the county as reported by the Census Bureau. The census reports land in square miles, which was then converted to square kilometers (Table 4.9). Cape Cod is the sum of Barnstable, Nantucket and Duke counties.

| Parameter | Community       | Value | Units  | Source                |
|-----------|-----------------|-------|--------|-----------------------|
| Land Area | Cape Cod        | 1417  | sq. km | US Census data (2000) |
|           | Miami-Dade      | 5040  |        |                       |
|           | St. Mary Parish | 1587  |        |                       |

**Table 4.9:** The total land area for Cape Cod, Miami-Dade County, and St. Mary Parish.

## Fraction developable and fraction developed

I conducted interviews with county planning commissions to determine the amount of developable land. Many of the interviewees appeared to have estimates readily available. After soliciting estimates, I confirmed that they were reasonable by comparing the land area using Google Earth.

The fraction of land area developable is the fraction of land that can be built upon during a simulation. Developable land excludes land off-limits to development, such as the fraction of Miami-Dade County that is in Everglades National Park. Land that is suitable for construction but not currently zoned is included. For example, in Miami-Dade the dry land that is outside the urban development boundary currently being used as agricultural land is considered to be developable. The area of developable land is summarized in Table 4.10.

| Parameter                       | Community       | Value | Units    | Source        |
|---------------------------------|-----------------|-------|----------|---------------|
| Fraction Area Developable       | Cape Cod        | 0.67  | fraction | Dray (2009)   |
|                                 | Miami-Dade      | 0.25  |          | McCune (2009) |
|                                 | St. Mary Parish | 0.8   |          | Fink (2009)   |
| Fraction Area Already Developed | Cape Cod        | 0.5   | fraction | Dray (2009)   |
|                                 | Miami-Dade      | 0.6   |          | McCune (2009) |
|                                 | St. Mary Parish | 0.2   |          | Fink (2009)   |

**Table 4.10:** Fraction of land area developable and developed for Cape Cod, Miami-Dade County, and St. Mary Parish.

## Wetland area

The wetland area for each of the communities was backed out from the fraction of developable land. Initially, I tried to use the DIVA database wetland values but these proved infeasible. The spatial resolution and vagueness of the database definition yielded wetland areas that were inconsistent with the total land area in the community.

Instead of using the wetland values in the DIVA database directly, the proportion of wetland biomes from the database were used. The total area of wetlands in the

community is assumed to be the fraction of undevelopable land, based on the fraction above. The area is then allocated into wetland biome types according to the ratio in the DIVA database. The resulting wetland area is consistent with the total area in the community and the biome make-up described in the DIVA database.

The wetland allocation method is reasonable for coastal communities that cannot develop a large portion of their land area because it is wetlands. The assumption is reasonable for Miami-Dade and St. Mary Parish. For the Cape Cod community, a fraction of its undevelopable area is dry land state park and national seashore. The method likely over-estimates the area of wetlands for Cape Cod.

| <b>Parameter</b> | <b>Community</b> | <b>Value</b> | <b>Units</b> | <b>Source</b> |
|------------------|------------------|--------------|--------------|---------------|
| Wetland Area     | Cape Cod         | 283          | sq. km       | Dray (2009)   |
|                  | Miami-Dade       | 3780         |              | McCune (2009) |
|                  | St. Mary Parish  | 320          |              | Fink (2009)   |

**Table 4.11:** The initial wetland area for Cape Cod, Miami-Dade County, and St. Mary Parish.

#### 4.5.6 Insurance and mitigation

Infrastructure mitigation and insurance coverage differ across the three communities. The National Flood Insurance Program (NFIP) is a federal program that provides flood insurance to all three communities. In addition to insurance, the NFIP also provides building guidelines for property constructed in flood zones. The fraction of properties covered by insurance or constructed according to NFIP building guidelines varies by region of country.

##### **Fraction built to NFIP compliance**

The initial fraction of properties of properties built according to the NFIP guidelines depends on the age of the capital stock. The NFIP has been in force since 1971. Properties built before this date are grandfathered into the insurance and emergency aid program.

Determining the fraction of buildings that comply with NFIP (*New Construction NFIP Compliance* in Chapter 3) is difficult. Mathis and Nicholson (2006) were contracted by the NFIP to evaluate the state of the program. They generated a data set by visiting a selection of communities and extrapolating. They only surveyed properties constructed after 1990, so the data set is not of total community compliance. Their data suggests that compliance for recent construction varies by region (Table 4.12).

| Parameter                   | Community       | Value | Units  | Source                      |
|-----------------------------|-----------------|-------|--------|-----------------------------|
| Fraction of NFIP Compliance | Cape Cod        | 0.587 | sq. km | Mathis and Nicholson (2006) |
|                             | Miami-Dade      | 0.608 |        |                             |
|                             | St. Mary Parish | 0.661 |        |                             |

**Table 4.12:** The fraction of post-1990 structure built in compliance with NFIP standards, for Cape Cod, Miami-Dade County, and St. Mary Parish.

To determine the initial fraction of NFIP compliance, US Census data was used to determine the fraction of infrastructure that was newer than 1990 (Table 4.13). The infrastructure constructed after 1990 was assumed to have a compliance rate indicated by Mathis and Nicholson (2006). Pre-1990 infrastructure was assumed to have a lower rate of compliance. No data could be found to bound the parameter. It is assumed that half of the properties pre-1990 comply with NFIP building standards. Hopefully future studies will provide better data.

| Parameter                           | Community       | Value | Units  | Source                  |
|-------------------------------------|-----------------|-------|--------|-------------------------|
| Fraction of Infrastructure Pre-1990 | Cape Cod        | 0.852 | sq. km | US Census Bureau (2000) |
|                                     | Miami-Dade      | 0.848 |        |                         |
|                                     | St. Mary Parish | 0.863 |        |                         |

**Table 4.13:** The fraction of infrastructure built pre-1990 for Cape Cod, Miami-Dade County, and St. Mary Parish.

### Fraction with NFIP Insurance

Along with compliance to NFIP building standards, insurance coverage also varies by community. Dixon et al. (2006) studied the penetration rate of flood insurance

coverage for NFIP participating communities. They found that Florida and Gulf Coast communities had a higher rate of coverage than communities in other regions of the US (Table 4.14). The northeast was particularly low, with only 28 percent of homes carrying a flood insurance policy.

Dixon et al. (2006) identify several reasons for insurance coverage variation. Two reasons that are important to the communities in this dissertation are the occurrence of flooding events and home ownership. Communities that have experienced a recent flooding event have higher insurance coverage. Miami-Dade and St. Mary Parish likely fall into this category. Communities with high rates of unmortgaged homes (i.e., homes paid off in full) have lower insurance penetration, which is important for the Cape Cod region. A federal law requires homeowners with federally backed mortgages (most in the US) to have flood insurance. When a mortgage is paid off, there is no mandatory requirement for flood insurance.

| Parameter                      | Community       | Value | Units  | Source              |
|--------------------------------|-----------------|-------|--------|---------------------|
| Fraction of Insurance Coverage | Cape Cod        | 0.28  |        | Dixon et al. (2006) |
|                                | Miami-Dade      | 0.61  | sq. km |                     |
|                                | St. Mary Parish | 0.61  |        |                     |

**Table 4.14:** The fraction of NFIP insurance penetration for Cape Cod, Miami-Dade County, and St. Mary Parish.



# Chapter 5

## Reference Scenario Results

### 5.1 Introduction

The following chapter details the FRACC model's results for the default set of parameters, or Reference scenario. The Reference scenario serves as a comparison for the sensitivity and policy scenarios presented in Chapters 6 and 7, respectively. After reviewing the default parameter values of the Reference scenario, the reader will walk through a specific simulation of those parameters. The walk-through will illustrate the model's behavior for a single pattern of random storms. Each simulation of the reference parameters could have different results because of the model's stochastic storm component. The final section presents the results of a Monte Carlo analysis of the Reference parameters. For the Monte Carlo analysis, only the arrival and intensity of storms change.

### 5.2 Reference Scenario

The default parameters vary depending on which community is being examined. Each community has unique population characteristics, economic density, and wetland acreage. These parameters have been presented in Chapter 4 and can be found in more detail in Appendix C.

While the community-specific parameters differ, the Reference scenario defines the parameters that remain constant. The FRACC model contains many different “switches” that can be activated and deactivated depending on the assumptions being tested. The switches have been fixed for the Reference scenario.

The important parameters choices include:

- assuming that investors and residents use their own perceived storm frequency when evaluating storm risk
- using random storms, as opposed to a lack of storms or a predefined storm
- using storm frequency and intensity, as defined by Emanuel’s hurricane model using GFDL-20 data sets
- activating land loss
- activating all attractiveness feedbacks
- allowing public adaptation, using the BCA decision rule
- assuming that coastal managers have a 50-year time horizon
- assuming an exogenous quadratic global SLR of 1.5 m by 2100
- allowing public adaptation failure, based on the fragility curve
- assuming that coastal managers protect against a Category 2 storm when building public adaptation structures
- activating insurance payments
- activating government disaster relief
- assuming public protection maintenance budgets are funded at 90 percent

The public adaptation response differs for each community (Chapter 4). For example, Miami-Dade County is only allowed to defend its coastline using beach nourishment. Miami-Dade’s adaptation preference considers the region’s strong tourism industry and dependency on its beaches to support its local economy. Alternative public adaptation measures, such as building a levee, would destroy the value of the beaches and adversely affect Miami-Dade’s economic well-being. On the contrary, St. Mary Parish already has levees and is likely to respond to climatic threats by building

taller levees. Cape Cod is assumed not to respond with large-scale public adaptation options, because of political constraints and cultural values of the area.

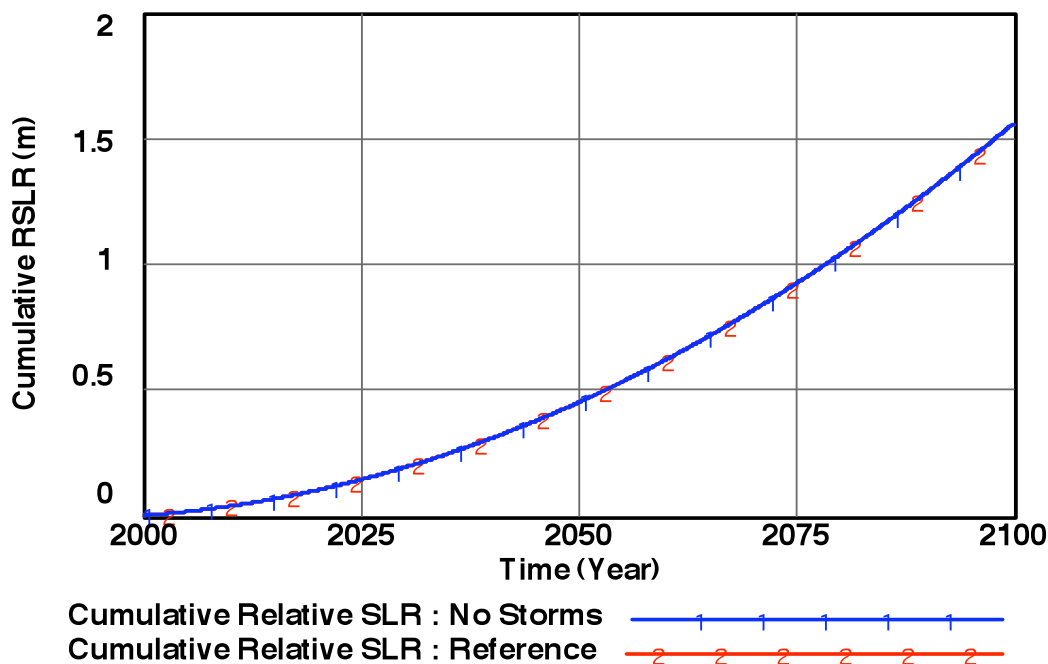
### 5.3 Reference Behavior

I examine the FRACC model’s response to one storm arrival pattern for Miami-Dade County. The following is not intended to be predictive or to describe the mean or average case for the community. Instead, figures will highlight how economic and other key parameters behave over time.

The fundamental interactions of the model described in the next sections are the same for all three locations: Miami-Dade, Cape Cod, and St. Mary Parish. There are differences in the underlying growth projections of each community. The differences arise from variations in land, capital, and population endowments (Chapter 4). The growth projections have implications for coastal adaptation. This section denotes differences between Miami-Dade and the other two communities, which are described in more detail in Section 5.4.

For the following example, the model’s storm and RSLR results are presented first because they drive the remainder of the model components. Next, risk perception and investment are discussed. These parameters are inputs to capital investment, and ultimately gross economic output. Labor is discussed next, including the importance of storm evacuations. Finally, wetlands and other important parameters are discussed.

For comparison, a second “No Storm” scenario is plotted in the figures. In the “No Storm” scenario, all the parameters remain the same as in the Reference scenario, except that storms are deactivated. The scenario allows communities to build coastal protection against RSLR and has the normal economic adjustment mechanisms for jobs, housing, and capital activated. The scenario is plotted for comparison to a world with storm events.



**Figure 5-1:** Relative SLR from 2000–2100 results for the sample simulation of the Reference scenario for Miami-Dade County.

### 5.3.1 Reference SLR and storms

For the Reference scenario, the quadratic 1.5 m global SLR path is used. Local subsidence conditions for Miami-Dade add an additional 0.6 mm/year, for a total of 1.56 m of RSLR by 2100. Figure 5-1 illustrates the path of RSLR through 2100.

In this particular simulation, Miami-Dade experiences nine storms before 2100. The sample pattern was chosen because it reflects the parameters of the GFDL-20 data set, which has a mean of 0.0925 storms per year. The distribution of storm intensities for the nine storms approximates the expected distribution of GFDL-20 (Table 5.2). Storm inter-arrival times vary, with the shortest and longest periods of inactivity being 1.5 and 25 years, respectively (Figure 5-2). The storm size and arrival years are summarized in Table 5.1.

The storm patterns for St. Mary Parish and Cape Cod differ from Miami-Dade’s because of the variations in frequency and intensity parameters (Section 4.5.3). The

| Year   | Storm Category |
|--------|----------------|
| 2018   | 1              |
| 2025   | 5              |
| 2050   | 4              |
| 2070   | 1              |
| 2071.5 | 2              |
| 2075   | 4              |
| 2077   | 1              |
| 2088   | 2              |
| 2093   | 3              |

**Table 5.1:** The sample storm pattern storms, by year and intensity (Miami-Dade).

|              | Miami GFDL-20 | Sample Pattern |
|--------------|---------------|----------------|
| Annual Mean  | 0.0925        | 0.09           |
| # Category 1 | 3.1           | 3              |
| # Category 2 | 1.7           | 2              |
| # Category 3 | 1.7           | 1              |
| # Category 4 | 1.9           | 2              |
| # Category 5 | 0.8           | 1              |

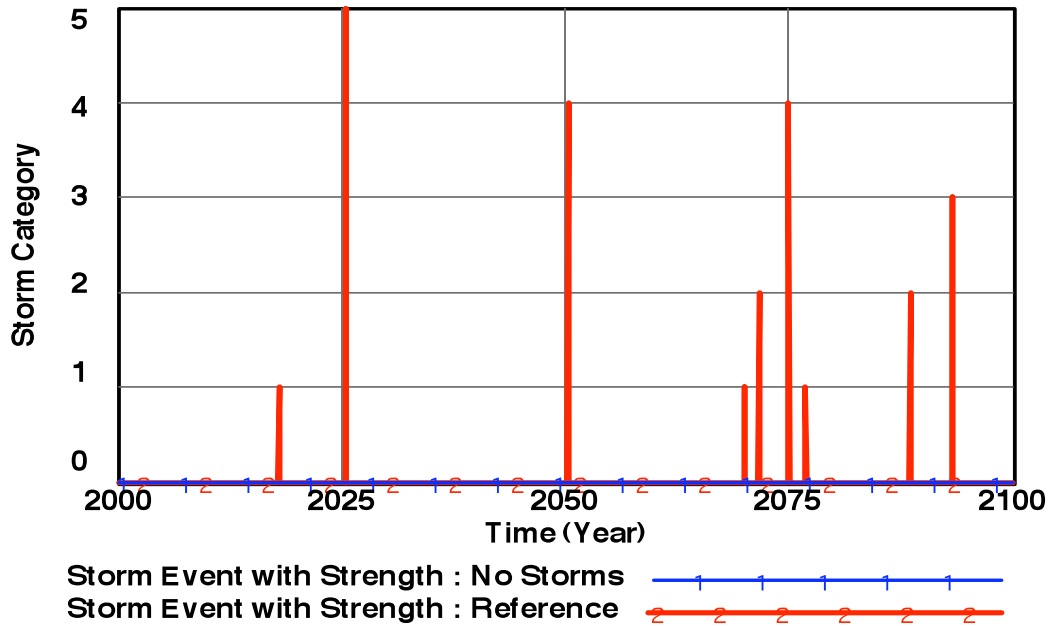
**Table 5.2:** Comparison of the expect number of storm in a century and the sample pattern chosen to illustrate behavior (Miami-Dade).

implications are discussed in Section 5.4.

### 5.3.2 Perception of storms and damage

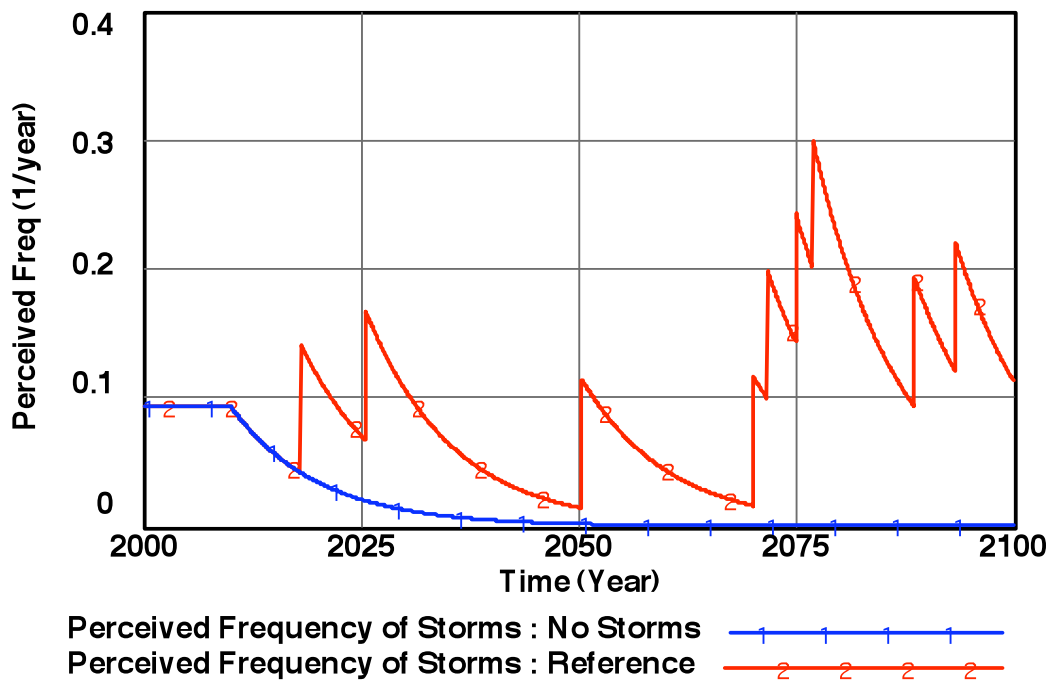
Investors and residents use their own perceived frequency of storms to evaluate the risk of investing in the community. The *Perceived Frequency of Storms* for investors changes based on the arrival of storm events. The parameter in both scenarios is initialized to the actual *Annual Storm Frequency* for Miami-Dade. When a storm strikes, the perceived frequency increases (Figure 5-3). During the periods between storms, the perceived frequency of storms falls as older storms move out of the assessment window. When the next storm arrives, the process repeats.

The *Perceived Frequency of Storms* falls to zero during the No Storms scenario, beginning in 2010. Perceived storm frequency falls from the initial value to zero because there are no storm events.

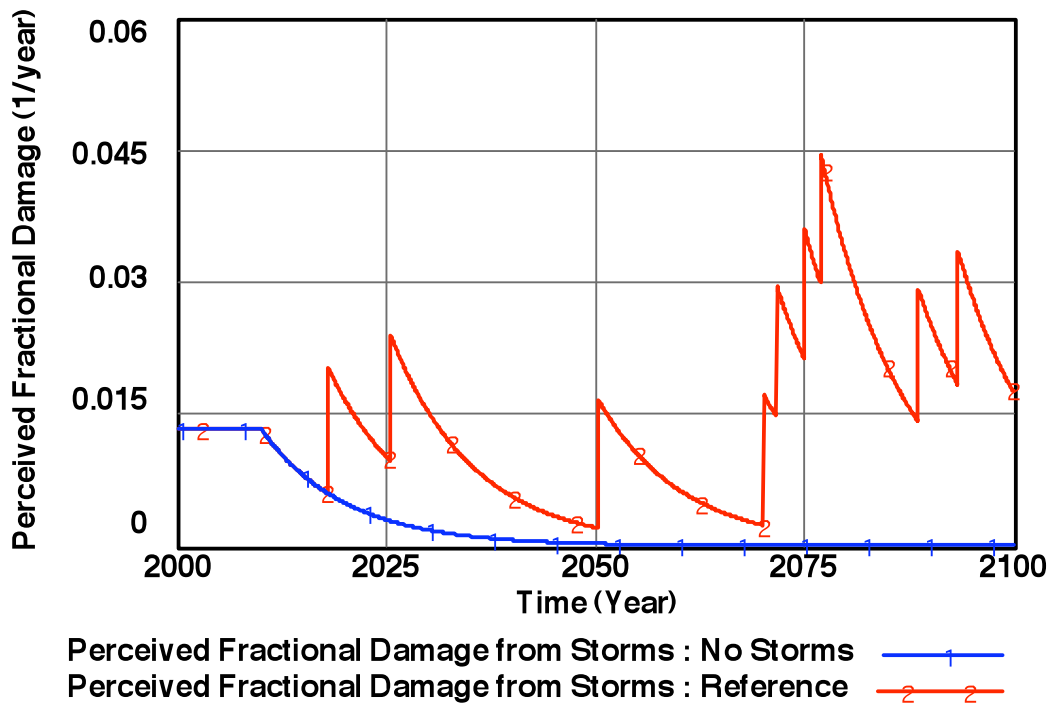


**Figure 5-2:** The storm pattern from 2000–2100 of the sample simulation of the Reference scenario, for Miami-Dade County.

*Perceived Fractional Storm Damage* is a function of *Perceived Frequency of Storms*, so the behavior is similar (Figure 5-4). Investors perceive that storms will cause more damage during the life of an investment when they believe storms will arrive more frequently. For the No Storms scenario, *Perceived Fractional Storm Damage* again falls to zero because, if an investor believes that storms will never arrive, then they also believe that their investments will never be damaged by storms.



**Figure 5-3:** The response of *Perceived Frequency of Storms* from 2000–2100 to a sample storm pattern of the Reference scenario and a No Storm scenario, for Miami-Dade County.



**Figure 5-4:** The behavior of *Perceived Fractional Damage from Storms* from 2000–2100 for a sample simulation of the Reference scenario for Miami-Dade County.



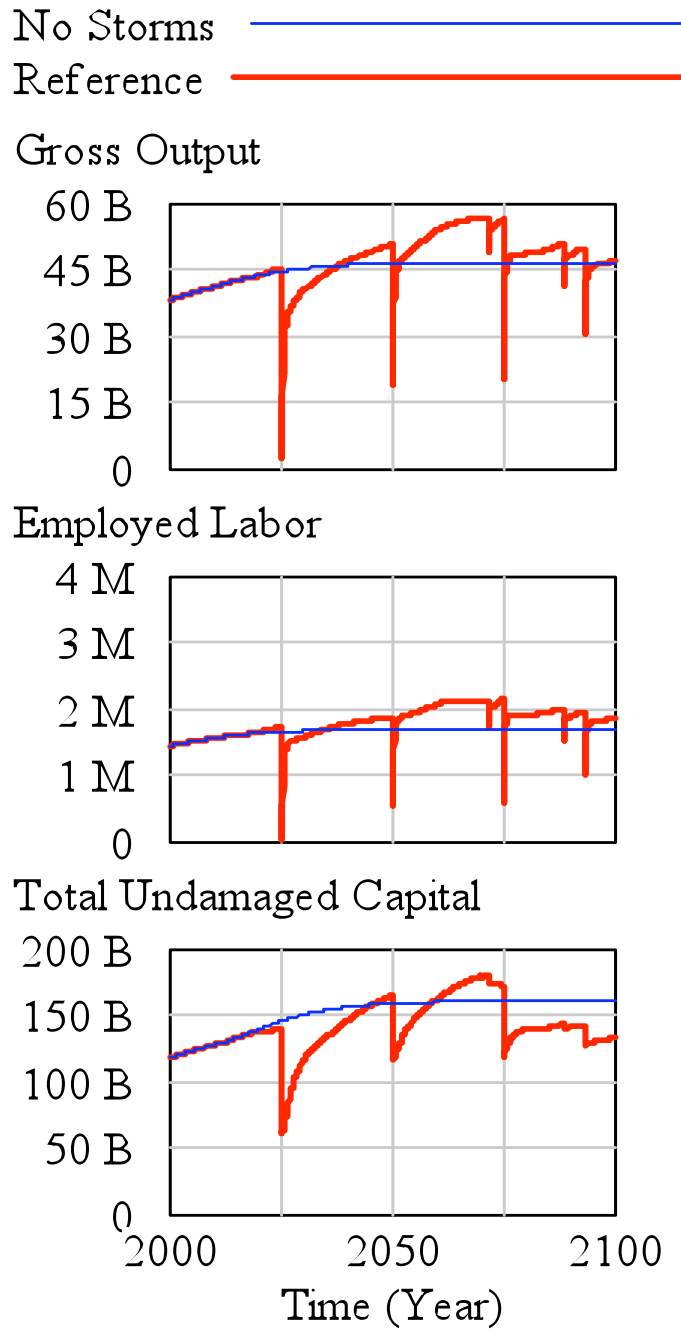
### 5.3.3 Gross economic output

Figure 5-5 depicts the behavior of *Gross Output* and the two factors of production. Economic output declines in the Reference scenario because of damage to capital stock, evacuation of the labor force, and the overall decline of the community.

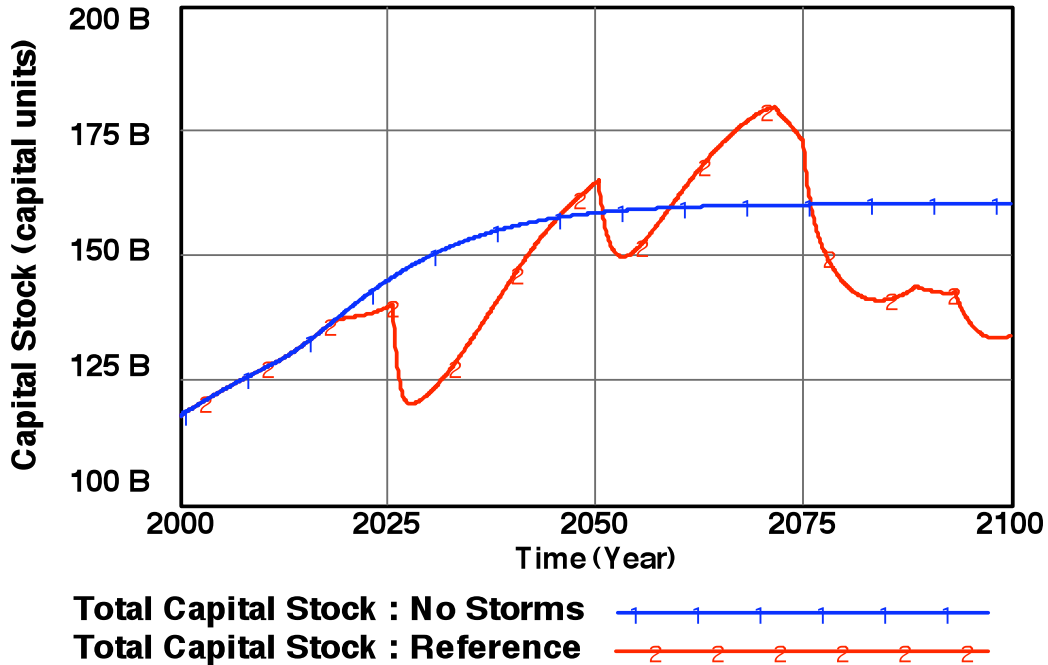
*Gross Output* is both the culmination of model behavior and the driver of further model behavior. The model includes many positive feedbacks that could either grow the economy or cause it to decline. In the No Storms scenario, the community experiences growth in capital, population, economic output, and jobs. These attributes make the community more attractive to people and create more economic demand, which in turn leads to further growth in capital, population and economic output. Growth levels off from 2050–2100 because the community reaches land constraints on capital development, discussed further in the next section.

For the Reference scenario, with the sample storm pattern, the economy rebounds after storms and the positive feedbacks continue long-term economic growth until 2070. The storms after 2070 cause a decline in gross output that is sustained through the end of the simulation. The results are sensitive to the assumptions of insurance and disaster aid. Chapter 7 shows what might happen if communities do not have disaster assistance for reconstruction.

Both capital and labor will be discussed in more detail in the next sections, but Figure 5-5 depicts their high-level effects on gross output. A storm causes the community to evacuate, causing a downward spike in labor and, hence, gross output. Labor recovers relatively quickly as people return but gross output remains low. The sustained decline in economic output is because capital is does not recover as quickly after a storm.



**Figure 5-5:** *Gross Output* and the behavior of labor and capital from 2000–2100 for the sample simulation of the Reference scenario for Miami-Dade County.

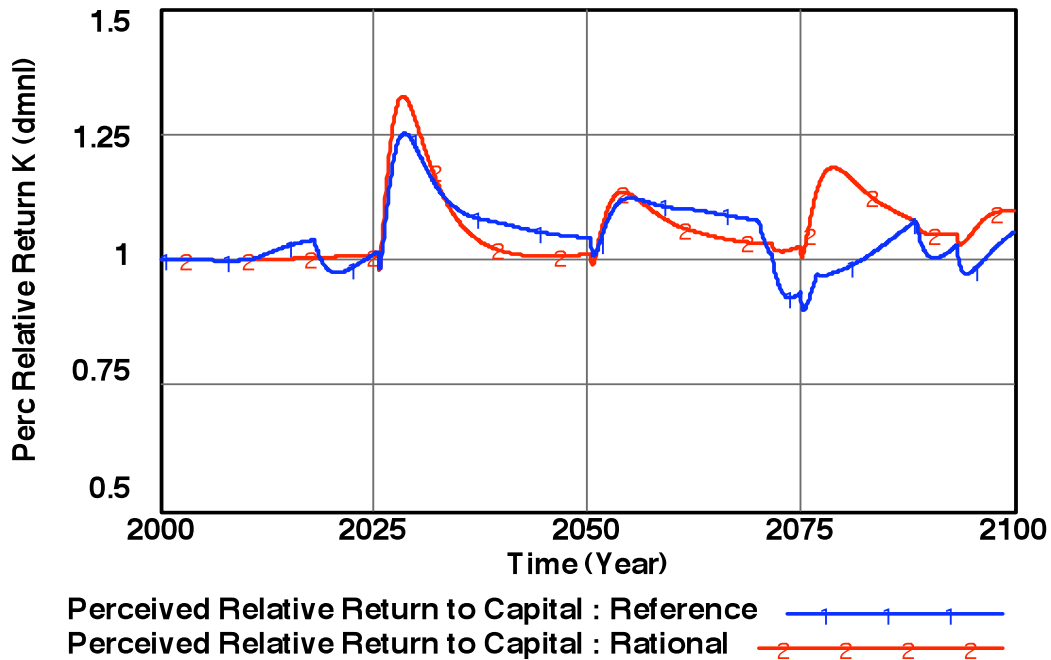


**Figure 5-6:** Behavior of total capital from 2000–2100 for the sample Reference scenario for Miami-Dade County—the sum of all four capital stocks.

### 5.3.4 Capital

The total capital stock in the community drops after storms due to storm damage (Figure 5-6). Examining the first two storms highlights two important capital stock dynamics. The Category 1 storm in 2018 slows economic growth, but growth continues with a positive slope. The Category 5 storm in 2025 decreases the total amount of capital in the community.

Slower economic growth between 2018 and 2025 occurs because, after the Category 1 storm, investors perceive that storm damage will be more likely. Investors use their estimates of *Perceived Fractional Storm Damage* to calculate the *Perceived Relative Return to Capital* (Figure 5-7). The relative return rises slightly before the first storm, corresponding to the fall in the perceived frequency of storms. In 2018, the storm causes the perceived frequency to rise, which increases the perceived fractional damage to capital. The result is a decrease in the perceived relative return to capital from 2018 to 2025. The perceived relative return starts to rise a few years prior to



**Figure 5-7:** The behavior of *Perceived Relative Return to Capital* from 2000–2100 for the sample Reference scenario for Miami-Dade County.

2025, as memories of the first storm begin to fade. The Category 1 storm does not cause significant direct damage to the capital stock (Figure 5-8). Only 0.4 percent of the capital is damaged, entirely from wind. A beach nourishment structure protected the community from flood damage (Section 5.3.6).

In 2025, the Category 5 storm causes significant capital damage (Figure 5-8). Most of damage in the region is caused by wind, so mitigating property against flooding reduces county-wide fractional damage only 2 percent (i.e., fractional damage is 57 percent and 55 percent for unmitigated and mitigated capital, respectively).

Figure 5-9 illustrates the behavior the two unmitigated capital stocks, damaged and undamaged. The mitigated capital stocks behave similarly, but are excluded from the figure for clarity. The damaged stock, which is initialized to zero, has no appreciable rise after the Category 1 storm (2018). At 2025, undamaged capital becomes damaged, causing the appropriate corresponding changes to stock levels—damaged capital rises and undamaged capital falls. Damaged capital begins to return

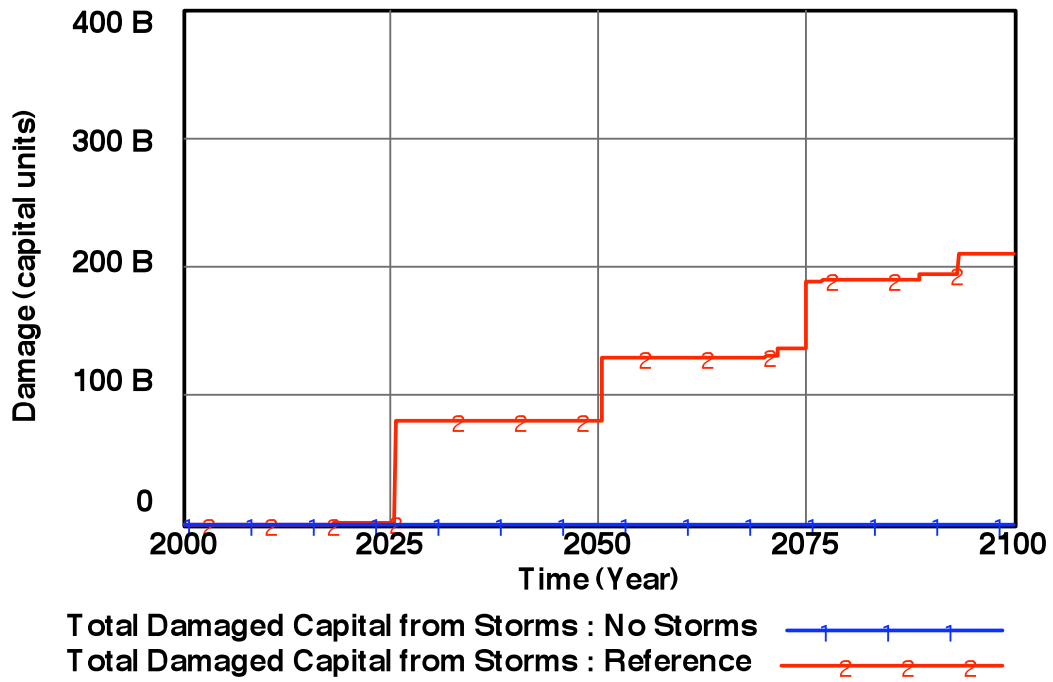


Figure 5-8: The cumulative amount of storm damage to capital from 2000–2100 for the sample Reference scenario for Miami-Dade County.

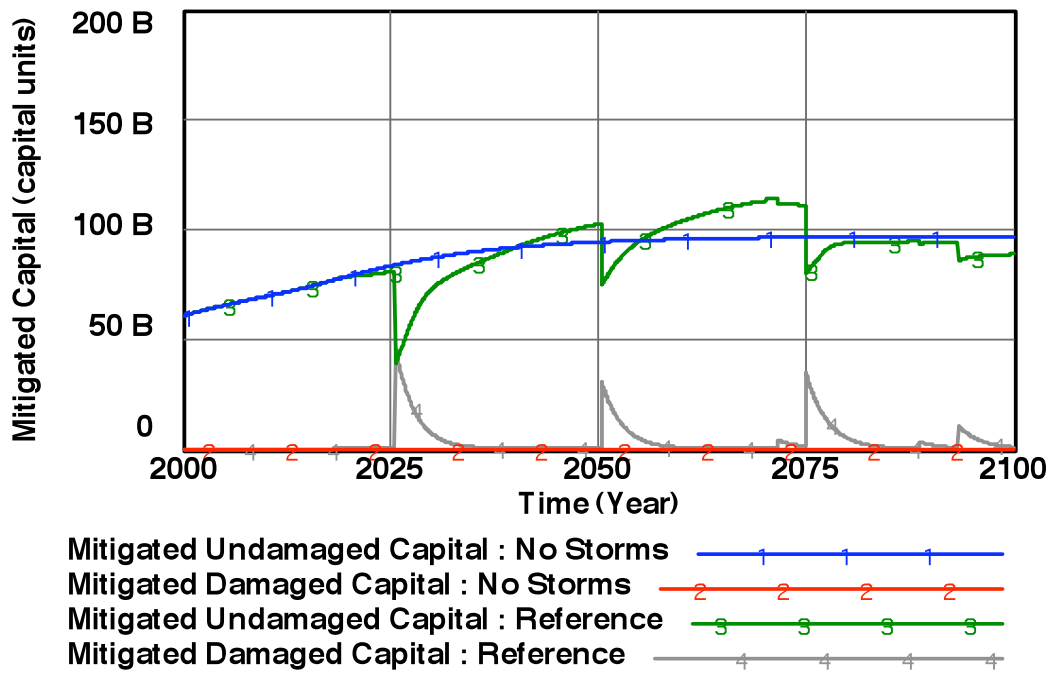
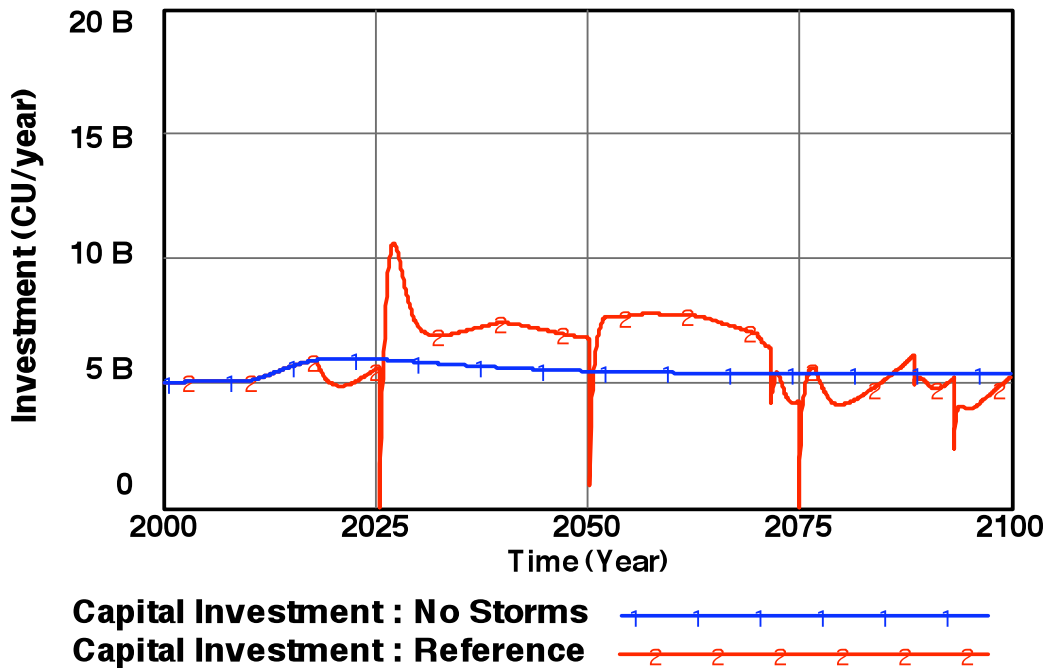


Figure 5-9: Behavior of the mitigated capital stocks from 2000–2100 for the sample Reference scenario for Miami-Dade County.



**Figure 5-10:** Behavior of capital investment from 2000–2100 for the sample Reference scenario for Miami-Dade County.

to zero as capital is rebuilt or discarded. Rebuilt capital increases the undamaged capital stock. For the No Storms scenario, damage does not occur and the lines are smooth.

Along with rebuilding damaged capital, new capital investment increases the undamaged capital stock after the Category 5 storm (Figure 5-10). The increase in capital investment is the net of the capital adjustment effects (Section 3.5.2). From 2026 to 2050, the perceived relative return to capital is positive, even though investors perceive fractional storm damage to be more likely. All else being equal, higher perceived fractional damage should lower investment, as occurred from 2018–2025. Instead, investors also evaluate the marginal productivity of capital when calculating relative return to capital. Marginal productivity increases after the Category 5 storm because capital is relatively more scarce than labor (Figure 5-11). Marginal productivity dominates the fear of damage, increasing the *Perceived Relative Return to Capital*.

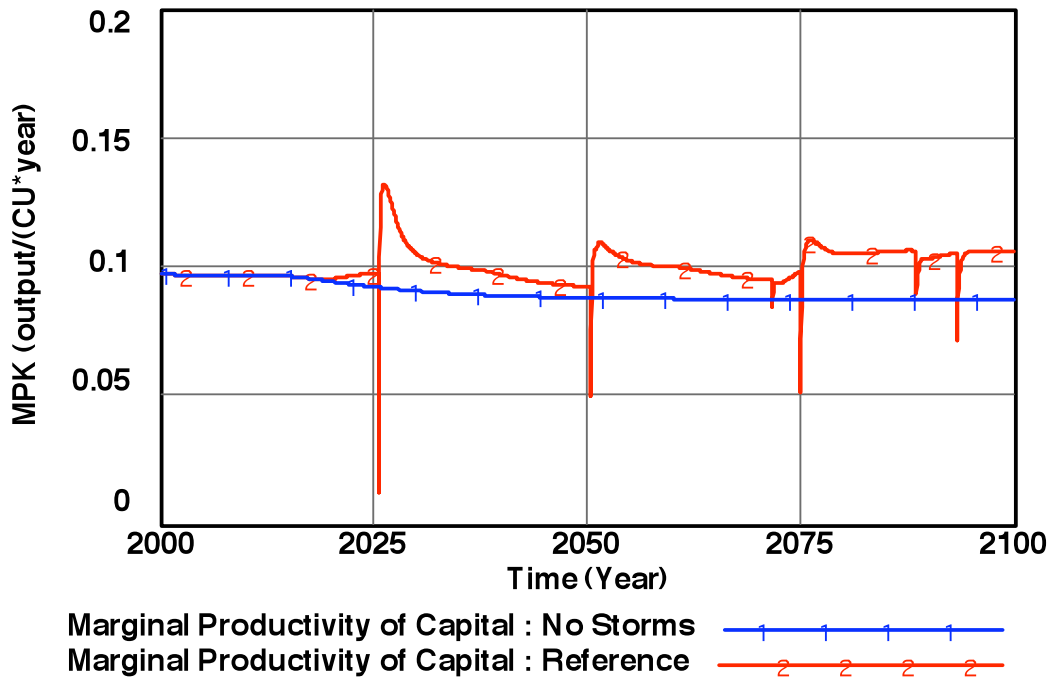


Figure 5-11: Behavior of the marginal productivity of capital from 2000–2100 for the sample Reference scenario for Miami-Dade County.

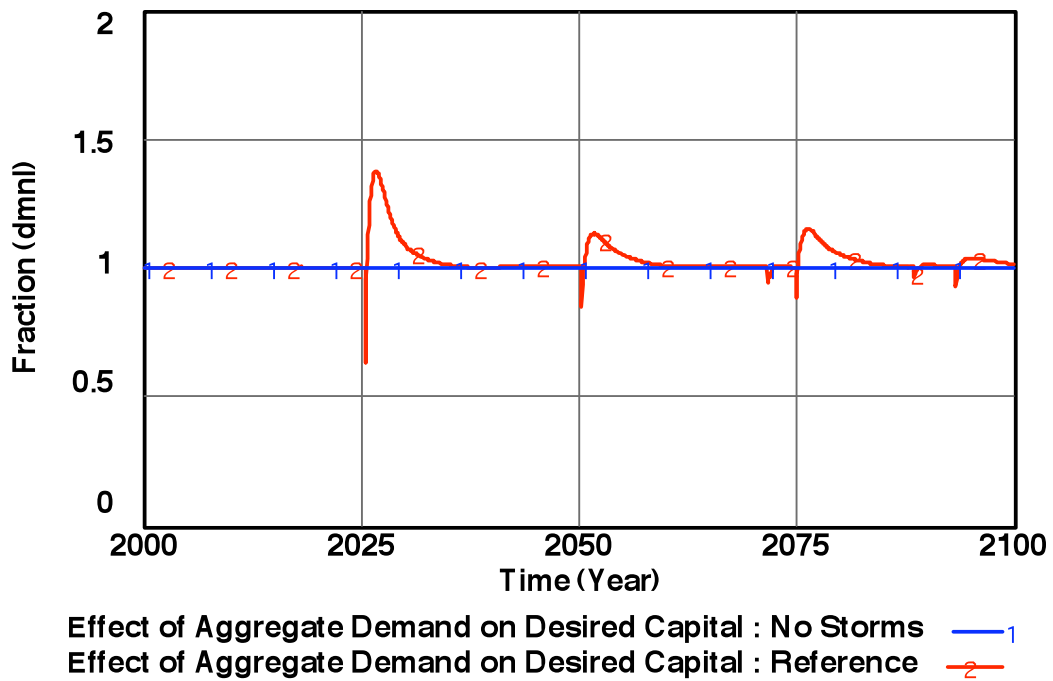
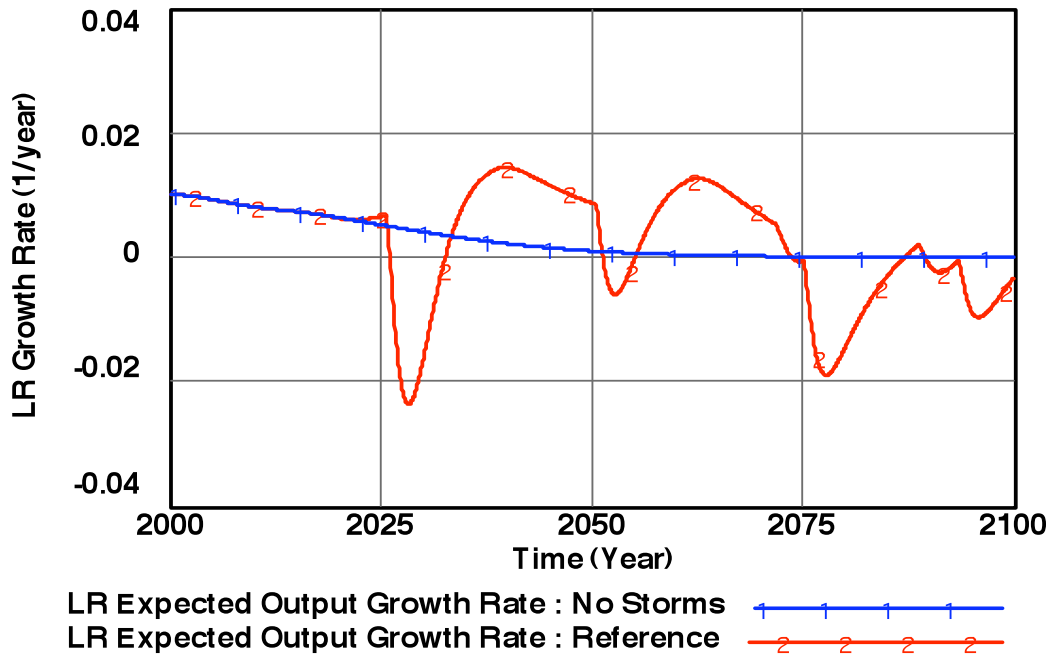


Figure 5-12: Behavior of aggregate demand effect on capital investment from 2000–2100 for the sample Reference scenario for Miami-Dade County.

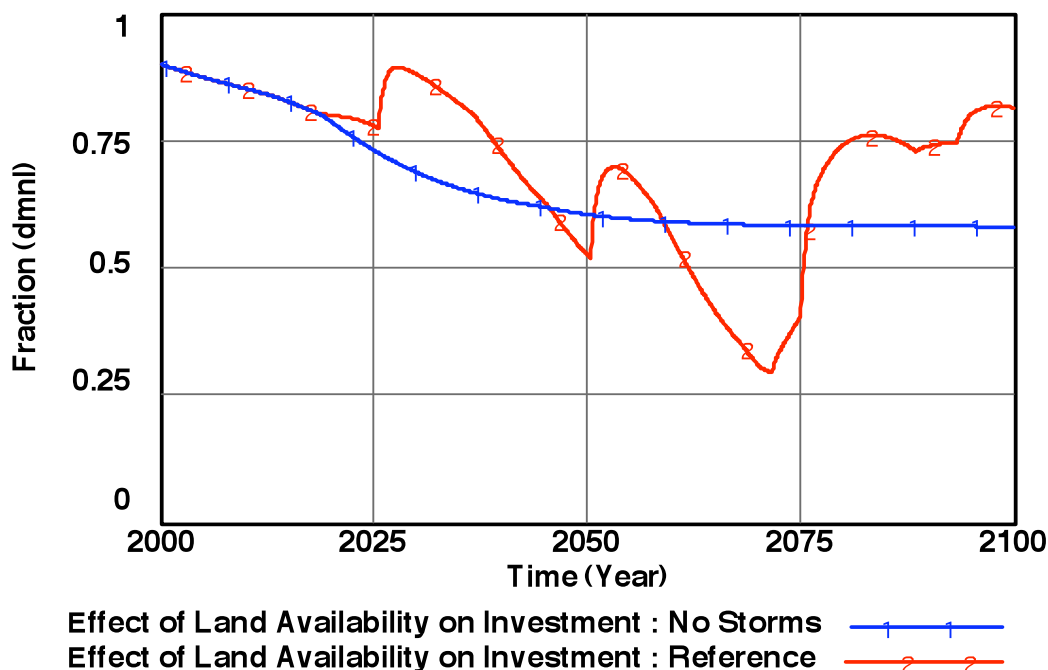


**Figure 5-13:** Behavior of the expected long-run economic growth rate from 2000–2100 for the sample Reference scenario for Miami-Dade County.

Capital investment also increases because of aggregate demand within the region. Immediately after the Category 5 storm, aggregate demand spikes downward because people have evacuated from the area (Figure 5-12). As people return, aggregate demand increases to the pre-storm level. Demand increases above the pre-storm level because of storm relief payments. Money from insurance claims and governmental disaster relief increases the demand for economic output. The increased demand translates to an increase in the desired level of capital, and more capital investment.

The aggregate demand and the relative return effects explain the higher than normal investment rates from 2025–2050. The dip in investment around 2030 is due to the adjustment for long-term economic growth expectations. After the storm, economic output falls. Expectations for long-run economic growth fall because economic output is lower after the storm (Figure 5-13), reducing adjustments for the aggregate demand and relative return feedbacks. Expectations about economic growth rise again, becoming positive around 2033 and remaining positive until the next storm.





**Figure 5-14:** Behavior of land availability on investment from 2000–2100 for the sample Reference scenario for Miami-Dade County.

Notably, capital in the community rises above the No Storms scenario prior to 2050. The behavior is due to two factors: 1) the slowdown of the No Storm community and 2) the investment effects of the storms scenario. First, capital in the No Storms scenario grows from 2000–2050 and then begins to flatten (Figure 5-6). Capital remains relatively flat from 2050–2100 because capital investment becomes increasingly constrained by land availability (Figure 5-14). As land become developed, the amount of capital investment declines. Over time the economy comes into equilibrium with the land constraint.

The land availability effect is weaker (i.e., less constraining) for the Reference scenario because storms decrease capital investment (e.g., 2018–2025) and deplete capital (e.g., Category 5 in 2025), which increases undeveloped land. From 2060–2070, land availability is more constrained than the No Storms scenario because housing is built to support the community’s population, which is discussed in the next section.

In addition to increased land availability, capital increases above the No Storms scenario because of the capital investment adjustment mechanisms. Perceived relative return to capital, the effect of aggregate demand on capital, and long-run growth expectations all remain above the No Storms scenario prior to 2050. In particular, the expectations for long-run growth remain elevated from 2035–2050 (Figure 5-13), which increases capital investment. The lag of expectations about long-run growth keeps capital investment high, exceeding the equilibrium level of development of the No Storms scenario. In general, the Reference scenario does not exceed the No Storms scenario for every community, which is discussed further in Section 5.4.

The community's response to the 2050 Category 4 storm is similar to the 2025 storm. The system reacts differently for the cluster of storms occurring between 2070 and 2077—four storms of varying intensity arriving in less than a decade. The rapid succession of storms increases the perceived frequency of storms, increasing the perceived fractional damage, and decreasing the relative return to capital. The relative return effect dominates the other capital adjustment mechanisms for the first two weaker storms (Category 1 in 2070 and Category 2 in 2071). In 2075 a Category 4 storm arrives, causing a large amount of damage. The decrease in undamaged capital increases the marginal productivity of capital, which increases the perceived relative return to capital. The long-run growth adjustment is negative after the Category 4 storm, decreasing the capital investment for the remainder to the century.

The capital investment adjustments compounded with the storm damage cause a decrease in capital in the community. From 2070–2075 capital falls because fear depresses capital investment. In 2075, total capital falls because of storm damage, and continues to fall because the expected long-run economic growth rate is negative. As capital begins to recover, the final two storms arrive, driving total capital lower still.

The housing market adjustment mechanism behaves in a similar manner to the capital adjustments, due to the assumption that storms damage both capital and

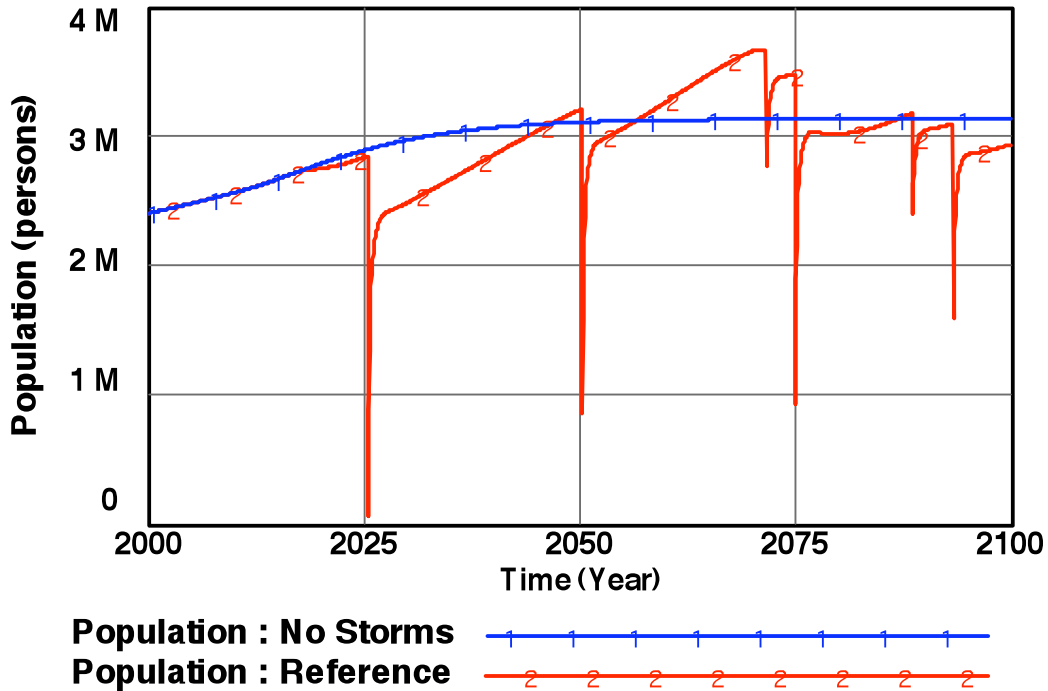
housing equally.

Overall, for the Reference scenario, the magnitude and speed of capital recovery after a storm depends on the ability of the community to pay for reconstruction. Recovery is sensitive to the assumptions regarding insurance and governmental disaster relief, which increase the aggregate demand in the community, kick-starting the economic growth cycle. Insurance and disaster relief are policy options that can be explored in the model (see Chapter 7).

### **5.3.5 Population and labor**

As a result of the economy reaching equilibrium, Miami-Dade's population grows and then levels off when no storms strike the community (Figure 5-15). Growth is strongest from 2000–2050, because births are greater than deaths, and immigration is greater than emigration (Figure 5-16). Births and deaths are proportional to the size of the community, so they level off as the total population levels off. Migration rates depend on the attractiveness of the community (Figure 5-17). The three factors of attractiveness are housing occupancy, storm risk, and job availability (Figure 5-18), as described in Section 3.7.3. In the first part of the simulation, the decrease in perceived storm risk increases community attractiveness. The storm risk effect is overwhelmed by the job and occupancy effects for starting in 2025, as economic growth begins to slow. The result is that community attractiveness falls below one, meaning people are more likely to live in other communities. Job availability and storm risk are the strongest two effects and counterbalance one another, leveling community attractiveness, which in turn levels the flows of immigration and emigration.

In the Reference scenario with storms, the population grows through 2070 but dips during evacuations (Figure 5-15). Immediately after a storm, community attractiveness changes (Figures 5-17 and 5-18). When a storm strikes, housing is damaged in a similar manner to capital, as described above. The decrease in available housing creates a housing deficit, which decreases community attractiveness. At the same



**Figure 5-15:** Behavior of population from 2000–2100 for the sample Reference scenario for Miami-Dade County.

time, the decrease in population decreases the aggregate internal demand for economic production, putting downward pressure on the job market, which decreases the number of jobs in the community. The decrease in employment opportunities makes the community even less attractive. Also, when a storm strikes, residents perceive the community to be riskier than other communities, so they would prefer to live elsewhere, reflected in the storm risk effect.

These downward pressures on community attractiveness are counteracted by the reconstruction of housing and other infrastructure. Similar the capital reconstruction process, insurance payments and government disaster relief increase aggregate demand in the community. The increased demand for output increases the number of jobs in the community and increases housing construction. The improvements in employment and housing, along with the gradual drop in perceived risk of storms, makes the community more attractive. Community attractiveness remains above one between storms, allowing population to grow to levels higher than the No Storm

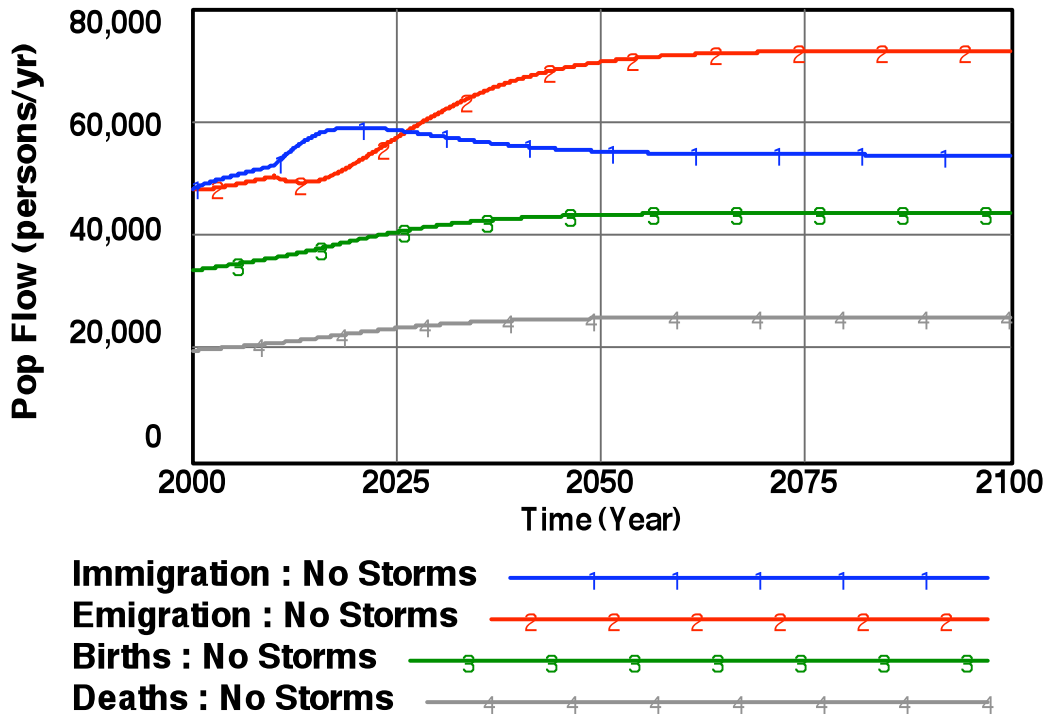
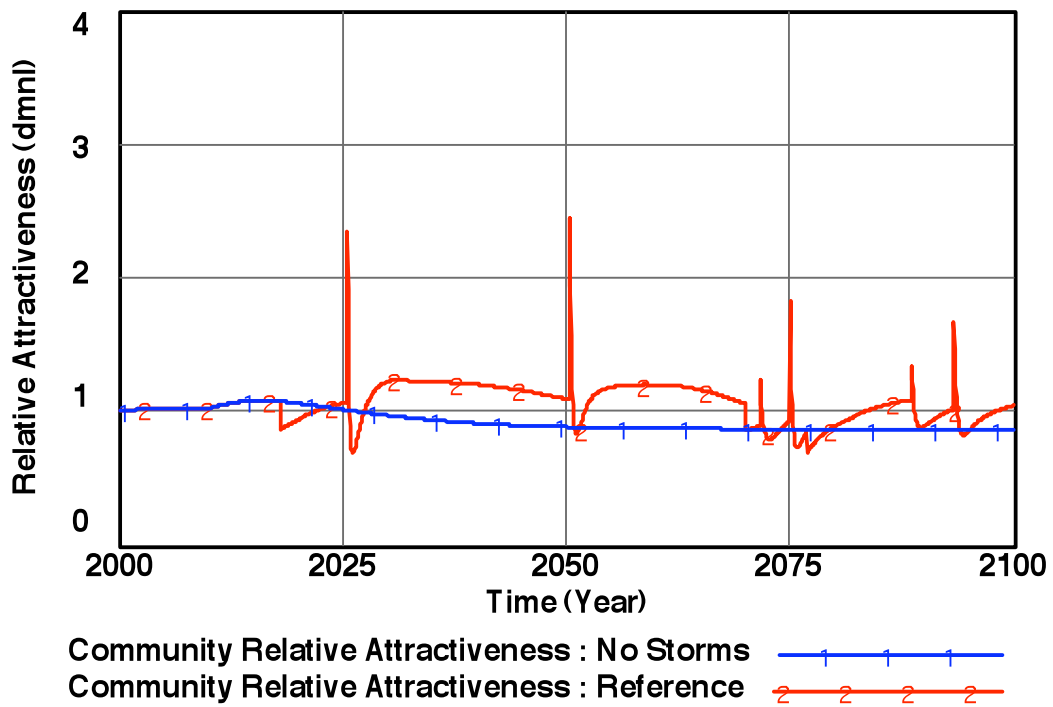


Figure 5-16: Behavior of immigration, emigration, births, and deaths from 2000–2100 for the No Storms scenario.

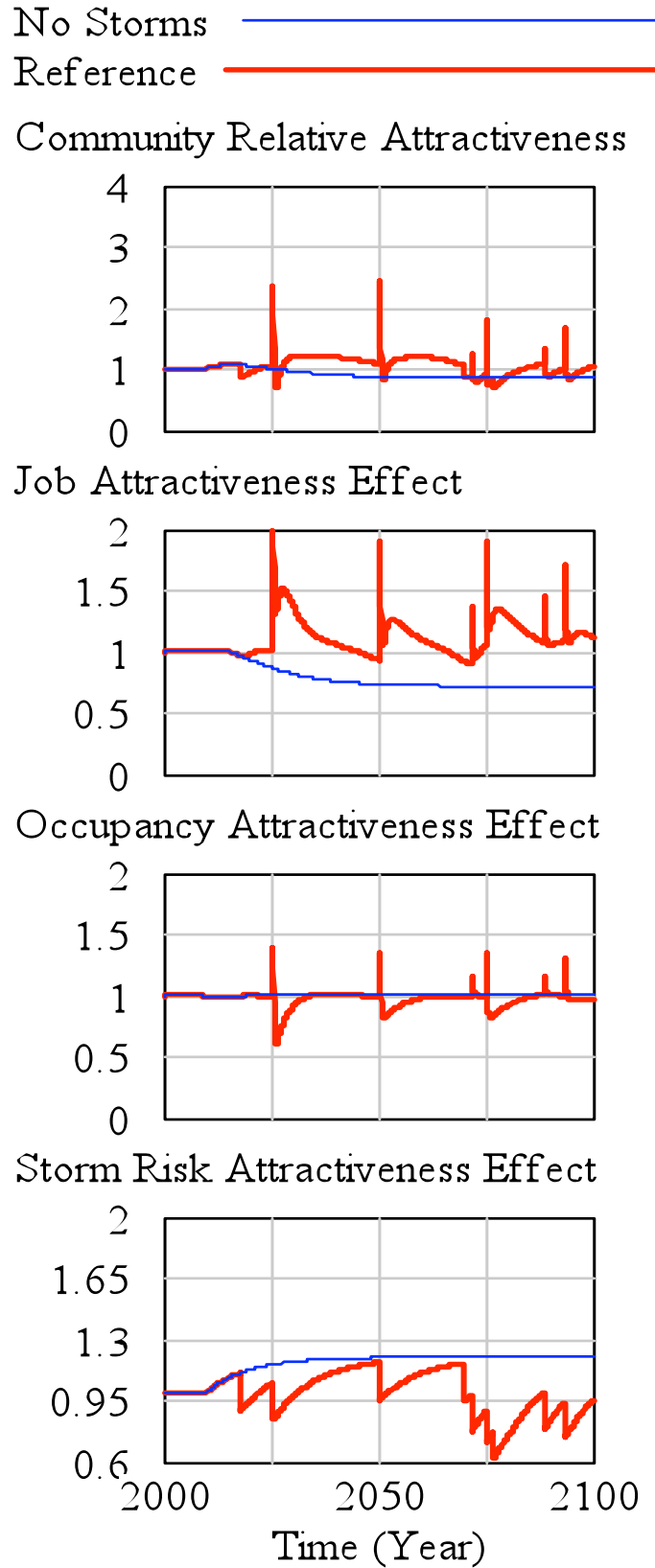
scenario.

The portion of the community that evacuates during a storm depends on the storm category. The first storm, Category 1, does not cause an evacuation while the Category 5 storm causes most of the community to evacuate (Figure 5-19).

The evacuations cause a temporary decrease in the population as well as a corresponding decrease in the *Labor Force* (Figure 5-20). At different times during the simulation, the *Employed Labor* is constrained by the size of the *Labor Force* (e.g., immediately after a storm) or the number of *Jobs* (e.g., approximately tens years after a storm).



**Figure 5-17:** Behavior of Community Attractiveness from 2000–2100 for the sample Reference scenario for Miami-Dade County.



**Figure 5-18:** Behavior of the three community attractiveness effects from 2000–2100 for the sample Reference scenario for Miami-Dade County.

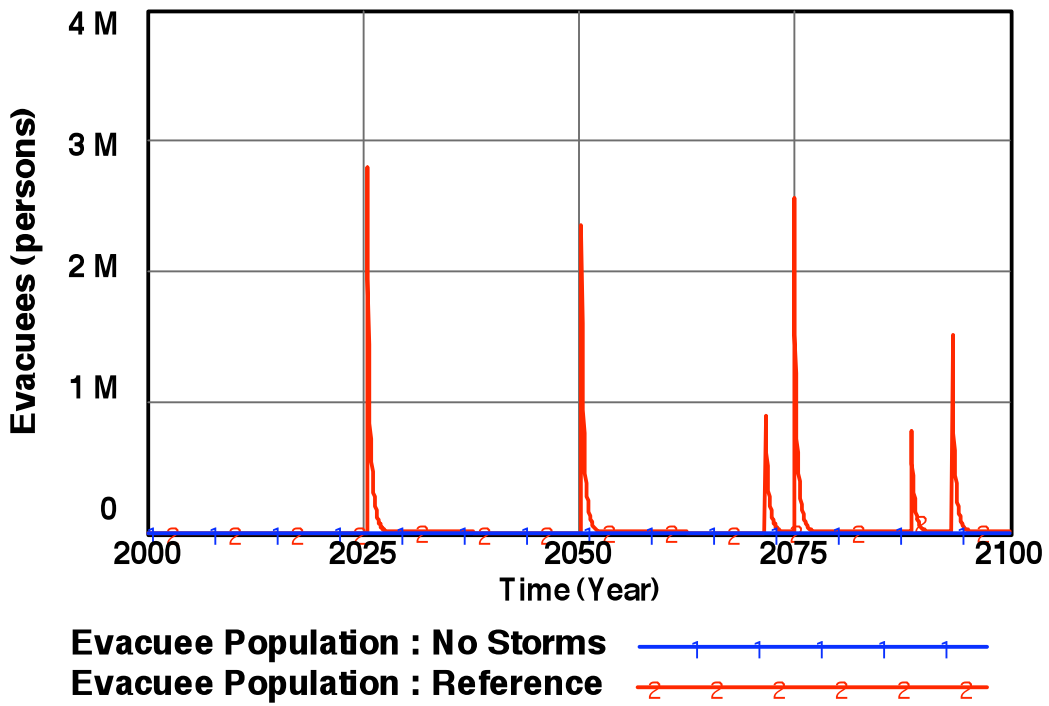


Figure 5-19: The evacuees because of storms from 2000–2100 for the sample Reference scenario for Miami-Dade County.

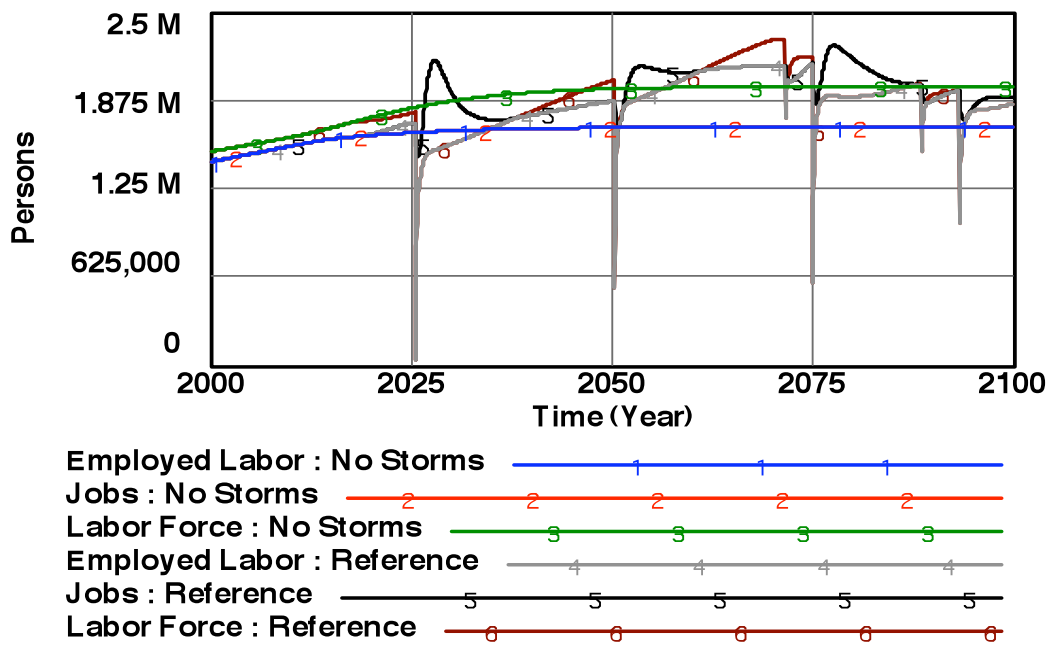


Figure 5-20: The interaction between *Labor Force*, *Jobs*, and *Employed Labor* from 2000–2100 for the sample Reference and No Storm scenarios for Miami-Dade County.



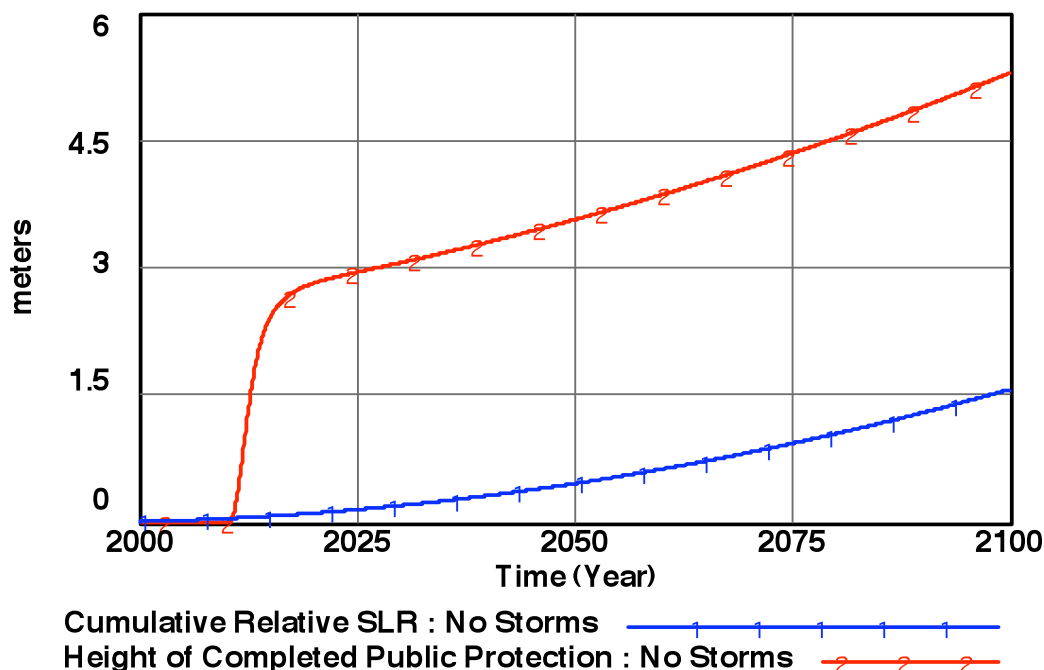
### 5.3.6 Adaptation responses

The community responds to the threat of storms through several different mechanisms. The coastal managers recommend using beach nourishment to protect the large amount of coastal infrastructure. Additionally, the National Flood Insurance Program (NFIP) promotes private adaptation through building standards that decrease flood exposure, along with insurance to reduce financial risk to the owner.

For the sample simulation, the coastal manager recommends starting a beach nourishment project in 2010, after evaluating the cost of the project relative to the infrastructure and the damage nourishment would likely prevent. For both the No Storms and the Reference scenarios, nourishment provides protection against a Category 2 storm. Coastal managers recommend building the dune to be approximately 2.8 m tall initially, given the global SLR trends and local subsidence rates (Figure 5-21). They continually evaluate the height of the protection and recommend upgrading it to compensate for future SLR. Continuous evaluation is not very likely, but follows the “brick-by-brick” assumptions of Fankhauser (1995). The dune height protects against RSLR and storm surge, so always reflects the cumulative RSLR.

The beach nourishment protection prevents flooding for six of the nine storms (Figure 5-22). When the total water height (i.e., RSLR plus storm surge) exceeds the height of the protection, the protection is more likely to breach. For the sample scenario, a breach occurs each time the protection height is exceeded. The Category 3 storm in 2093 does not overtop the protection and cause a breach, even though the protection is designed for a Category 2 storm. The protection is built such that it can withstand the Category 2 design storm at the end of the coastal managers’ planning horizon (50 years). Fifty years of RSLR plus the surge of a Category 2 storm is less than the RSLR in 2093 plus the surge of the Category 3 storm.

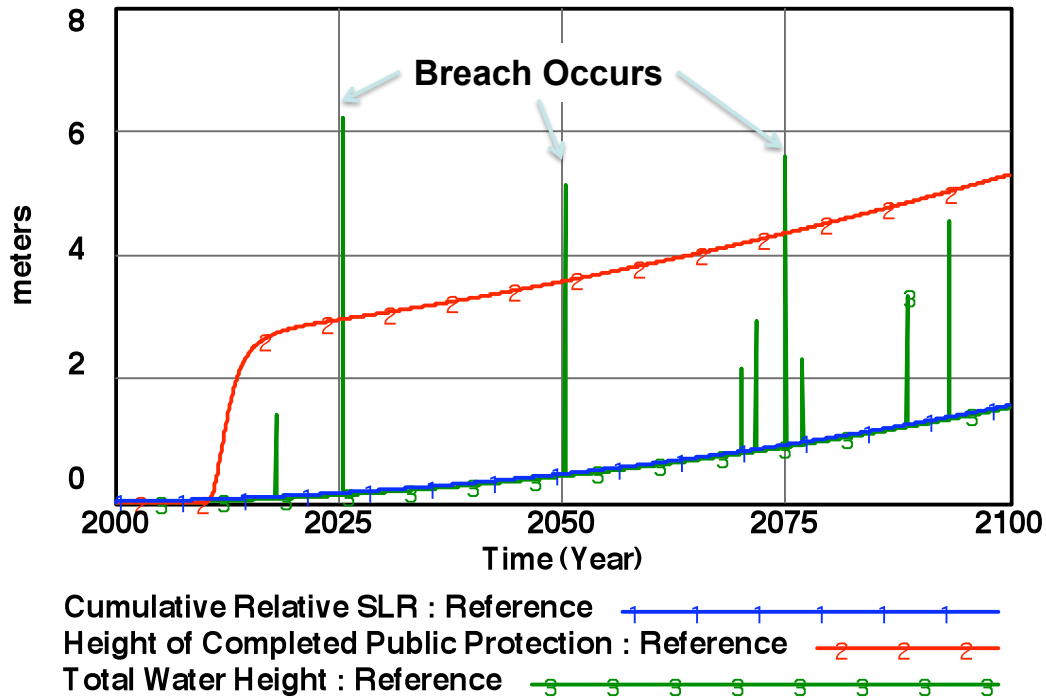
Building standards help reduce the total amount of flood damage in the community. The fraction of properties mitigated is initialized to the fraction of properties that



**Figure 5-21:** The path of RSLR and the height of the protective dune from 2000–2100 for the sample Reference scenario for Miami-Dade County.

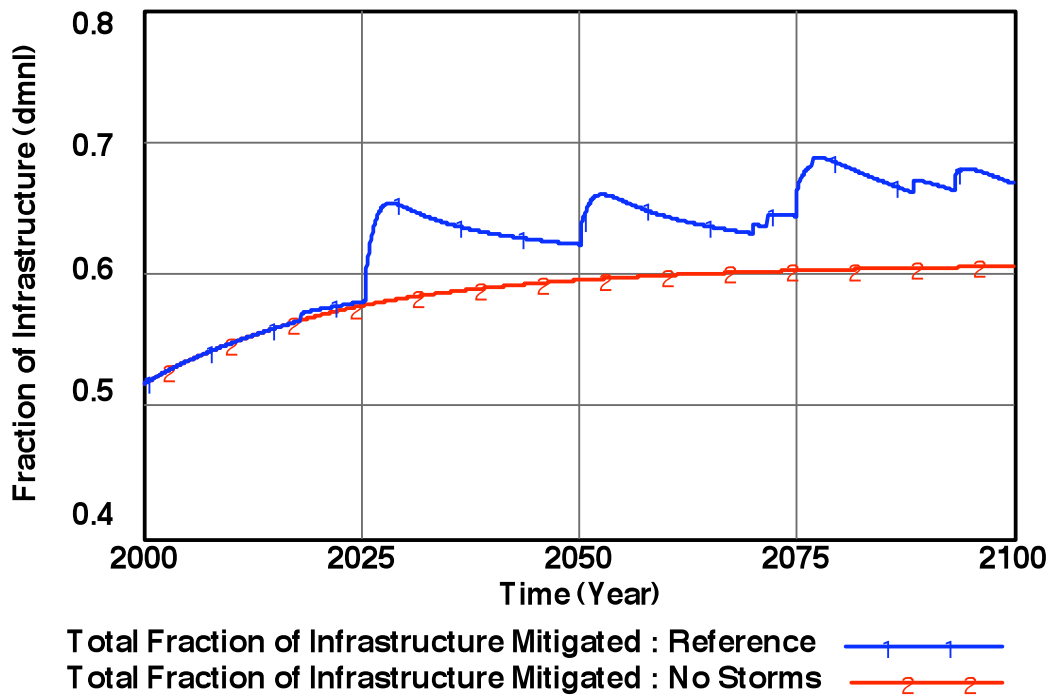
are built to the NFIP guidelines, weighted by the age of the building (Section 3.10.2). For the No Storm scenario, the fraction of mitigated properties rises slowly over time as older unmitigated properties are replaced by newer mitigated properties. Over the long run, the fraction equals the exogenous fraction of compliance for new construction, which is a parameter for the stringency of building code enforcement. The same long-run trend underlies the Reference scenario. Additionally though, after a storm, the fraction mitigated increases (Figure 5-23) because damaged property is retrofit (Section 3.10.2) and unmitigated property is damaged more extensively than mitigated property (by water; minor effect). The fraction of mitigated properties falls after the storm, reflecting the real-world habituation to storm risk and city inspectors relaxing their enforcement. The cycle repeats for future storms, with the spike in compliance roughly proportional to the size of the storm.

Insurance coverage is initialized at 61 percent for Miami-Dade County. After a storm, compliance increases as FEMA and the NFIP impose group policy purchasing

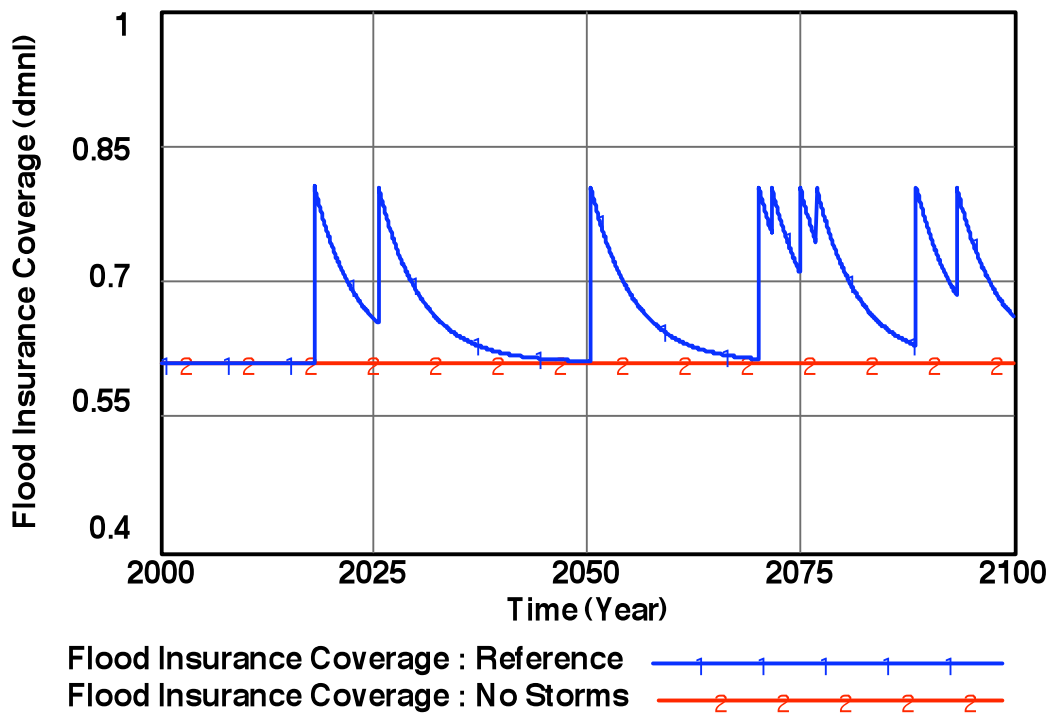


**Figure 5-22:** The path of RSLR and the height of the protective dune, with total water height during storms, from 2000–2100 for the sample Reference scenario for Miami-Dade County.

to qualify for disaster relief, and residents seek coverage on their own. Coverage falls as people choose not to renew their policies and become habituated to the risk (Figure 5-24). If there is not another storm event, insurance returns to the base level of coverage. The cycle repeats for subsequent storms.



**Figure 5-23:** The fraction of mitigated infrastructure for the sample Reference scenario from 2000–2100 for Miami-Dade County.



**Figure 5-24:** The fraction of flood insurance coverage from 2000–2100 for the sample Reference scenario for Miami-Dade County.

## 5.4 Community Comparison

The previous section described the FRACC model’s behavior for a single simulation of the Miami-Dade region. The following section describes a similar “typical” simulation for Cape Cod and St. Mary Parish, allowing for a comparison among different community types.

The FRACC model simulates the economic and adaptation impacts for Cape Cod and St. Mary Parish in a similar manner to Miami-Dade. The structure of the model is unchanged, so mechanisms of risk perception, capital adjustment and community attractiveness provide a dynamic response to storm events and RSLR.

The initial parameters of the communities differ, as described in Chapter 4 and detailed in Appendix C. While parameters such as initial GDP per capita and initial population are important in determining initial total economic output (i.e., the scale of economic activity), storm characteristics and land development shape the long-run path of growth.

Storm-related parameters differentiate community response. Table 5.3 summarizes the differences of storm parameters among the communities. Miami-Dade has the highest number of storms (9), while Cape Cod and St. Mary Parish have fewer (1 and 4, respectively). The intensity of the storms also differ, highlighted by Cape Cod whose single storm is the least powerful—Cape Cod’s most likely event is a Category 1 storm. Both Miami-Dade and St. Mary Parish have more intense storm activity. Cape Cod has few tropical storm events, but also has nor’easters that are not simulated by FRACC.

Storm events drive the model similarly for all three communities. When a storm occurs, the perception of storm risk rises for boundedly rational investors. The rise in perceived risk then effects investment and community attractiveness. The exact effect differs because the number and timing of storms differ, but the relationships

|                | <b>Miami-Dade</b> | <b>Cape Cod</b> | <b>St. Mary Parish</b> |
|----------------|-------------------|-----------------|------------------------|
| Actual Freq    | 0.0925            | 0.0108          | 0.0399                 |
| Simulated Freq | 0.09              | 0.01            | 0.04                   |
| # Category 1   | 3                 | 1               | 2                      |
| # Category 2   | 2                 | 0               | 1                      |
| # Category 3   | 1                 | 0               | 0                      |
| # Category 4   | 2                 | 0               | 1                      |
| # Category 5   | 1                 | 0               | 0                      |

**Table 5.3:** Table comparing the expect number of storm in a century and the pattern chosen for illustrating behavior for all three communities.

among model parameters are the same. The number and timing of storms in part determines the magnitude of parameters, like perceived risk. As in the Miami-Dade example, several storms arriving close together can increase perceived frequency to higher than normal levels. Communities with low storm frequency are less likely to have clusters of storms, and the related model dynamics.

Land endowments have important implications for the long-run growth of the community. Figures 5-25 through 5-27 show that growth paths for each of the communities varies even without perturbations from storms. Miami-Dade, which starts the simulation with relatively dense development, grows for 25 years and then begins to flatten. The community reaches equilibrium with its land constraints relatively early in the simulation.

By contrast, Cape Cod and St. Mary Parish each grow through 2070 because they initially have a lower fraction of land already developed (Figure 5-28). With less land developed, Cape Cod and St. Mary Parish are less restricted when building new infrastructure. In the FRACC model, a decrease in land availability lowers infrastructure investment (Section 3.2.3). St. Mary Parish only faces land restrictions after 2075 (Figure 5-29), which allows the community to grow through 2100, and likely reaching equilibrium with the land constrain after 2100. Cape Cod development is constrained by available land in 2000, but less than Miami-Dade. As a result, Cape Cod can sustain a higher rate of economic growth for a longer time than Miami-Dade.

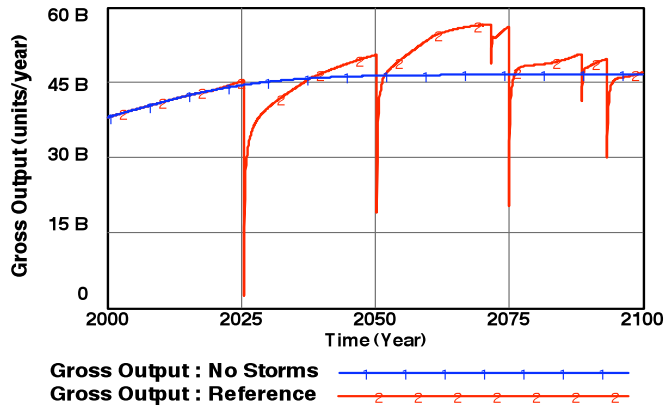


Figure 5-25: Behavior of gross economic output from 2000–2100 for Miami-Dade.

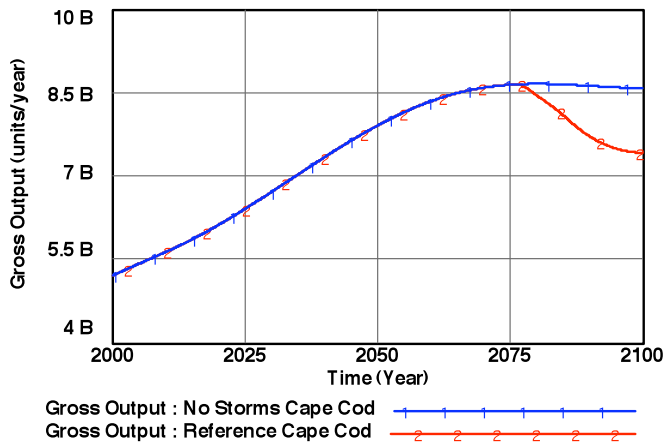


Figure 5-26: Behavior of gross economic output from 2000–2100 for Cape Cod.

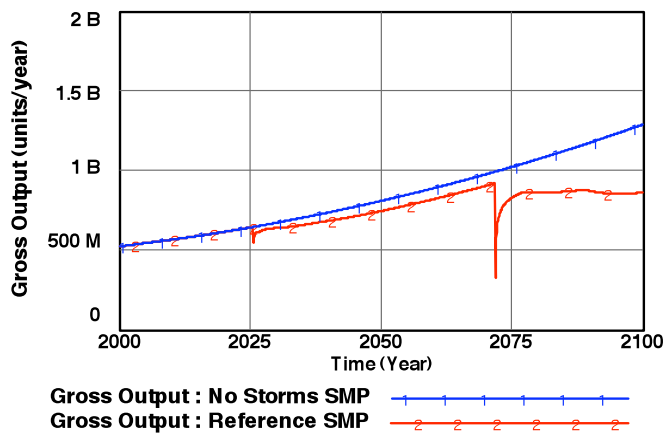
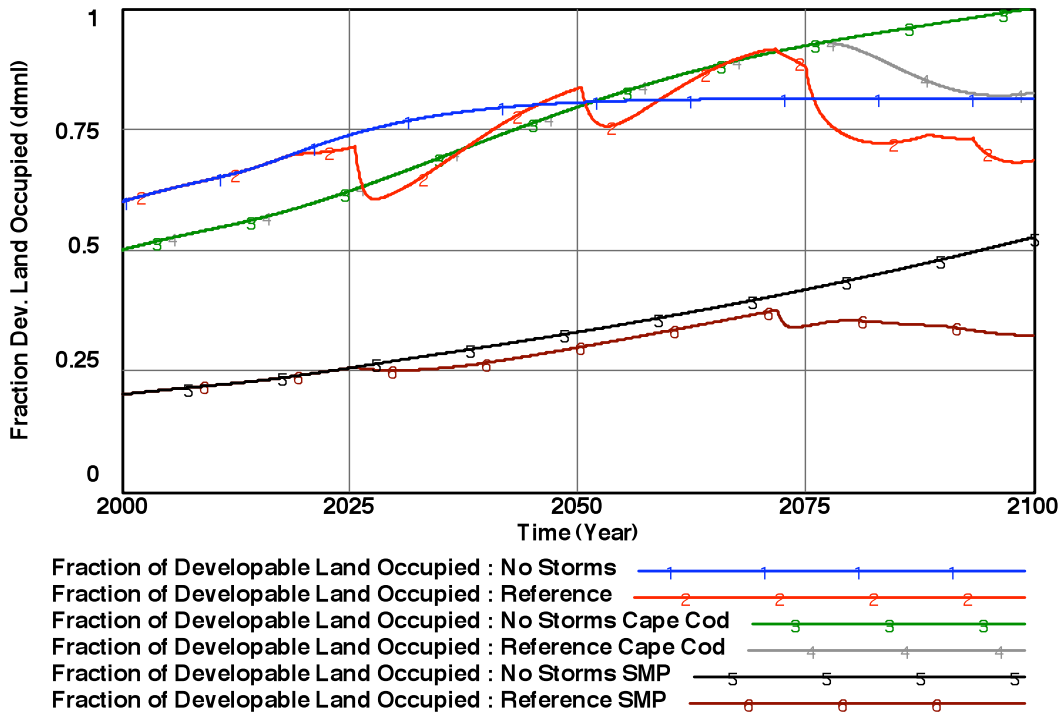
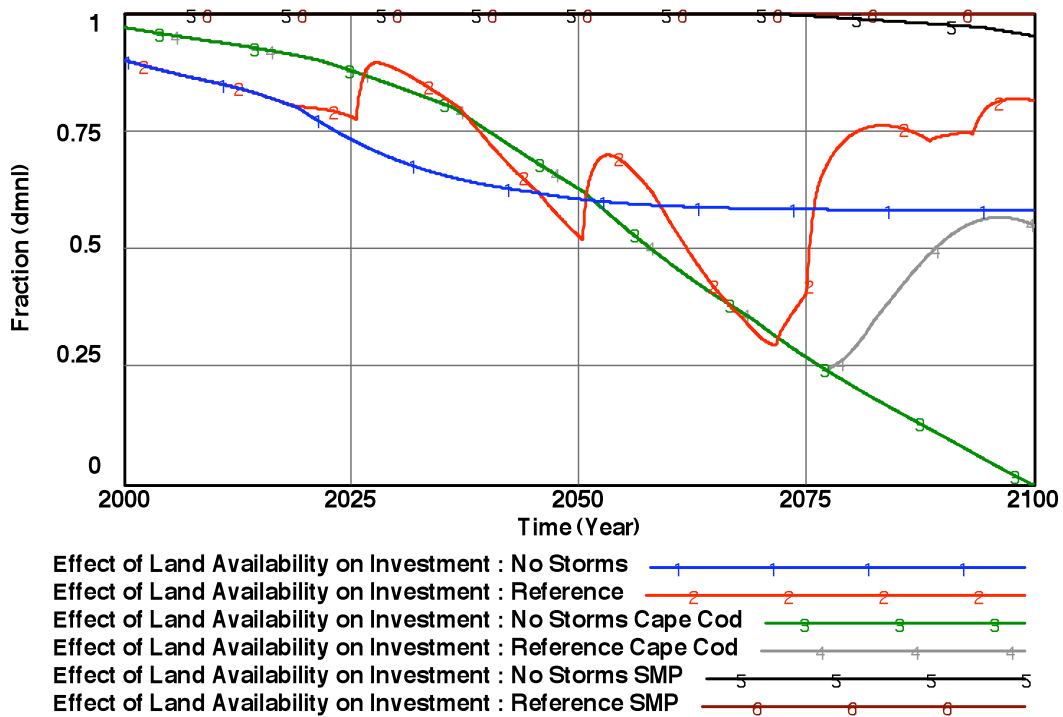


Figure 5-27: Behavior of gross economic output from 2000–2100 for St. Mary Parish.



**Figure 5-28:** The fraction of land from 2000–2100 that is available for infrastructure development, for Miami-Dade, Cape Cod, and St. Mary Parish.



**Figure 5-29:** The effect of land availability on investment in new infrastructure, from 2000–2100 for Miami-Dade, Cape Cod, and St. Mary Parish.



Another difference among the communities is the outcome of the public adaptation benefit-cost decision. Both Miami-Dade and St. Mary Parish choose to build public adaptation structures, which protect their land from the rising sea. Cape Cod does not protect its shoreline because the costs outweigh the benefits. As a result, Cape Cod loses available land throughout century due to permanent inundation. The loss of land occurs faster than the depreciation of infrastructure (which would free land), which increases the fraction of land developed even after new investments have ceased (shown by the No Storms Cape Cod line in Figure 5-29).

The economic growth of the community for the No Storms scenario provides a reference for comparing the impact of storms. For the land-restricted Miami-Dade, large storms damage capital, freeing up land. More available land allows for higher rates of infrastructure investment. Additionally, as described earlier in this chapter, insurance and disaster relief spur economic activity.

Cape Cod is also land restricted, but the Category 1 storm in 2075 does not have the same effect. A Category 1 storm does not cause significant infrastructure damage. The result is that land does not become available and insurance and disaster relief payments are insignificant. Instead, the storm causes an increase in perceived storm risk, which decreases investment and causes the community to slowly decline through 2100.

St. Mary Parish is unrestricted by land until 2075, so economic growth continues through 2100 with little restriction. Storm activity lowers economic output below the unrestricted growth path. Storms do cause significant infrastructure damage, freeing land and triggering post-storm monetary relief. These effects do not increase economic activity above the No Storms scenario, unlike Miami-Dade, which faced restricted growth for the entire simulation.

| <b>Community</b>     |        | <b>Gross Output</b><br>units/year | <b>Population</b><br>persons | <b>Cumulative<br/>Capital Damage</b><br>capital units | <b>Cumulative<br/>Evacuees</b><br>persons |
|----------------------|--------|-----------------------------------|------------------------------|---|---|
| Cape Cod             | Mean   | 7.30 B                            | 372,000                      | 1.28 B  | 24,300                                    |
|                      | Median | 7.70 B                            | 388,000                      | 649 M   | 0   |
|                      | StdDev | (1.50 B)                          | (86,500)                     | (3.10 B)  | (60,700)                                  |
| Miami-Dade<br>County | Mean   | 44.3 B                            | 2.82 M                       | 158.2 B B   | 8.48 M                                    |
|                      | Median | 46.1 B                            | 2.91 M                       | 152.3 B   | 8.45 M                                    |
|                      | StdDev | (10.0 B)                          | (677,000)                    | (73.5 B)  | (3.10 M)                                  |
| St. Mary<br>Parish   | Mean   | 821.0 M                           | 84,300                       | 946.8 M   | 70,500                                    |
|                      | Median | 810.3 M                           | 83,000                       | 710.3 M   | 67,700                                    |
|                      | StdDev | (270.6 M)                         | (27,400)                     | (845.7 M)   | (46,100)                                  |

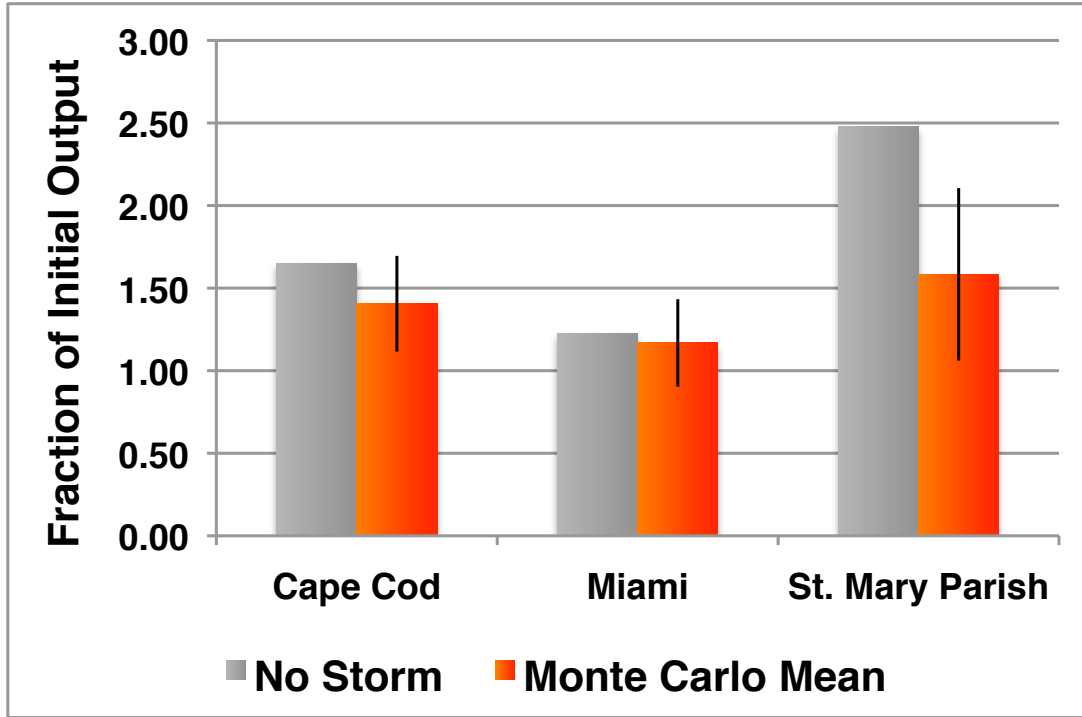
**Table 5.4:** The Monte Carlo results for the Reference scenario. Results are calculated from the 2100 values of 1000 simulations.

## 5.5 Monte Carlo Analysis

The results above describe one particular pattern of storms generated by the random model processes. I performed a Monte Carlo analysis to better understand the results over a range of possible storm patterns. One thousand different storm patterns were simulated using the Reference scenario defaults for each of the three regions. Each storm pattern was drawn from the appropriate storm distributions for the three regions: Cape Cod, Miami-Dade County, and St. Mary Parish.

The final values of model parameters for each of the thousand simulations were recorded. The mean, median, and standard deviations are shown in Table 5.4. The distributions are skewed differently depending on the community. For example, Gross Output is left-skewed for Cape Cod and Miami-Dade, but right-skewed for St. Mary Parish. St. Mary Parish has a higher growth path for low-storm runs, which extends the tail and increases the mean.

*Gross Output* is a reasonable proxy for comparing the final economic outcomes of the communities. The means values are normalized by the initial economic output of the community and plotted in Figure 5-30. Every community has lower economic output under the Reference scenario than the No Storms scenario, on average (Table 5.5). Miami-Dade shows the least change, partly because its long-run growth without storms is the lowest of three communities. That is, even without storms,



**Figure 5-30:** *Gross Output* compared between No Storms and the Monte Carlo means, as a fraction of the initial *Gross Output*. (Standard deviation plotted on Monte Carlo bars.)

Miami-Dade’s economy only grows 24 percent, for reasons described in the previous section.

| Community  | No Storm Gross Output | Monte Carlo Mean Gross Output |
|------------|-----------------------|-------------------------------|
| Cape Cod   | 8.57 B                | 7.30 B                        |
| Miami-Dade | 46.56 B               | 44.3 B                        |
| St. Mary   | 1.285 B               | 821.0 M                       |

**Table 5.5:** The Monte Carlo mean gross output compared to the gross output of No Storms scenarios. Gross output in 2100 for each community.

### 5.5.1 Economic growth rates

The final values of economic output are a snapshot of a community’s economic situation but do not capture economic growth trends. I calculated the annual economic growth rate from 2010–2100 to better understand the impact on a community’s economy. The growth rates below describe the Reference scenario results for Cape Cod,

Miami-Dade, and St. Mary Parish.

I estimated the annual growth rate for the period of time in which storms may arrive, 2010–2100. Equation 5.1 calculates the annual growth rate during that period of time.

$$g = \ln\left(\frac{GDP_{2100}}{GDP_{2010}}\right)/90 \quad (5.1)$$

where

$g$  is the annual growth rate

$GDP_{2100}$  is Gross Output in 2100

$GDP_{2010}$  is Gross Output in 2010

Stochastic storm arrival poses a problem when measuring economic growth. If a storm strikes between 2090–2100, final economic output could be significantly lower than the 2090 value. Additionally, economic recovery could be prevented arbitrarily by the end of the simulation. Averaging the growth rates over 1000 simulations should minimize the effect of late-arriving storms.

The annual growth rate was estimated for each Monte Carlo simulation. The 1000 annual growth rates for a given community were averaged and reported in Table 5.6.

Miami-Dade has the lowest growth rate of the three communities. The result is in part because of the low base growth rate in the No Storm scenario. Miami-Dade's percentage change is on par with St. Mary Parish (-63.0 percent and -61.6 percent, respectively), which has the highest growth rate. Both of these communities experience frequent storms. Cape Cod experiences fewer storms and growth declines less than the other two communities (-44.8 percent).

|                        | <b>No Storm</b>              | <b>Reference</b>             |                                 |
|------------------------|------------------------------|------------------------------|---------------------------------|
|                        | <b>Mean Rate<br/>(StDev)</b> | <b>Mean Rate<br/>(StDev)</b> | <b>Change from<br/>No Storm</b> |
| <b>Cape Cod</b>        | 0.0047                       | 0.0026                       | -0.0021                         |
|                        | (--)                         | (.0029)                      | -44.8%                          |
| <b>Miami-Dade</b>      | 0.0014                       | 0.0005                       | -0.0009                         |
|                        | (--)                         | (.003)                       | -63.0%                          |
| <b>St. Mary Parish</b> | 0.0092                       | 0.0035                       | -0.0057                         |
|                        | (--)                         | (.004)                       | -61.6%                          |

**Table 5.6:** Annual economic growth rates from 2010-2100 for Cape Cod, Miami-Dade, and St. Mary Parish. No Storm values are calculated from the single No Storm simulation for a community. Reference values are the mean of the Monte Carlo simulations. Percentage change values are the absolute change from No Storms divided by the No Storm growth rate.

Importantly, all the annual growth rates are lower than would be expected. Low growth rates are an artifact of the model and my assumption on the total factor productivity parameter of the Cobb-Douglas production function (Equation 3.20). I chose a value of 1.0, which assumes no improvements in technological productivity. A value greater than one would be reasonable and would increase economic growth rates overall.

The economic growth rates are presented here as a basis for future chapters. They will be used in later chapters for comparison, as key parametric assumptions are examined.

### 5.5.2 Economic recovery time

Another metric that compares the performance of communities under different scenarios is economic recovery time. Economic recovery time is the length of time after a storm until economic output returns to the pre-storm level.

To test economic recovery time, I artificially impose a storm arrival in 2050, once for each category of storm (i.e., Category 1, etc.). The recovery time is number of

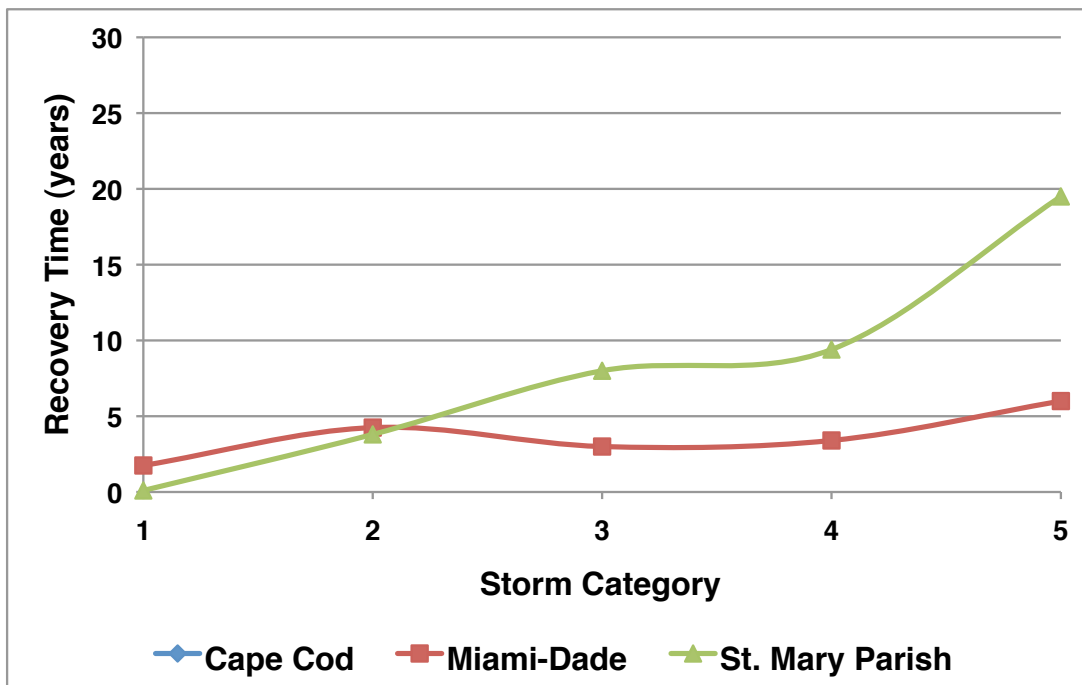
years required for gross output to return to the 2050 level.

The recovery times for each of the communities differ (Table 5.7). Cape Cod does not recovery from any intensity of storm before 2100, the end of the simulation. Under the assumptions of the Reference scenario, Cape Cod’s economy stagnates after a storm, never returning to pre-storm levels.

| <b>Community</b> | <b>Category</b> | <b>Years to Reach Pre-Storm GDP</b> |
|------------------|-----------------|-------------------------------------|
| <b>Cape Cod</b>  | 1               | --                                  |
|                  | 2               | --                                  |
|                  | 3               | --                                  |
|                  | 4               | --                                  |
|                  | 5               | --                                  |
| <b>Miami</b>     | 1               | 1.75                                |
|                  | 2               | 4.25                                |
|                  | 3               | 3                                   |
|                  | 4               | 3.4                                 |
|                  | 5               | 6                                   |
| <b>SMP</b>       | 1               | 0.1                                 |
|                  | 2               | 3.8                                 |
|                  | 3               | 8                                   |
|                  | 4               | 9.4                                 |
|                  | 5               | 19.5                                |

**Table 5.7:** Time for the Reference scenario to recover to the pre-storm level of economic output, after an exogenous storm of a particular intensity was imposed in 2050.

Miami-Dade’s large economy recovers the fastest of the three communities. Recovery is aided by disaster relief (examined in Chapter 7) and the increased availability of land after a storm causes infrastructure damage. St. Mary Parish recovers, showing a positive relationship with storm intensity (Figure 5-31). St. Mary Parish’s development is not constrained by land prior to the storm, so recovery primarily is a function of the extent of damage and disaster relief.



**Figure 5-31:** Recovery Time for Reference Scenario by Community. Time to recover to the pre-storm level of economic output, after an exogenous storm of a particular intensity was imposed in 2050. Cape Cod is not plotted because it did not recover prior to the end of the simulation.

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# Chapter 6

## Sensitivity to Assumptions

The FRACC model Reference results are due to the model's structure and assumptions about initial parameter values. This chapter will focus on several key assumptions to understand how they influence the simulation results.

Rationality assumptions, one of the main questions examined in this dissertation, are examined in Sections 6.1 and 6.2. A comparison is made between the boundedly rational assumptions used by default in FRACC and perfect rationality assumption used by other adaptation models. Additionally, the FRACC model assumes that coastal zone managers, the actors that construct public protection, have perfect foresight and are unconstrained by budget and political realities.

The importance of stochastic storms is the other main focus of this research. Four storm scenarios are tested in Section 6.4 to see how model projections change. The other climatic driver of coastal adaptation, SLR, is also examined.

### 6.1 Sensitivity to the Rationality Assumption

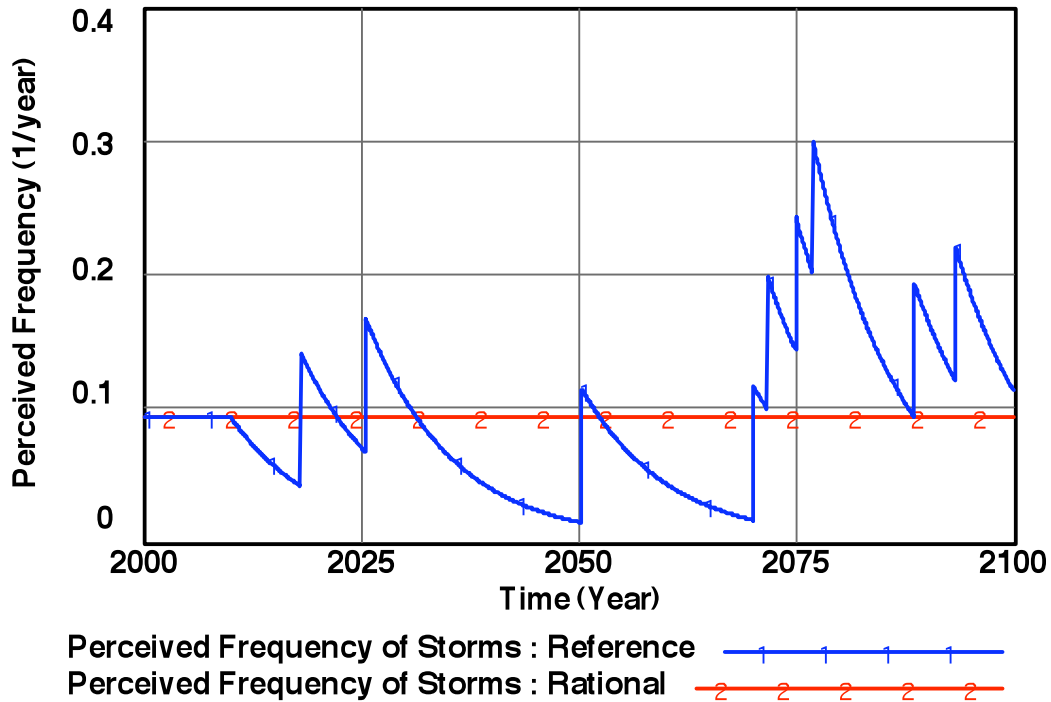
Many previous coastal adaptation studies have assumed that a rational agent optimizes coastal management decisions. However, as discussed in Chapter 2, some decision makers use their own perceptions to estimate the risk of damage, while others

use expert training and data. The FRACC model can explore rationality assumptions because it separates investment and public adaptation decisions. This section describes what happens when relaxing the rational agent assumption.

Along with the Reference scenario used in Chapter 5, an additional scenario was developed to explore investor rationality. The Reference scenario includes boundedly rational investors who use their own perception of storm frequency when evaluating investment decisions. In the new Rational scenario, investors use the actual annual storm frequency to make their decisions. The actual frequency is the true frequency of storm arrivals and is not based on their experience. As a reminder, the actual storm frequency in the standard FRACC model is the value defined in the GFDL-20 storm data set (see Section 4.5.3).

Figure 6-1 illustrates the behavior of the *Perceived Frequency of Storms* variable for Miami-Dade County, driven by the same sample storm pattern previously used. Boundedly rational investors change their beliefs about the frequency of storms after a storm event. The behavior is the same as described in Chapter 5, increasing after a storm and decreasing as the storm is forgotten. The Rational investors' beliefs about storm frequency are unaffected by storms. They perceive storm frequency to be the actual frequency for the entire simulation.

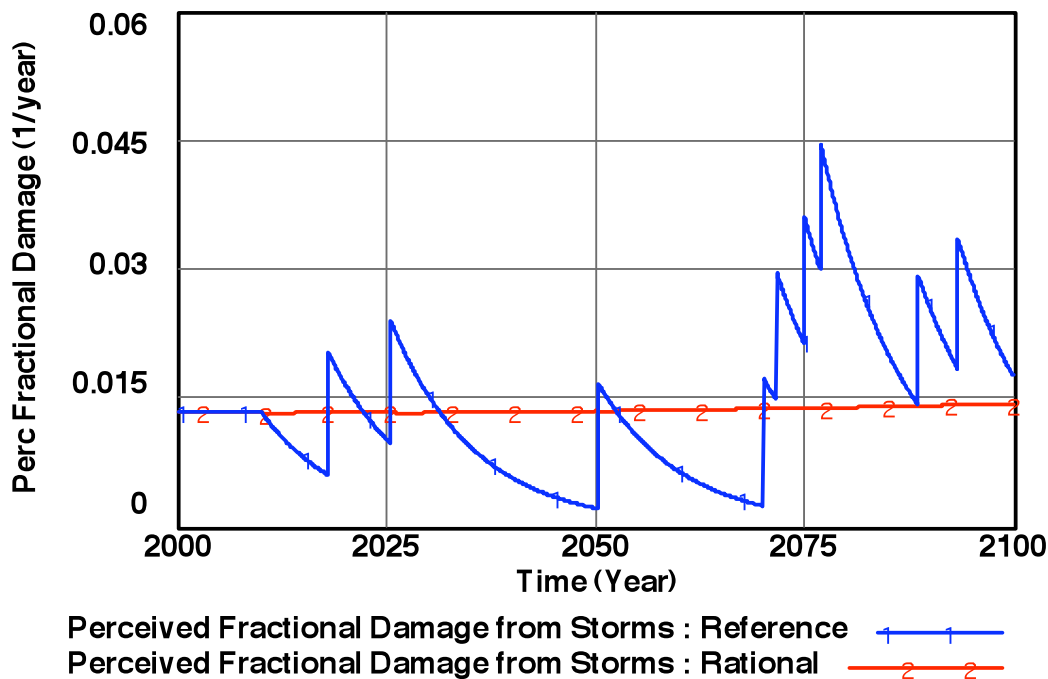
*Perceived Frequency of Storms* changes the *Perceived Fractional Damage from Storms*, which is investors' expectation about likely storm damage. Perceived fractional damage closely follows the expected frequency of storms (Figure 6-2). Damage remains mostly constant for the Rational scenario, with a very slight upward trend due to increased relative surge from long-term RSLR. Perceived damage fluctuates more for the Reference scenario, as the perceived frequency changes. *Perceived Frequency of Damage from Storms* is an important variable that affects the economic components of the FRACC model, described further in the next sections.



**Figure 6-1:** The *Perceived Frequency of Storms* for the rationality scenarios, driven by the sample storm pattern for Miami-Dade County.

Similar to the behavior presented in Chapter 5, *Perceived Fractional Damage from Storms* changes the rate of capital investment. Investors change their rate of investment because they perceive a change to the relative return on capital (Figure 6-3), the ratio of the marginal return to capital to the marginal cost of capital.

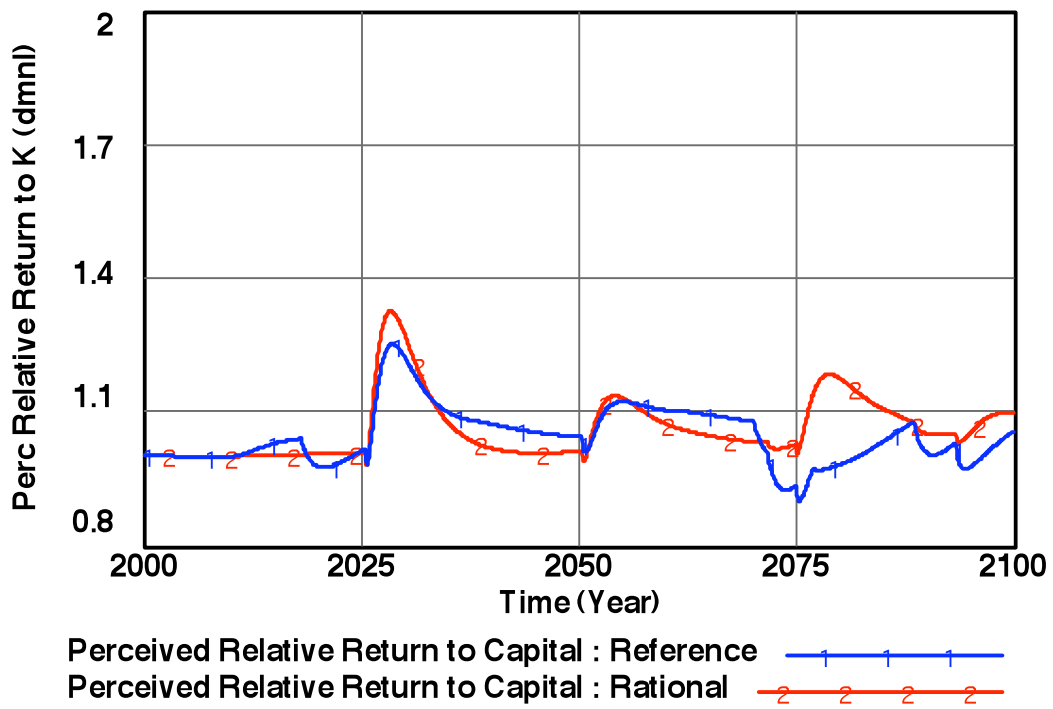
Rational investors do not change their perceived relative return to capital if a small storm occurs. In the Rational scenario, the Category 1 storm that strikes the community in 2018 causes little capital damage (Figure 6-4) and the perceived return to capital remains constant. Instead, Rational investors perceived the return to capital to rise after larger storms strike causing capital damage, such as the Category 5 storm in 2025. After a storm with capital damage, the return to capital increases because the marginal productivity of capital increases (Figure 6-5). Marginal productivity rises because capital recovers slower than labor after a storm. When labor is relatively more abundant than capital, each unit of additional capital is marginally more productive, since capital is the limiting factor of production. Marginal cost of capital,



**Figure 6-2:** The *Perceived Fractional Damage from Storms* for the rationality scenarios, driven by the sample storm pattern for Miami-Dade County.

the denominator of relative return, is a function of the perceived frequency of storms. Since the rational investors have a constant frequency storms, the cost of capital is also constant (Figure 6-6). For the Rational scenario, the marginal productivity of capital drives perceived return to capital, which drives changes to capital levels in the community.

In the Reference scenario, boundedly rational investors perceive a changing cost of capital when estimating the relative return of capital. The marginal cost of capital begins to fall from the initial value in 2010 until the first storm arrives in 2018. Even though the Category 1 storm does not cause significant capital damage, boundedly rational investors change their expectations of likely fractional storm damage because they perceive storms to be more likely. The change in likely damage affects the marginal cost of capital, which rises when the damage is more likely. For the boundedly rational investor, from 2010–2018 relative return is higher than the Rational scenario because marginal costs are falling. After the Category 1 storm, rel-



**Figure 6-3:** The *Perceived Relative Return to Capital* for the rationality scenarios, driven by the sample storm pattern for Miami-Dade County.

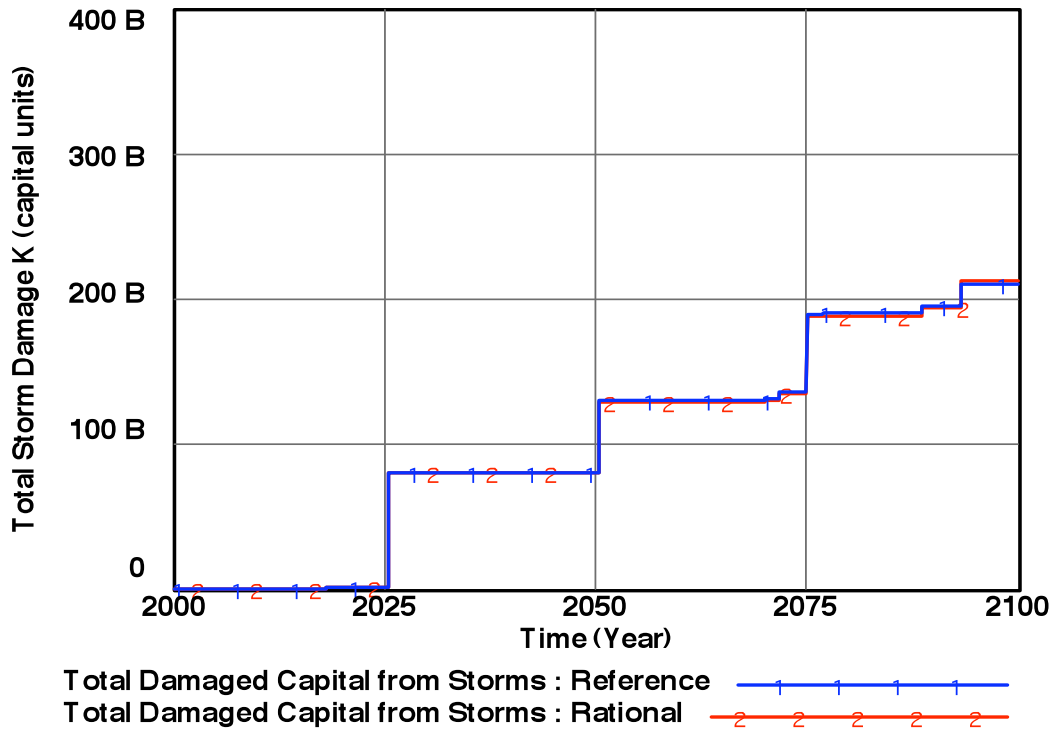


Figure 6-4: Cumulative storm damage to capital for the rationality scenarios, driven by the sample storm pattern for Miami-Dade County.

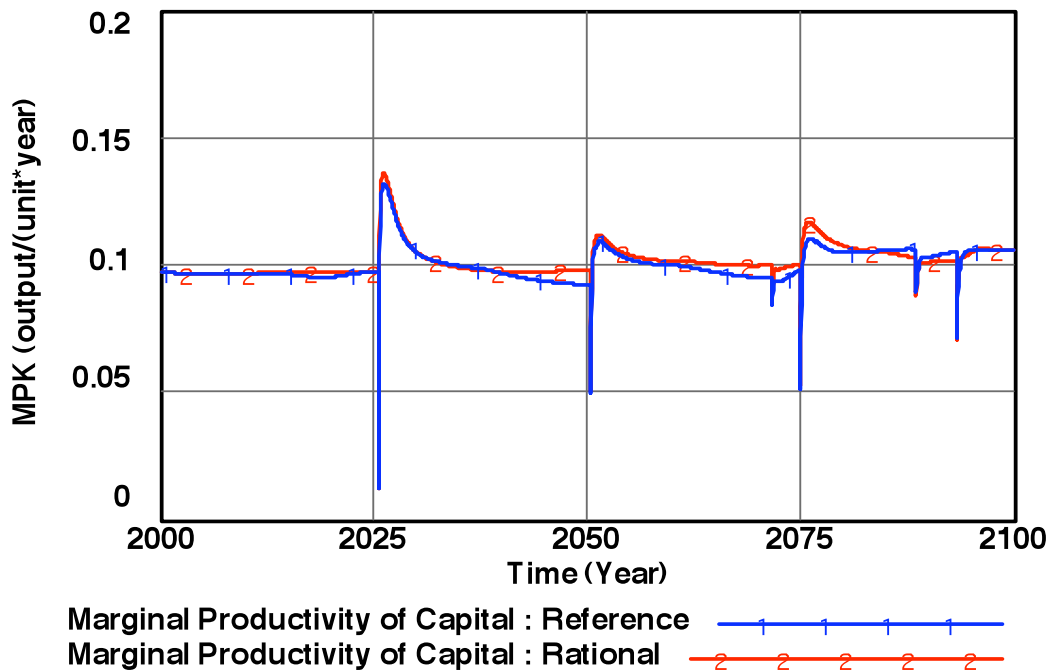
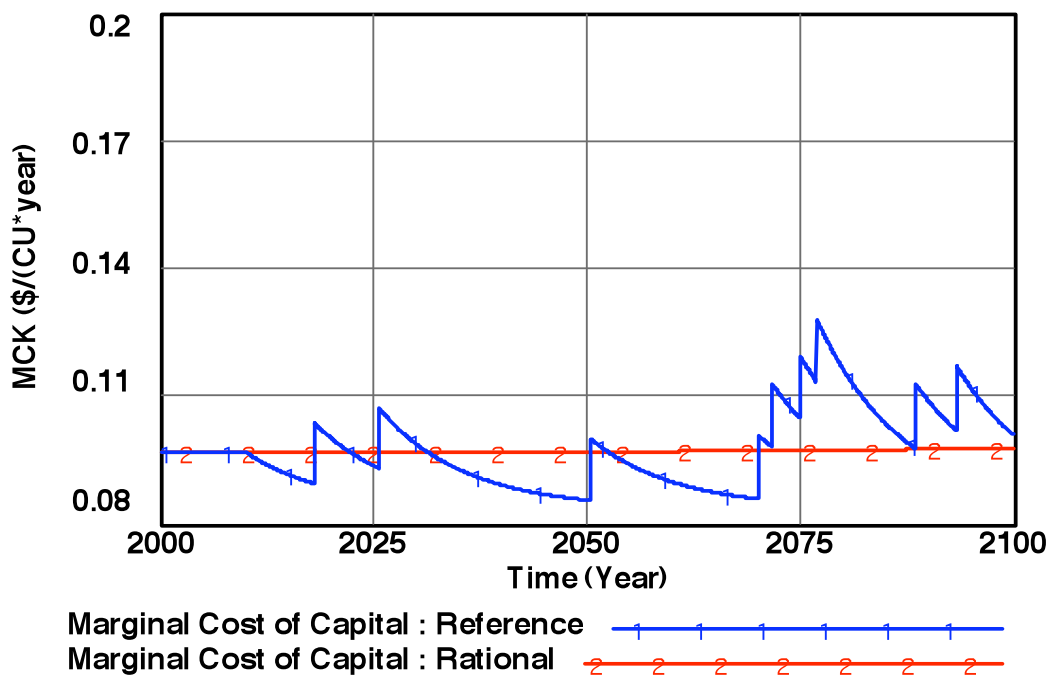
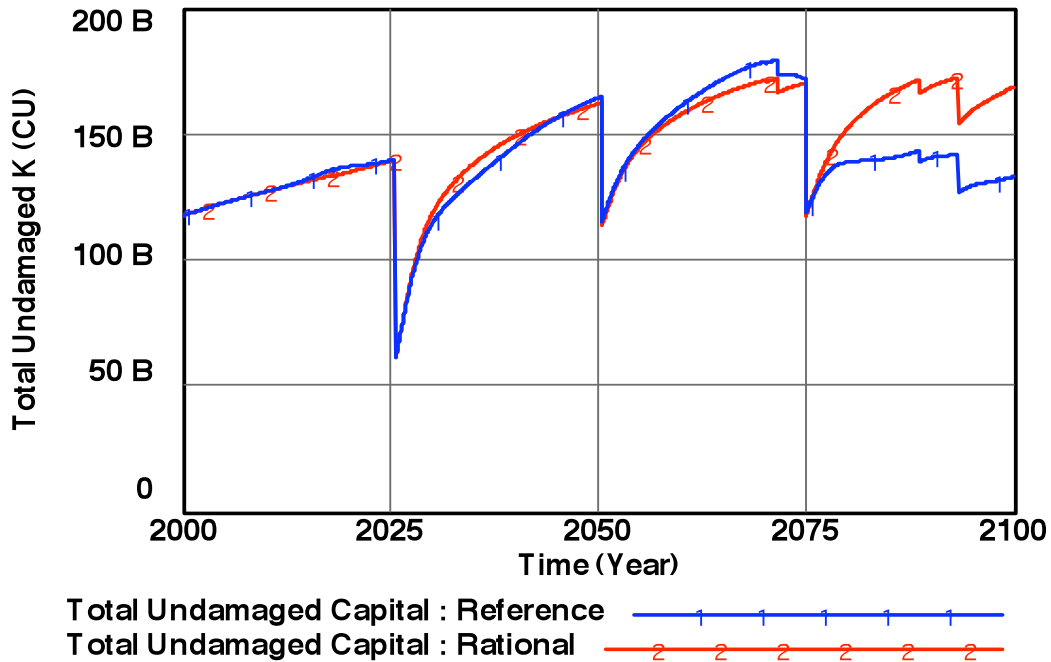


Figure 6-5: The Marginal Productivity of Capital for the rationality scenarios, driven by the sample storm pattern for Miami-Dade County.



**Figure 6-6:** The *Marginal Cost of Capital* for the rationality scenarios, driven by the sample storm pattern for Miami-Dade County.



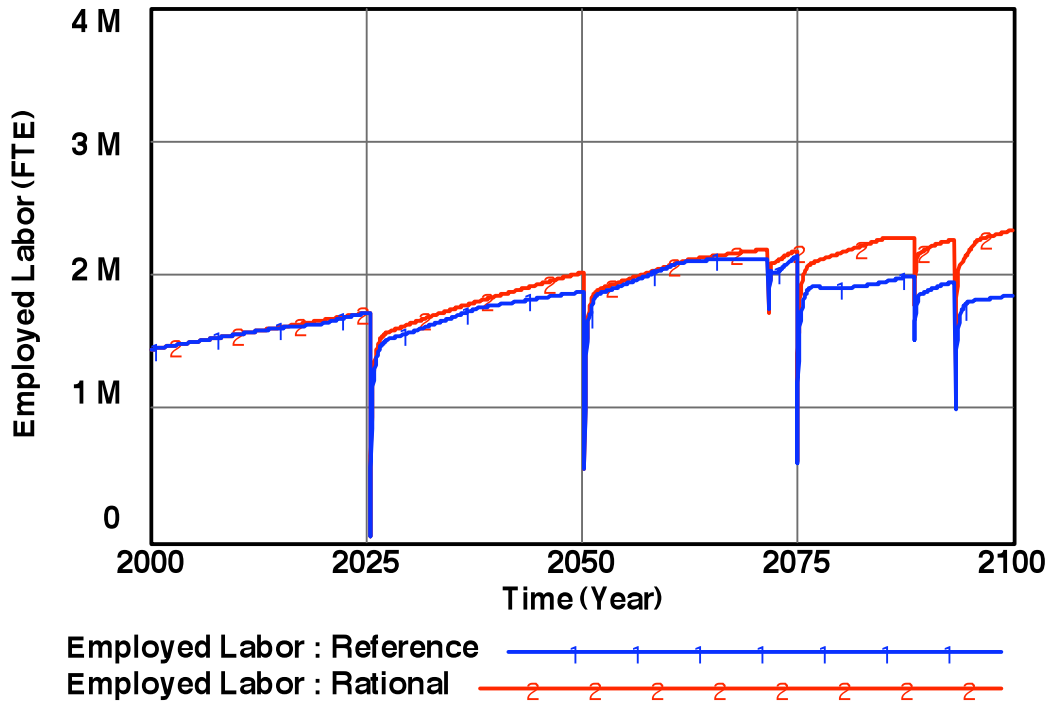
**Figure 6-7:** *Total Undamaged Capital* for the rationality scenarios, driven by the sample storm pattern for Miami-Dade County.

actively return is lower, with the marginal cost of capital changing while the marginal productivity remains relatively constant.

In 2025, when a large amount of capital damage occurs, the change in the marginal productivity of capital dominates the change in the marginal cost. Perceived relative return increases, though the peak is lower than the Rational scenario because of the change in marginal cost. The net effect is that capital stock recovers quicker in the Rational scenario (Figure 6-7).

In 2070 four storms strike in relatively quick succession, highlighting an important difference between the two rationality scenarios. For the Reference, people perceive the frequency of storms to rise as each additional storm strikes. The increased perceived frequency increases the perceived fractional damage, which ultimately increases the marginal cost of capital. The storms occur often enough that storm memories compound, increasing the marginal cost of capital to its highest level of the simulation. Contrarily, the storms have no effect on the cost of capital for rational investors.



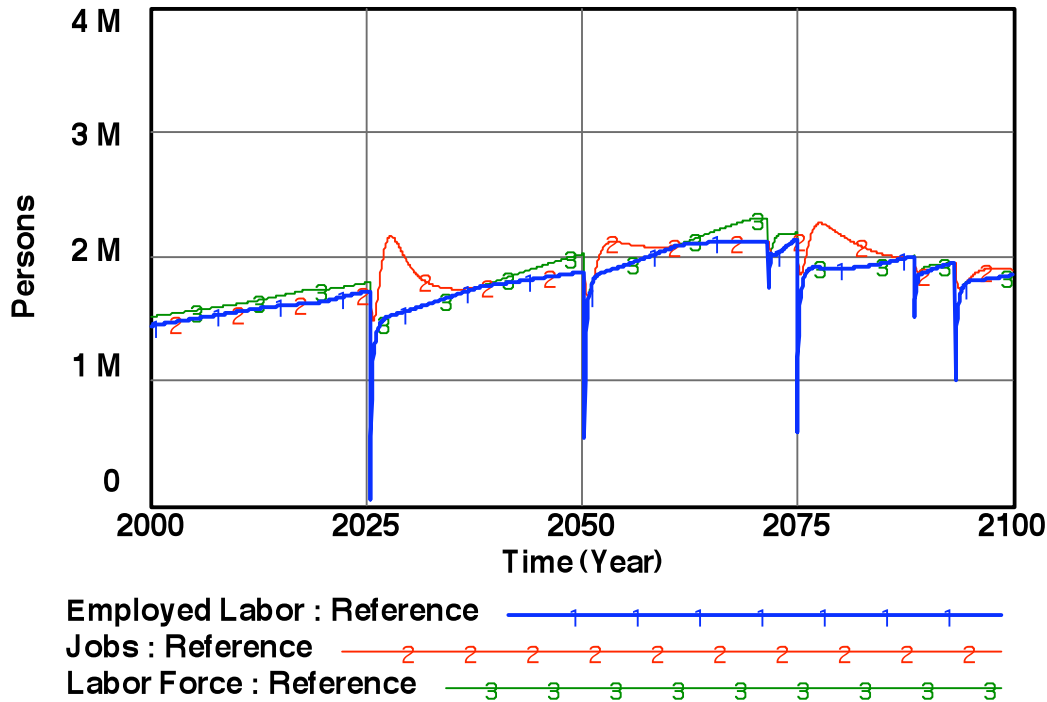


**Figure 6-8:** *Employed Labor* for the rationality scenarios, driven by the sample storm pattern for Miami-Dade County.

The high cost of capital drives the perceived relative return to capital downward in the Reference scenario. The decrease incentive for capital investment causes a significant divergence in the capital levels of the two scenarios. Rational investors continue to make investment decisions based on the true frequency of storms, while boundedly rational investors decrease investment because they perceived storm damage to be more likely.

The perceived frequency of storms also has important implications for the community's *Employed Labor*, the second factor of production (Figure 6-8). *Employed Labor* is similar for both the Reference and Rational scenarios until the Category 5 storm in 2025.

Between the 2025 storm and the 2050 storm, *Employed Labor* growth occurs in two phases, which can be seen by a subtle kink in 2034 (Figure 6-8). *Employed Labor* is limited by *Labor Force* size during first phase (2025–2034) and by *Jobs* in the



**Figure 6-9:** *Employed Labor* in the community, which is the minimum of *Jobs* and *Labor Force*, for Reference scenario, driven by the sample storm pattern for Miami-Dade County.

second phase (2034–2050). Both scenarios are limited by either labor force or jobs (Figures 6-9 and 6-10), though the growth of both labor force and jobs differ after the storm.

*Labor Force* growth differs immediately after the storm because the community is less attractive in the Reference scenario than the Rational scenario (Figure 6-11). For the Reference, attractiveness falls initially because people perceived the risk of storms to be higher (Figure 6-12). Over time, the lack of storms makes the community more attractive, increasing labor force growth.

During the second phase, *Employed Labor* is limited by jobs availability because job growth does not keep pace with labor force growth. Community attractiveness declines prior to 2050 because of the *Job Attractiveness Effect* (Figure 6-13). The Rational scenario has a constant *Storm Risk Attractiveness Effect*, which means com-

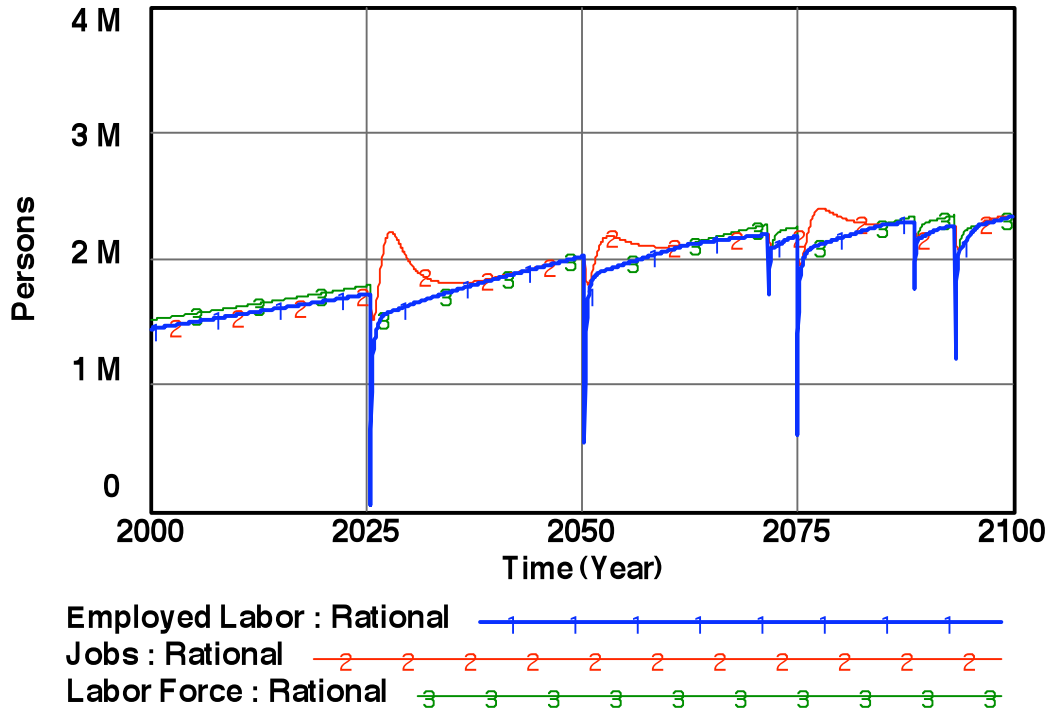


Figure 6-10: *Employed Labor* in the community, which is the minimum of *Jobs* and *Labor Force*, for Rationality scenario, driven by the sample storm pattern for Miami-Dade County.

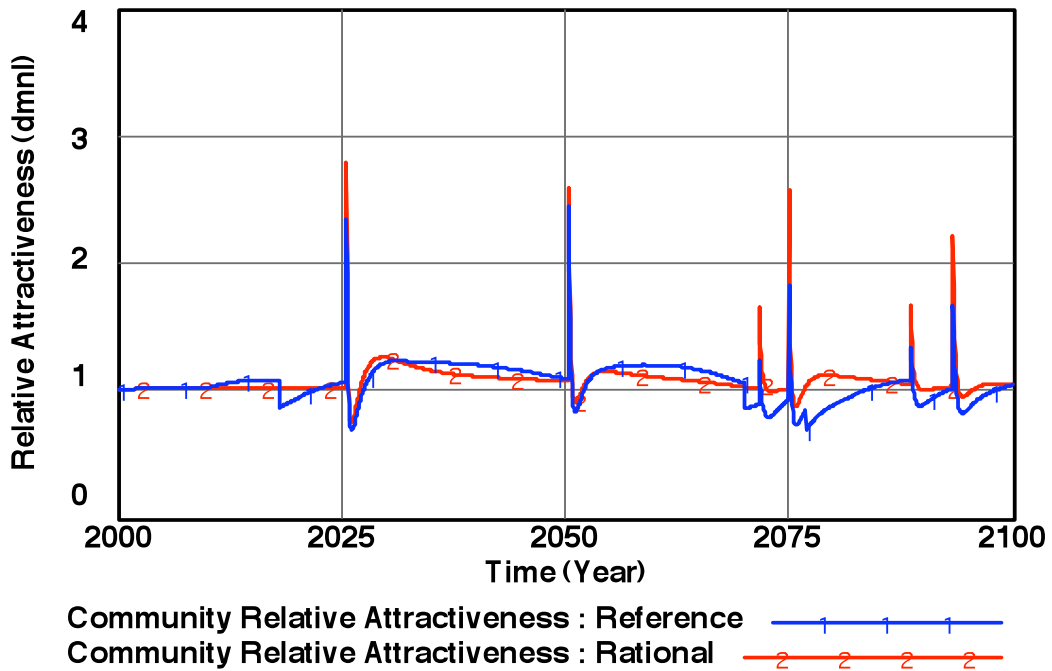
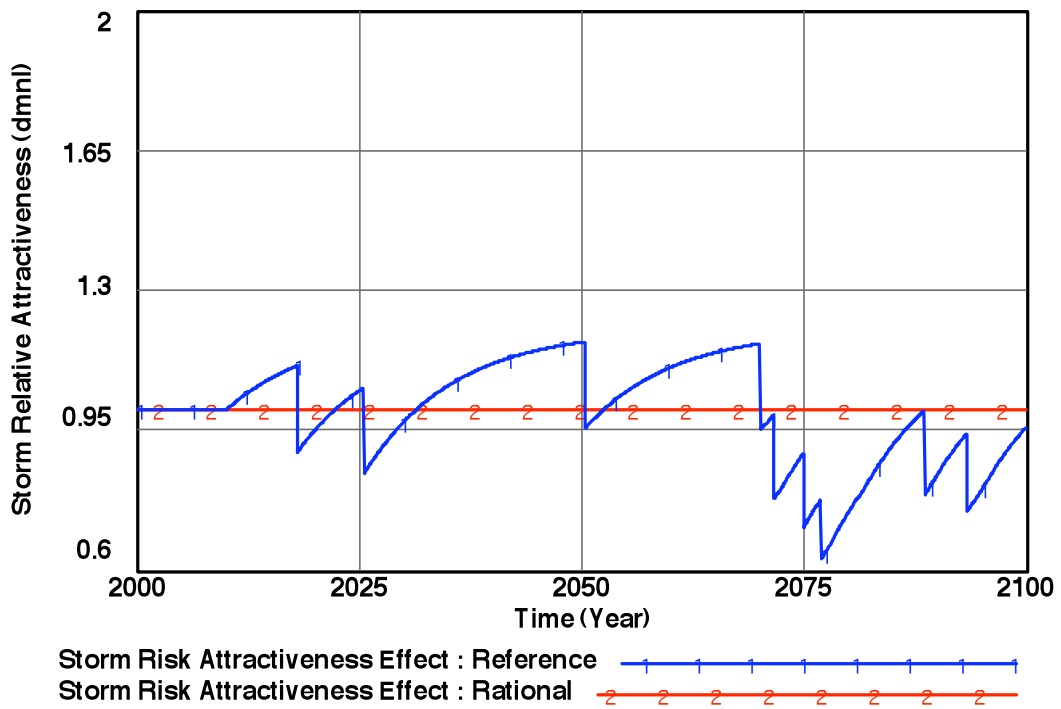
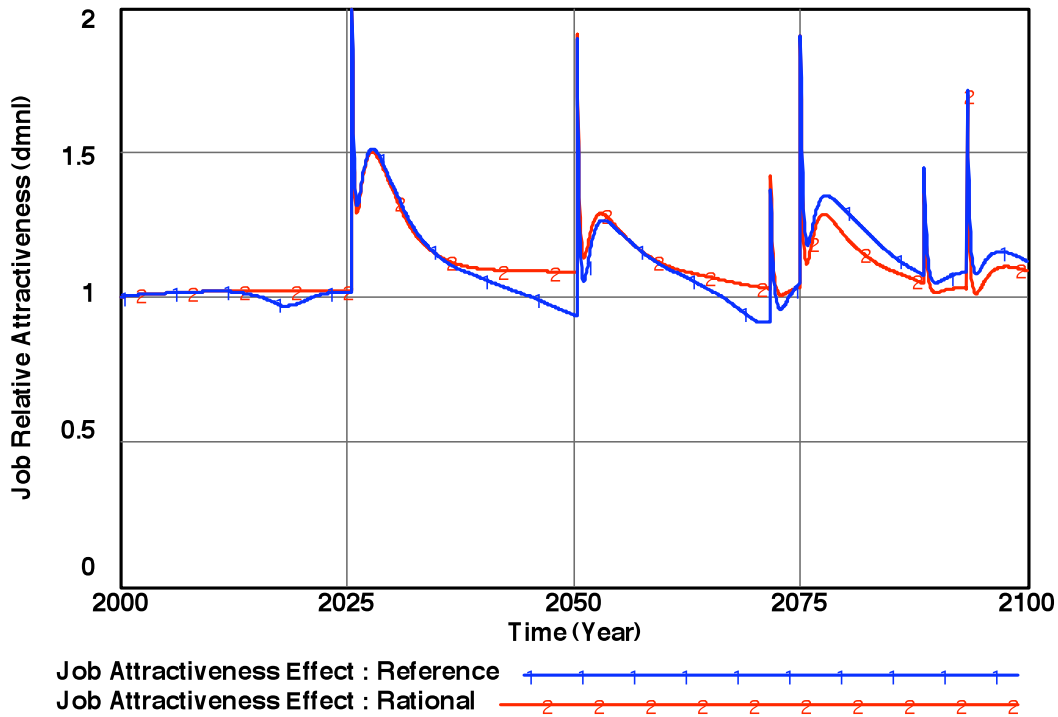


Figure 6-11: *Community Relative Attractiveness* for the rationality scenarios, driven by the sample storm pattern for Miami-Dade County.



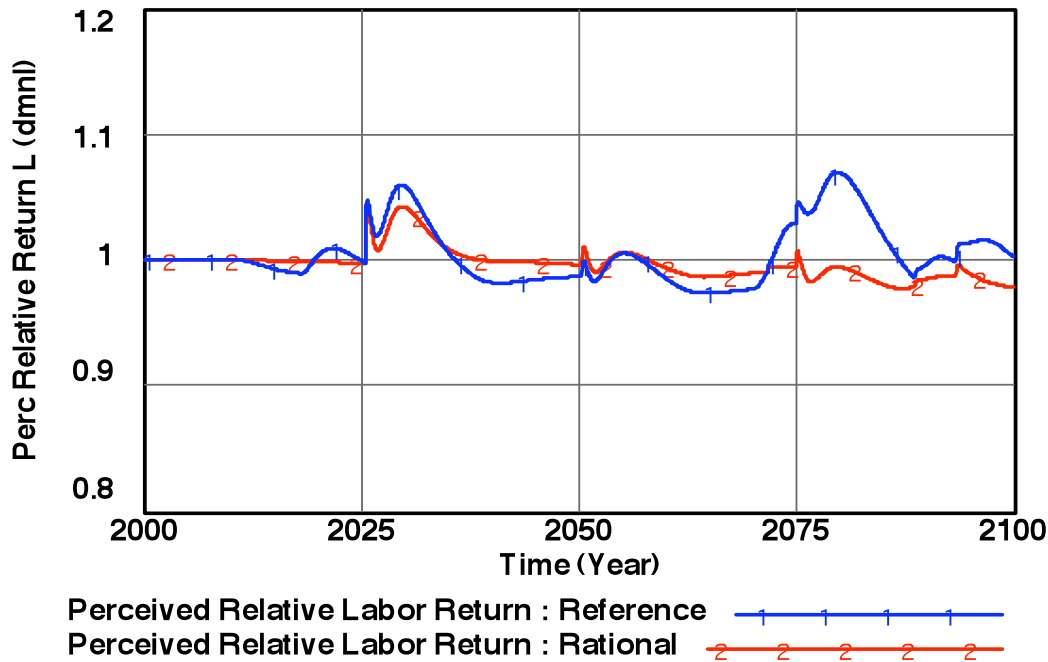
**Figure 6-12:** Storm risk attractiveness for the rationality scenarios, driven by the sample storm pattern for Miami-Dade County.



**Figure 6-13:** Job attractiveness for the rationality scenarios, driven by the sample storm pattern for Miami-Dade County.

munity attractive is constant prior to the storm in 2025 and does not fall as much in the decade prior to 2050, because of job attractiveness.

Job growth differs between the two scenarios because investors perceived the relative return to labor differently (Figure 6-14). Job growth immediately after a storm is driven by aggregate demand (Figure 6-15), which affects both scenarios similarly. The scenarios differ because the *Price of Output* changes the relative return to labor. The *Price of Output* falls lower in the Reference scenario than the Rational scenario. Price of output is a determined in part by the cost of producing a unit of output, which is a function of the marginal cost of capital. As discussed above, the cost of capital does not fluctuate for rational investors but does change for boundedly rational investors. After a storm, when boundedly rational investors perceive the cost of capital to be higher, the price of output also increases. The higher price of output means that the marginal return to labor is higher, because each unit of output produced by a unit of labor is worth more. Prior to 2050, the price of output declines for the Reference



**Figure 6-14:** The *Perceived Relative Return to Labor* for the rationality scenarios, driven by the sample storm pattern for Miami-Dade County.

scenario because of the lower cost of capital (i.e., low perceived storm risk reflected in capital cost). The price of output remains higher for the Rational scenario, keeping the relative return to labor higher. Ultimately the relative return to labor dynamic lowers the job growth in the Reference relative to the Rational, making jobs in the community relatively scarcer.

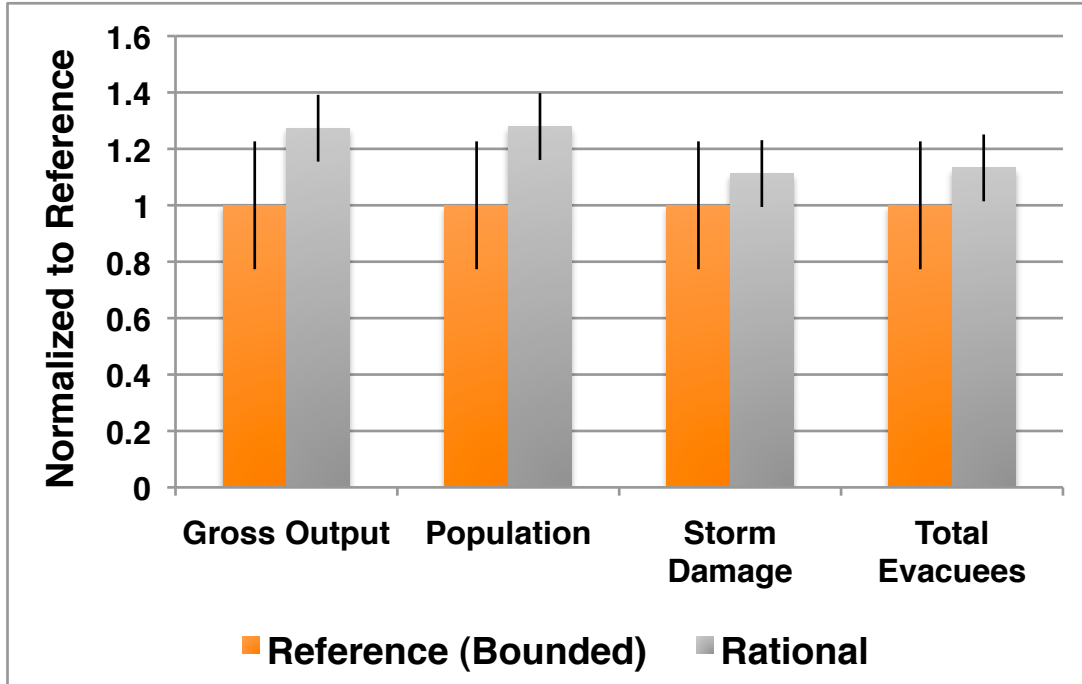
*Employed Labor* behaves similarly for subsequent storms, with labor force limiting in the first phase and jobs limiting the second. For the series of four storms starting in 2070, the rational investor continues to follow a similar pattern (Figure 6-10). Labor force generally remains the less constraining factor of *Employed Labor*, even through the end of the simulation. The boundedly rational community reacts differently to the series of storms. The four storms increase the perceived frequency of storms to its highest level (Figure 6-1), which decreases the attractiveness of the community significantly because of storm risk (Figures 6-11 and 6-12). The decrease in attractive decreases the community’s population, causing labor force to become a limiting fac-



**Figure 6-15:** The *Effect of Aggregate Demand on Jobs* for the rationality scenarios, driven by the sample storm pattern for Miami-Dade County.

tion for longer after the 2075 storm (Figure 6-9). The labor force continues to remain depressed for the remainder of the simulation.

In summary, rationality changes the dynamics of economic growth because the actors perceive storm risk differently. Boundedly rational investors change their investment strategy in response to storm events, while rational investors do not. A similar response occurs in the labor market, where storm risk drives changes in attractiveness of the community, affecting the size of the labor force.



**Figure 6-16:** Comparison of Reference and Rational scenarios for Miami-Dade County. Results are normalized to the mean of the Reference scenario.

### 6.1.1 Rationality Monte Carlo Results

A Monte Carlo analysis with 1000 storm patterns was performed for the Reference and Rational scenarios. The Reference results are the same as in Chapter 5. The Rational results were generated using the same set of storm patterns. For the Rational scenario, investors made investment choices using a constant estimate of storm frequency. The results of the Monte Carlo analysis are shown in Figure 6-16. The data are normalized by the means of the Reference scenario. A Student's t-test was performed comparing the two scenarios for each metric. The differences between the scenarios for all four metrics were statistically significant (Gross output: p-value=1.3461E-258; Population: p-value=9.6322E-274; Storm damage: p-value=4.51485E-96; Evacuees: p-value=2.0938E-142).

The economy grows more with a rational investor. Gross output averages 27 percent more than the boundedly rational scenario. Population also grows more in the Rational scenario than the Reference scenario, increasing 28 percent on average. The



increase in economic activity and population in the Miami-Dade area increases its exposure to storms. The Rational scenario has more storm damage and more evacuees than the boundedly rational Reference scenario, 11 and 13 percent respectively. A rational agent assumption increases both economic growth and exposure, on average.

### 6.1.2 Rationality and economic growth rates

The increase in economic growth is reflected in the annual economic growth rates from 2010–2100 (Table 6.1). All three communities have higher average annual growth rates under rational assumptions. Miami-Dade’s growth rate is 500 percent higher when compared to the boundedly rational Reference scenario. Cape Cod and St. Mary Parish also show increases at 76 percent and 120 percent, respectively. Miami-Dade has a larger change in economic growth because the Reference growth rate is smaller than the other communities. Additionally, the high frequency of storm activity in Miami-Dade can cause boundedly rational investors to slow their investment. In light of storm activity, rational investors maintain the a higher level of investment, all else equal.

|                        | Reference            | Rational             |                             |
|------------------------|----------------------|----------------------|-----------------------------|
|                        | Mean Rate<br>(StDev) | Mean Rate<br>(StDev) | Change<br>from<br>Reference |
| <b>Cape Cod</b>        | 0.0026               | 0.0045               | 0.0020                      |
|                        | (.0029)              | (.0003)              | 75.8%                       |
| <b>Miami-Dade</b>      | 0.0005               | 0.0035               | 0.0030                      |
|                        | (.003)               | (.0016)              | 563.2%                      |
| <b>St. Mary Parish</b> | 0.0035               | 0.0079               | 0.0043                      |
|                        | (.004)               | (.0008)              | 123.1%                      |

**Table 6.1:** Annual economic growth rates for the Rational scenario from 2010-2100 for Cape Cod, Miami-Dade, and St. Mary Parish. Reference and Rational values are the mean of the Monte Carlo simulations. Percentage change values are the absolute change from Reference divided by the Reference growth rate.

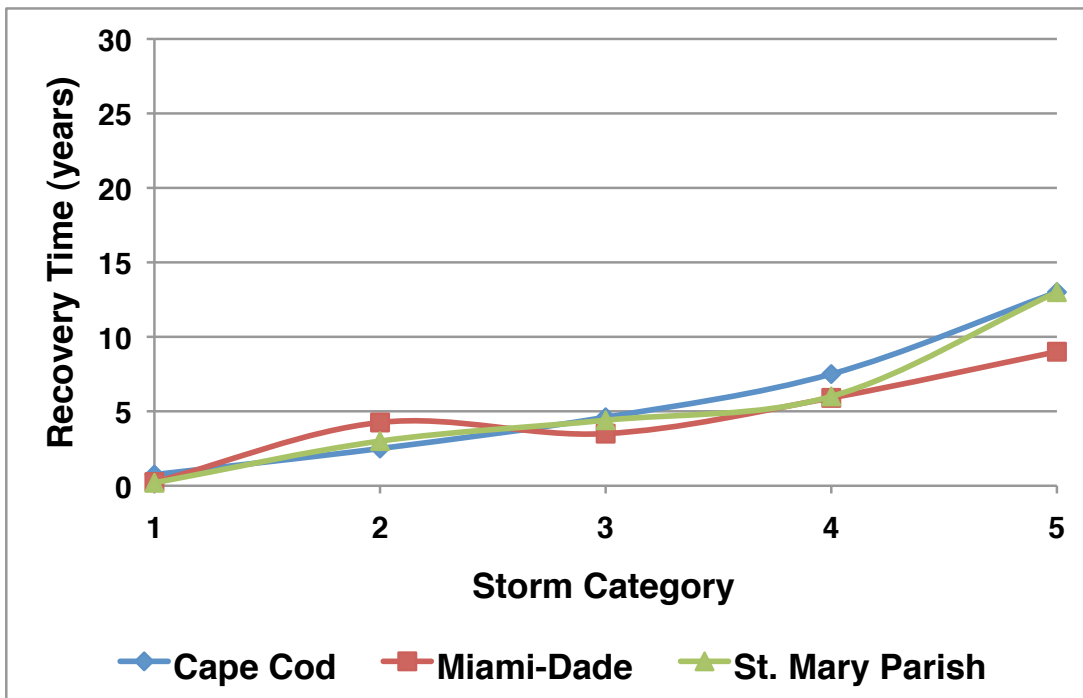
### 6.1.3 Rationality and economic recovery time

Similar to Section 5.5.2, economic recovery times were calculated for the Rational scenario for each community. Generally, rational simulations have lower recovery times than the bounded rational simulations. Cape Cod, which didn't recover before the end of the simulation for the Reference simulations, has recovery times below 15 years. Miami-Dade retains a similar recovery time for most storm intensities, but the Category 5 recovery time increases from 6 to 9 years, when compared to Reference scenario.

| <b>Community</b>       | <b>Category</b> | <b>Years to Reach Pre-Storm GDP</b> |
|------------------------|-----------------|-------------------------------------|
| <b>Cape Cod</b>        | 1               | 0.75                                |
|                        | 2               | 2.5                                 |
|                        | 3               | 4.6                                 |
|                        | 4               | 7.5                                 |
|                        | 5               | 13                                  |
| <b>Miami-Dade</b>      | 1               | 0.25                                |
|                        | 2               | 4.25                                |
|                        | 3               | 3.5                                 |
|                        | 4               | 5.9                                 |
|                        | 5               | 9                                   |
| <b>St. Mary Parish</b> | 1               | 0.2                                 |
|                        | 2               | 3                                   |
|                        | 3               | 4.4                                 |
|                        | 4               | 6                                   |
|                        | 5               | 13                                  |

**Table 6.2:** Time for the Rational scenario simulations to recover to the pre-storm level of economic output, after an exogenous storm of a particular intensity was imposed in 2050.

Overall recovery time increases as a function of storm intensity (Figure 6-17). Cape Cod and St. Mary Parish both have a clear upward trend. As with the Reference scenario, Miami-Dade remains relatively constant for the Rational scenario.



**Figure 6-17:** Recovery Time for Rational Scenario by Community. Time to recover to the pre-storm level of economic output, after an exogenous storm of a particular intensity was imposed in 2050.

## 6.2 Sensitivity to Coastal Planner Rationality

Although the FRACC model relaxes the assumption of perfect rationality and foresight for residents and investors, coastal managers are represented as rational actors who have a perfect understanding of climate change impacts and climate change risk. Specifically, coastal managers plan future levee and beach nourishment protection based on a perfect estimation of RSLR 50 years from when planning begins. Construction of public protection occurs in a comparatively short length of time, about 10 years for levees. The 50-year planning horizon and the decade-long construction time are parameter values derived from US Army Corps of Engineers (USACE) project planning guides (Blakey and Whittington, 2001).

The assumption that coastal planners know future RSLR for their region with certainty is unrealistic. Together with the relatively short construction process and the long planning horizon, the model yields highly optimistic public protection performance in the model. Real-world coastal protection projects are often delayed because of environmental impact assessments, political factors, community opposition, and lawsuits. Additional delays could occur because of funding constraints by either the federal government or local government, both of whom fund construction in the US (Section 2.5). The long planning horizon is also optimistic. Delays in project completion after the initial planning phase effectively shorten the planning horizon. For instance, if a levee was designed in 2000 to protect against climate conditions in 2050, but isn't completed until 2015, the project would only provide effective protection for 35 years.

Along with planning and foresight, public protection requires regular maintenance. Regular maintenance can be neglected because funding is difficult to sustain over the life of the protection project. In the United States, local governments are responsible for maintenance and upkeep of public protection projects. Politicians and budget conditions change, which can result in maintenance being neglected.

Hurricane Katrina's devastation of New Orleans is an example of degraded protection performance from both long construction delays and poor maintenance. Engineering studies after the storm concluded that years of project delays, improper funding, and poor maintenance contributed to the large number ( $\sim 50$ ) of levee breaches (USACE, 2009). The US Army Corps of Engineers has acknowledged that the coastal protection structures were not optimal, as assumed in the FRACC model.

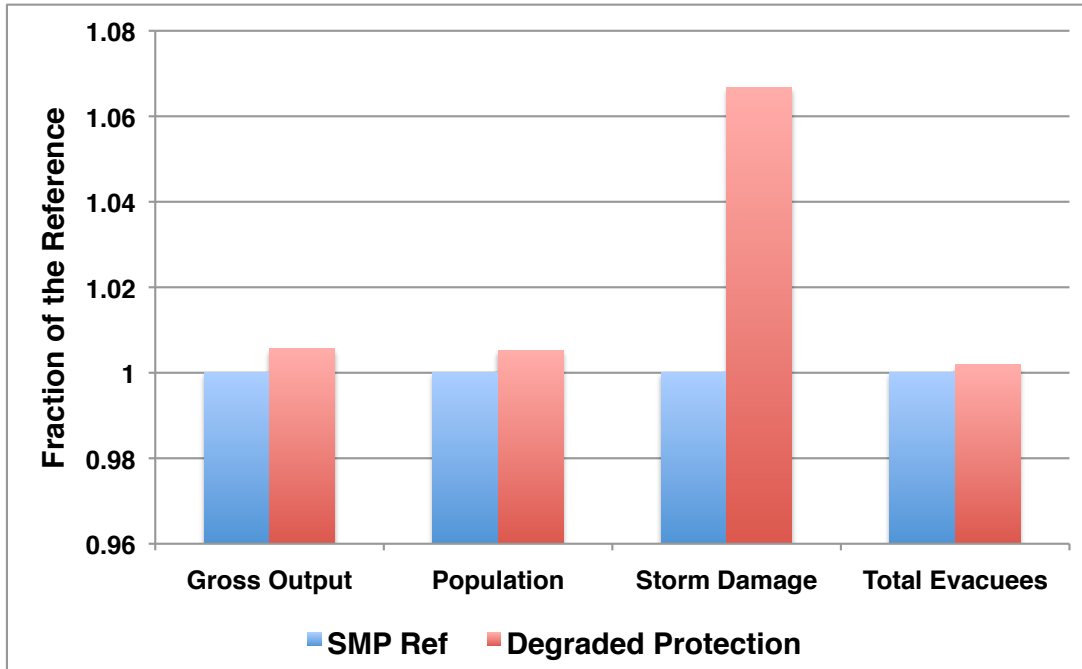
To examine the sensitivity of FRACC model results to these optimistic assumptions regarding coastal protection, a Degraded Protection scenario was developed. The Degraded Protection case differs from the Reference scenario in two ways. First, the level of maintenance performed is lowered from 90 percent of the needed value (Reference) to 50 percent. Second, the planning time horizon for coastal managers is lowered from 50 years to 35 years. Both of these changes approximate real-world difficulties in achieving optimal public protection performance over the life of a project.

### **6.2.1 Monte Carlo Results**

The Degraded Protection scenario was tested using St. Mary Parish, a community with levee protection. A Monte Carlo analysis with 1000 storm patterns was performed for the Reference and Degraded Performance scenarios. The Reference results are the same as those presented in Chapter 5. The Degraded Protection results were generated using the same set of storm patterns.

The results of the Monte Carlo analysis are shown in Figure 6-18. The data are normalized by the means of the Reference scenario. A t-test was performed comparing the two scenarios for each metric. The differences between the scenarios for all four metrics were highly statistically significant (Gross output: p-value= $2.3E-34$ ; Population: p-value= $2.0E-50$ ; Storm damage: p-value= $4.5E-35$ ; Evacuees: p-value= $1.1E-27$ ).

Total storm damage is the largest difference between the two scenarios. Average storm damage increases 6.6 percent under the Degraded Protection scenario, when



**Figure 6-18:** Comparison of Reference and Degraded Protection scenarios for St. Mary Parish. Results are normalized to the mean of the Reference scenario.

the levees are poorly maintained and are constructed for conditions 35 years in the future (instead of 50 years). The lower level of protection causes a slight increase in the average number of breaches (0.76 vs. 0.73 breaches per century). The increased frequency of breaches, plus the increased likelihood of overtopping, increases storm damage.

Gross output is larger by a substantively small amount (0.5 percent on average) on average under the Degraded Protection scenario. Correspondingly, the community’s population also grows slightly more. Table 6.3 summarizes the small relative change in the annual growth rate from 2010–2100. The small increase in economic growth is because of increased insurance claim and disaster relief payments from the higher levels of damage.

The increase in average damage is 12 times greater than the increase in gross output. Degraded public protection structures, such as happened in New Orleans, cause the level of damage to increase an order of magnitude more than demographic changes

|                        | Reference            | Degraded Protection  |                             |
|------------------------|----------------------|----------------------|-----------------------------|
|                        | Mean Rate<br>(StDev) | Mean Rate<br>(StDev) | Change<br>from<br>Reference |
| <b>St. Mary Parish</b> | 0.0035               | 0.0036               | 0.0001                      |
|                        | (.004)               | (.004)               | 1.9%                        |

**Table 6.3:** Annual economic growth rates for the Rational scenario from 2010-2100 for Cape Cod, Miami-Dade, and St. Mary Parish. Reference and Rational values are the mean of the Monte Carlo simulations. Percentage change values are the absolute change from Reference divided by the Reference growth rate.

in the community. As such, the damage results of the FRACC model are sensitive to assumptions about coastal managers. If funding or project delays occur, damages will be higher than in the standard Reference scenario. The large increase in damage and small increase in output means that overall economic welfare is reduced in the case where assumptions of perfect foresight and rationality for coastal planners and their funders are relaxed.

## 6.3 Sensitivity to SLR Scenarios

To examine the uncertainty in global SLR estimates, the FRACC model can simulate an arbitrary SLR scenario. By default, the model includes the low, medium, and high values from the IPCC SRES, and an even higher USACE scenario, as described in Section 3.2. The Reference scenario presented in the last chapter uses the higher USACE scenario, which also corresponds with the high end of other recent studies (Rahmstorf, 2007; Pfeffer et al., 2008). A quadratic fit was used instead of a linear fit because it better approximates the SRES paths and the output from GCMs.

Five different SLR scenarios (from Table 3.2) were chosen to test the model’s sensitivity to SLR. Each of these scenarios was run in a Monte Carlo analysis for 1000 different storm arrival patterns. To simplify the presentation, only one location was chosen: Miami-Dade County.

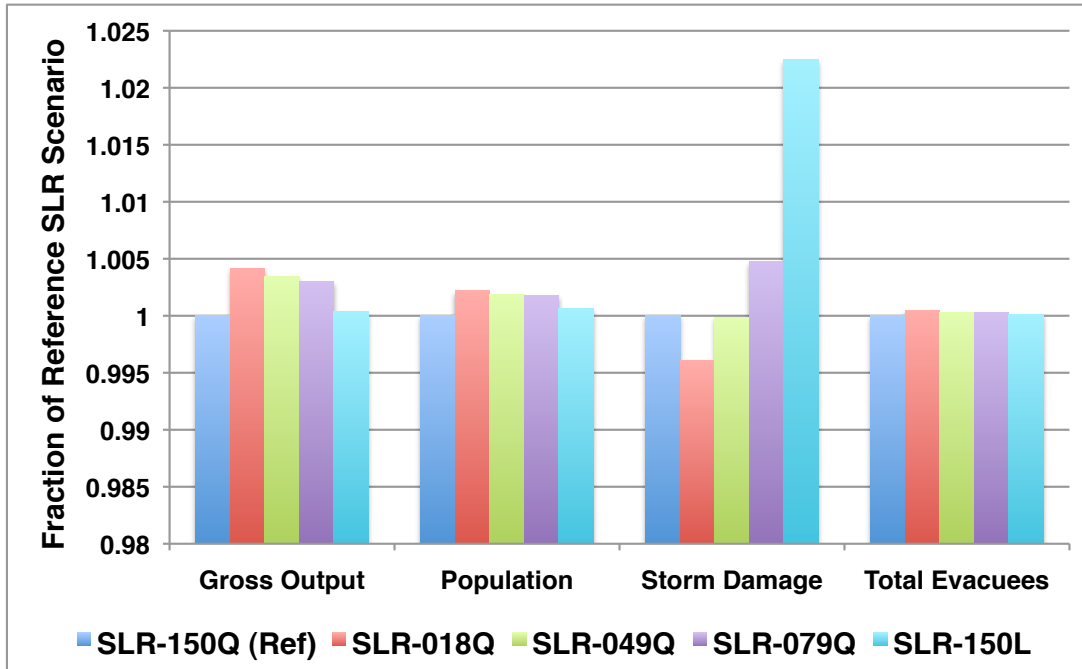
Global SLR scenarios influence economic growth in the community, but only slightly (Figure 6-19). Economic growth decreases by tenths of a percent for progressive larger SLR scenarios (Table 6.4). Economic growth is lower for both of the 1.5 m scenarios than the other SLR scenarios. The coast is protected effectively against a rising sea, so the impact on economic growth is minimal. A similar result occurs for community population.

| SLR Scenario   | Normalized Gross Output |
|----------------|-------------------------|
| SLR-150Q (Ref) | 1.0                     |
| SLR-018Q       | 1.0041                  |
| SLR-049Q       | 1.0034                  |
| SLR-079Q       | 1.0030                  |
| SLR-150L       | 1.0004                  |

**Table 6.4:** Normalized Gross Output for the five SLR Scenarios. Normalized to the Reference SLR scenario (SLR-150Q).

Most results are statistically different from the Reference SLR-150Q scenario (Table 6.5). Two results, storm damage for SLR-049Q and gross output for SLR-150L,





**Figure 6-19:** Comparison of four metrics for different SLR scenarios for Miami-Dade County. Results are normalized to the 2100 Monte Carlo mean of Reference scenario.

do not pass a 95 percent confidence test. The remaining results are significant.

| Scenario       | Storm Damage | Total Evacuees | Gross Output | Population  |
|----------------|--------------|----------------|--------------|-------------|
| SLR-150Q (Ref) | NA           | NA             | NA           | NA          |
| SLR-018Q       | 2.56456E-11  | 8.04151E-18    | 1.20078E-98  | 1.79607E-42 |
| SLR-049Q       | 0.82408912   | 2.12589E-13    | 6.58072E-85  | 1.3127E-40  |
| SLR-079Q       | 6.74117E-17  | 3.46662E-14    | 1.90563E-72  | 3.89234E-44 |
| SLR-150L       | 5.6389E-164  | 0.013037225    | 0.058488961  | 1.50458E-05 |

**Table 6.5:** Student’s t-test results. P-value results after comparing the Reference scenario (SLR-150Q) and other SLR scenarios, for each of the four metrics, for Miami-Dade County.

Economic growth falls because flood damage increases under the higher SLR scenarios. In particular, damage increases as the SLR increases (i.e., comparing the SLR-018Q, SLR-049Q and SLR-079Q scenarios). The SLR-150Q (Reference) scenario has lower damage than the lower SLR-079Q scenario because of the height of protection. Public adaptation structures are built to defend against expected RSLR 50 years from construction. Constructing for future RSLR adds additional protection from present-day RSLR and storm surge risk. Under the higher SLR-150Q, the

construction formula adds more than a 1 meter of additional protection than the SLR-079Q in 2030 (structure height minus scenario's RSLR).

Ultimately the additional protection from the high quadratic-path scenario reduces storm damage to levels similar to the SLR-049Q scenario. The linear-path of the alternative high SLR scenario, SLR-150L, does not benefit from the additional protection. A linear projection of RSLR does not add as much of a safety margin against present-day flood risk ( $\sim 30$  cm more than SLR-079Q in 2030). Instead, the high SLR scenario experiences the most damage because, when a breach occurs, water damage is higher than in any other scenario. The floodwater depth is higher than the other scenarios at any given time because the RSLR is higher at all times (Figure 3-3).

The number of evacuees is almost the same for each SLR scenario because the number and intensity of storms drives evacuation. Each SLR scenario was driven by the same thousands storm patterns, so each received the same forcing. The key determinant in the number of evacuees was the community's population. The SLR scenarios that had higher average population also had slightly higher number of evacuees.

Different SLR scenarios change the outcome of the model. Damage to infrastructure does increase with the amount of global SLR, as previous studies have illuminated (Tol, 2002; Nicholls and Tol, 2006). Importantly, though, the means of projecting protection height influence damage results. In previous studies, the height of a structure is assumed to be the present-day RSLR plus a margin for storm surge. The height increases every year to match the new RSLR amount. For this research, the height is future RSLR (50 year projection) plus a margin for surge. Depending on the SLR scenario, the projected amount of RSLR varies and can increase present day protection, as seen in the SLR-150Q damage results.

### 6.3.1 SLR and economic growth rates

Economic growth rates were calculated for the five global SLR scenarios for each of the communities. Overall RSLR does not affect economic growth as much as other model assumptions (Table 6.6). Growth rates typically increased slightly compared from the Reference scenario, which uses the high SLR-150Q SLR scenario.

|                        | Ref SLR-150Q      | SLR-18Q           |                       | SLR-49Q           |                       | SLR-79Q           |                       | SLR-150L          |                       |
|------------------------|-------------------|-------------------|-----------------------|-------------------|-----------------------|-------------------|-----------------------|-------------------|-----------------------|
|                        | Mean Rate (StDev) | Mean Rate (StDev) | Change from Reference | Mean Rate (StDev) | Change from Reference | Mean Rate (StDev) | Change from Reference | Mean Rate (StDev) | Change from Reference |
| <b>Cape Cod</b>        | 0.0026<br>(.003)  | 0.0029<br>(.003)  | 0.0004<br>14.1%       | 0.0029<br>(.003)  | 0.0003<br>10.8%       | 0.0028<br>(.0029) | 0.0002<br>7.7%        | 0.0023<br>(.0028) | -0.0002<br>-9.2%      |
|                        | 0.0005<br>(.003)  | 0.0006<br>(.003)  | 0.0001<br>10.7%       | 0.0006<br>(.003)  | 0.0000<br>8.8%        | 0.0006<br>(.003)  | 0.0000<br>7.3%        | 0.0005<br>(.003)  | 0.0000<br>0.2%        |
| <b>St. Mary Parish</b> | 0.0035<br>(.004)  | 0.0037<br>(.004)  | 0.0001<br>4.1%        | 0.0037<br>(.004)  | 0.0001<br>3.6%        | 0.0036<br>(.004)  | 0.0001<br>3.0%        | 0.0035<br>(.0041) | 0.0000<br>0.4%        |

**Table 6.6:** Annual economic growth rates for the SLR scenarios, from 2010-2100 for Cape Cod, Miami-Dade, and St. Mary Parish. Annual rates are the mean of the Monte Carlo simulations. Percentage change values are the absolute change from Reference divided by the Reference growth rate.

Of the three communities, Cape Cod shows the most change in economic growth among the SLR scenarios. It has been assumed that Cape Cod does not to protect its shorelines with public adaptation structures because of the low benefit to cost ratio (and lack of public support; see Section 4.2). As a result, RSLR permanently inundates land in Cape Cod, impacting economic growth. Cape Cod has more economic growth (14 percent) under the lowest SLR scenario and less economic growth (-9 percent) under the faster, linear, SLR-150L scenario, when compared to the Reference. Both St. Mary Parish and Miami-Dade construct public protection, which prevents permanent land inundation. RSLR primarily affects storm surge and floodwater height, causing more storm damage.

## 6.4 Sensitivity to Storm Scenarios

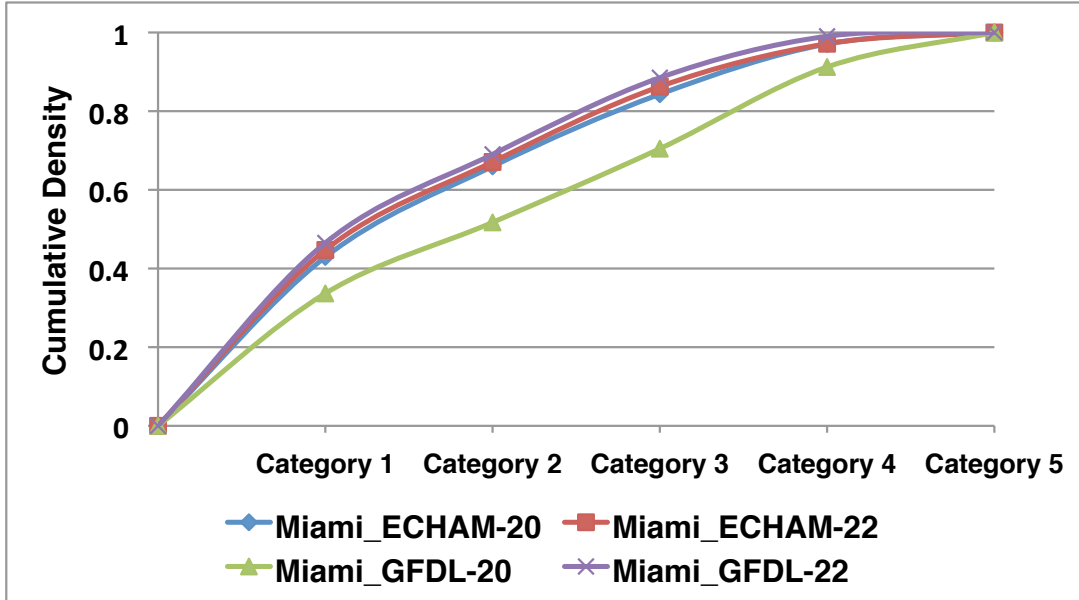
The FRACC model has four built-in hurricane scenarios that differ in two dimensions. First, the scenarios differ by which global circulation model (GCM) is used to generate climatic conditions of the Atlantic Ocean. Two GCMs were selected for comparison: the ECHAM model from the Potsdam Institute and the GFDL model from NASA. The second dimension of differentiation is the global climate scenario that was used to drive the GCMs. This research uses the present climate conditions and the IPCC SRES A1B (Chapter 2). The four pairings of GCM and climate conditions were run through Emanuel’s CHIPS model (Section 2.2) to generate the four storm scenarios of the FRACC model. Miami-Dade’s annual storm frequencies of the four storm scenarios are summarized in Table 6.7.

| Scenario Name | GCM   | Climate | Annual Frequency |
|---------------|-------|---------|------------------|
| GFDL-20 (Ref) | GFDL  | Present | 0.0925           |
| GFDL-22       | GFDL  | A1B     | 0.0851           |
| ECHAM-20      | ECHAM | Present | 0.1087           |
| ECHAM-22      | ECHAM | A1B     | 0.0514           |

**Table 6.7:** The annual storm frequency for Miami-Dade County of the four storm scenarios.

Both the ECHAM and GFDL models predict a decline in future storm activity for Miami-Dade. Also, the intensity distributions are similar for three of the storm scenarios. The outlier is the GFDL-20 scenario, which has stronger storms on average than the other three scenarios (Figure 6-20). Interestingly, the GCMs produce different trends for the other two regions. Annual storm frequency increases in the SRES scenario for Cape Cod and St. Mary Parish. The trends for intensity also depend on location, highlighting the importance of regionalized adaptation studies. Miami-Dade was chosen for the following tests as an example of model sensitivity to storms.

The Reference scenario, presented in Chapter 5, uses the GFDL GCM and the present climate conditions, or the GFDL-20 scenario. The other storm scenarios only



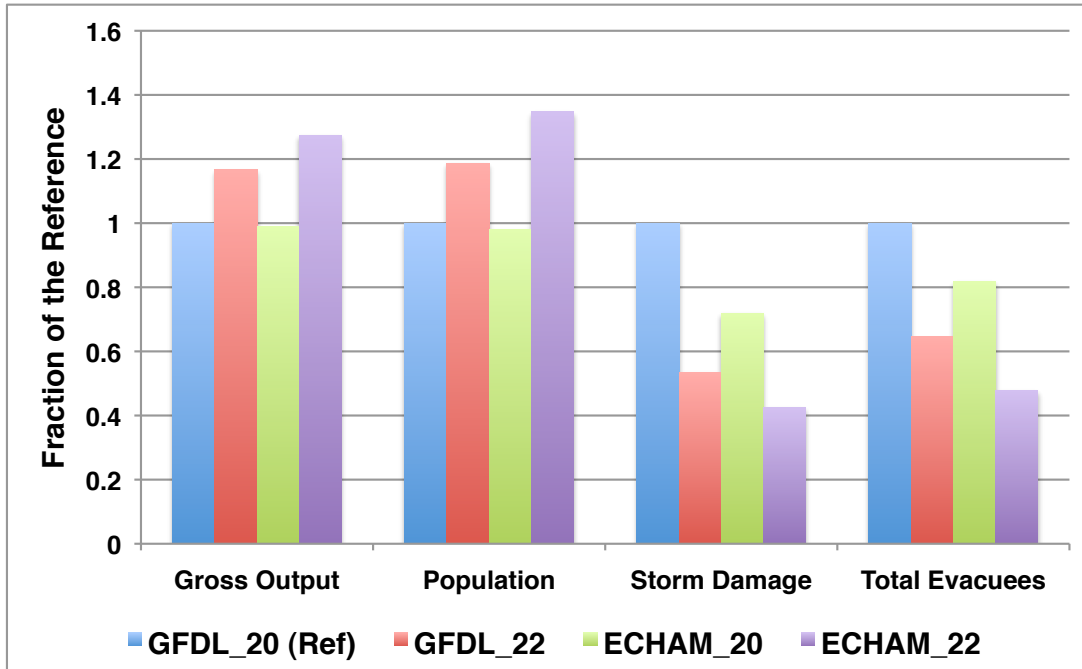
**Figure 6-20:** Storm intensity CDFs for Miami-Dade County for four different GCM climates.

differ by storm annual frequency and the storm intensity distributions. All other Reference scenario parameters remained unchanged. The results below are averages of a Monte Carlo analysis for Miami-Dade, which simulated 1000 storm patterns using the different storm parameters of the scenarios. All of the results for each of the storm scenarios were statistically significant, with the p-value results summarized in Table 6.8.

| Scenario      | Storm Damage | Total Evacuees | Gross Output | Population |
|---------------|--------------|----------------|--------------|------------|
| GFDL-20 (Ref) | NA           | NA             | NA           | NA         |
| GFDL-22       | 3.884E-244   | 5.902E-260     | 7.203E-193   | 3.077E-226 |
| ECHAM-20      | 4.912E-82    | 1.955E-67      | 2.186E-02    | 1.783E-04  |
| ECHAM-22      | 7.582E-190   | 4.457E-233     | 1.619E-194   | 7.389E-258 |

**Table 6.8:** Student’s t-test results. P-value results after comparing the Reference scenario (GFDL-20) and other storm scenarios, for each of the four metrics, for Miami-Dade County.

For the three scenarios with similar intensity distributions, GFDL-22, ECHAM-20, and ECHAM-22, frequency was a strong determinate of the outcomes. The results follow the rank order of frequency of these three scenarios. The scenario with the least storm activity, ECHAM-22, has the highest levels of economic activity and population



**Figure 6-21:** Comparison of storm scenarios for Miami-Dade County. Results are normalized to the Monte Carlo mean of Reference scenario.

(Figure 6-21). The scenario also has the least amount of storm damage and evacuees. ECHAM-20, the highest of the three, has the least average economic activity and population, and the highest cumulative storm damage and evacuees. The frequency of storms clearly drives damage and discourages economic growth. The economic growth changes reflect feedbacks between storm risk perception, investment, and community attractiveness.

Of the four scenarios, the GFDL-20 scenario has the third most frequent number of storms. Even though storm frequency is a strong determinant of model behavior, the GFDL-20 has the lowest amount of economic activity and the highest amount of storm damage of the four scenarios.

The GFDL-20 scenario generates the most average damage because it has a higher probability for more intense storms. Even with a lower frequency than ECHAM-20, storms are likely to be more intense on average, which causes more damage and decreases economic activity to the level of the ECHAM-20 scenario. More intense

storms also cause more infrastructure damage and induce more residents to evacuate, which is why this scenario has the highest levels of damage and evacuees.

Storm scenarios are an important driver of damage in the model. Importantly, it is the combination of frequency and intensity that determines how a community is affected.

### 6.4.1 Storms and economic growth rates

The storm frequency and storm intensities distributions of the four storm scenarios vary for each community. Under future climate conditions, a given GCM may predict more storms for one community but fewer storms in another, compared to the present (Table 6.9). The mixed projections make understanding the impact of future climate conditions on economic growth more difficult.

| Community         | GCM   | Storm Frequency |              |
|-------------------|-------|-----------------|--------------|
|                   |       | 20th Century    | 22nd Century |
| Cape Cod          | ECHAM | 0.0195          | 0.019        |
|                   | GFDL  | 0.0108          | 0.0343       |
| Miami-Dade County | ECHAM | 0.1087          | 0.0514       |
|                   | GFDL  | 0.0925          | 0.0851       |
| St. Mary Parish   | ECHAM | 0.0402          | 0.0441       |
|                   | GFDL  | 0.0399          | 0.0793       |

**Table 6.9:** Storm Frequencies by Region, GCM, and Climate Conditions. The storm frequency for the three communities for the present climate (20th Century; average climate from 1980-2000) and the A1B SRES scenario (22nd Century; average climate from 2180-2200). Measured in storms per year.

Table 6.10 summarizes the economic growth results. Economic growth is the outcome of a combination of storm frequency and storm intensity effects. Cape Cod, for instance, has the highest growth under the GFDL-20 scenario, which has the lowest frequency and a mid-range intensity distribution (for Cape Cod). Cape Cod has the lowest growth under the GFDL-22 scenario, which has similar storm frequency to both ECHAM scenarios, but has a stronger distribution of storms (Figure 4-9).

|                        | Ref GFDL-20       | GFDL-22           |                       | ECHAM-20          |                       | ECHAM-22          |                       |
|------------------------|-------------------|-------------------|-----------------------|-------------------|-----------------------|-------------------|-----------------------|
|                        | Mean Rate (StDev) | Mean Rate (StDev) | Change from Reference | Mean Rate (StDev) | Change from Reference | Mean Rate (StDev) | Change from Reference |
| <b>Cape Cod</b>        | 0.0026            | -0.0052           | -0.0078               | 0.0003            | -0.0023               | 0.0006            | -0.0019               |
|                        | (.003)            | (.0052)           | -300.9%               | (.004)            | -87.2%                | (.0038)           | -75.3%                |
| <b>Miami-Dade</b>      | 0.0005            | 0.0025            | 0.0019                | 0.0005            | 0.0000                | 0.0034            | 0.0028                |
|                        | (.003)            | (.0016)           | 367.2%                | (.0028)           | -5.2%                 | (.0008)           | 540.9%                |
| <b>St. Mary Parish</b> | 0.0035            | -0.0064           | -0.0099               | 0.0040            | 0.0005                | 0.0019            | -0.0017               |
|                        | (.004)            | (.0059)           | -282.0%               | (.0039)           | 13.3%                 | (.0047)           | -47.2%                |

**Table 6.10:** Annual economic growth rates for the SLR scenarios, from 2010-2100 for Cape Cod, Miami-Dade, and St. Mary Parish. Annual rates are the mean of the Monte Carlo simulations. Percentage change values are the absolute change from Reference divided by the Reference growth rate.

Miami-Dade has higher average growth under both future storm scenarios, GFDL-22 and ECHAM-22, because the frequency of storms is projected to decline. Storm intensity for Miami-Dade shifts slightly, but frequency drives the outcomes. St. Mary Parish’s economic growth is lowest under the GFDL-22 scenario, which doubles the frequency of storm activity.

The FRACC model is sensitive to assumptions about storm activity. The results here show that economic growth rates depend on the both the frequency of storm arrival and the distribution of Category 1 to Category 5 storms. Shifts in either can change the economic growth estimates.



## 6.5 Parametric Sensitivity Analysis

The previous sections of this chapter focused the sensitivity of key parameters of the FRACC model. Creating scenarios and testing each parameter systematically builds intuition into the model and insight for research results.

Unfortunately creating scenarios for each of the model parameters is infeasible given time constraints. An alternative is to identify the parameter assumptions that most influence the results of the FRACC model.

To discover which parameters influence the results of the model the most, model parameters were varied  $\pm 10$  percent from their initial value. The results were recorded for four different important outputs: gross output, population, storm damage, and evacuees. Four model outputs were chosen because sensitive parameters likely affect outputs differently.

The magnitude of the change was measured by comparing the modified-parameter run with the Reference scenario. To incorporate transient changes over time, the difference between the runs was squared and summed over time. The integration technique means that changes mid-simulation are captured, not simply change in the final outcomes.

The results of the sensitivity runs were compiled for each of the four output variables separately. Each input parameter was rank ordered by its sensitivity with respect to each output variable (e.g., “share of labor” with respect to gross output). For each input parameter, a mean rank was calculated by averaging its rank across the four output variables. Table 6.11 shows the 35 input parameters that had the highest mean rank. The sensitivity analysis was completed for Miami-Dade using the Reference scenario. Some specific variable names would change for other communities or scenarios.

| Parameter  | Gross Output | Population | Capital Damage | Evacuees |
|--|--------------|------------|----------------|----------|
| Initial Population of Miami                        | 3            | 1          | 4              | 3        |
| Storm Intensities for Miami 1990 GFDL[Cat5]        | 7            | 2          | 1              | 1        |
| Storm Intensities for Miami 1990 GFDL[Cat4]        | 13           | 8          | 3              | 2        |
| Reference Fractional Rate of Immigration           | 8            | 3          | 12             | 5        |
| Reference Fractional Rate of Emigration            | 9            | 4          | 15             | 6        |
| Total Factor Productivity                          | 1            | 11         | 11             | 12       |
| Fraction of Land Developed for Miami               | 10           | 7          | 9              | 9        |
| Share of labor                                     | 2            | 19         | 2              | 16       |
| Fractional Birth Rate                              | 11           | 5          | 17             | 7        |
| Max Damage from Wind                               | 16           | 12         | 8              | 14       |
| Reference Storm Freq for Miami                     | 12           | 6          | 22             | 10       |
| Storm Intensities for Miami 1990 GFDL[Cat1]        | 14           | 9          | 23             | 4        |
| Fraction of Working Age for Miami                  | 4            | 23         | 5              | 22       |
| Initial per Capita Income for Miami                | 6            | 22         | 6              | 21       |
| Labor Force Participation for Miami                | 5            | 24         | 7              | 23       |
| Fractional Death Rate                              | 15           | 10         | 25             | 11       |
| Storm Intensities for Miami 1990 GFDL[Cat2]        | 18           | 16         | 19             | 8        |
| Annual Storm Frequency for Miami in 1990 (GFDL)    | 23           | 15         | 21             | 13       |
| Capital correction time                            | 17           | 17         | 30             | 15       |
| Time for Evacuees to Resettle                      | 20           | 14         | 40             | 17       |
| Returning Time for Evacuees                        | 19           | 13         | 44             | 18       |
| Fraction of Damage Covered by Govt Relief          | 22           | 20         | 34             | 19       |
| Sensitivity of Desired Capital to Relative Return  | 24           | 28         | 32             | 20       |
| Average Living Area per House for Miami            | 25           | 25         | 36             | 24       |
| Initial Number of Houses for Miami                 | 26           | 26         | 37             | 25       |
| Time Horizon for Storm Frequency Assessment        | 21           | 18         | 48             | 28       |
| Initial Rent in Miami                              | 27           | 27         | 38             | 26       |
| Sensitivity of Desired Capital to Aggregate Demand | 28           | 30         | 35             | 29       |
| Sensitivity of Jobs to Aggregate Demand            | 29           | 21         | 47             | 27       |
| Design Storm for Mitigated Floor Height            | 36           | 33         | 20             | 36       |
| Sensitivity of Damage to Wind                      | 35           | 37         | 14             | 40       |
| Storm Intensities for Miami 1990 GFDL[Cat3]        | 34           | 35         | 24             | 34       |
| Disaster Relief Delay                              | 31           | 32         | 39             | 31       |
| Normal Rebuilding Time                             | 30           | 31         | 43             | 33       |
| Historical Output Growth Rate                      | 37           | 39         | 33             | 30       |

**Table 6.11:** Rank order of the model's most sensitive parameters. Variables are ordered by the mean of the four ranks.

The sensitive parameters can be divided into several different categories: economic, population, land development, storms, and adaptation. Economic parameters, such as share of labor (Cobb-Douglas exponent) and total factor productivity are obvious parameters that would influence economic conditions in the community. These parameters are specifically important in determining gross output and storm damage. Damage is a function of cumulative infrastructure, so variables that might increase or decrease investment are significant.

Population parameters are also important. The initial population of the model helps initialize the economic conditions, so it follows that this would be important for overall results. Additionally exogenous immigration, emigration, birth, and death rates are important parameters in determining the community's population and, as a result, the number of evacuees.

In Miami-Dade, land development and available land are binding constraints that reduce the rate of economic growth. Parameters that tighten or loosen the land constraint include Fraction of Land Developed, Average Living Area per House, and Initial Number of Houses. These parameters adjust the land constraint, which can increase or decrease infrastructure investment, and therefore economic growth.

Storm parameters heavily influence the results of the model, as shown previously in the chapter. Both storm frequency and storm intensity parameters ranked highly in the analysis. Additionally, storm damage function parameters are included. These parameters control the fractional damage amount for wind damage. Improving the damage function in the model should therefore be a high priority of future research.

Parameters that are not sensitive include parameters related to wetlands. Wetlands do not influence any of the four output variables. Additionally, parameters such as levee and beach nourishment costs per meter are not in the top 35. These parameters would likely only be important in communities in which the benefit-cost analysis is

relatively close. For Miami-Dade it is usually better to construct public adaptation structures.

One adaptation-related parameter that did rank highly is the fraction of storm damage covered by government disaster relief. Disaster relief from the government spurs economic activity. The importance of disaster relief is examined in more detail in the next chapter.

Future research could do a multivariate sensitivity analysis of the most highly ranked parameters. Defining the parameter PDFs is beyond the scope of this research. Importantly, many of the highly ranked parameters, such as storms and disaster relief, have been examined in other sections of the dissertation.

# Chapter 7

## Policy Scenario Results

The FRACC model evaluates different adaptation policy options. This chapter demonstrates the flexibility of the model by presenting the results of one public adaptation policy. Governmental disaster relief is common in many countries, and is a finance-based public adaptation option. The policy example illustrates a scenario in which the amount of government disaster relief is varied to demonstrate how such a policy would affect economic growth rates and economic recovery time. Government disaster relief was chosen both because it has public policy implications and is a sensitive model parameter, as identified in Section 6.5.

### 7.1 Disaster Relief Policies

The US federal government often provides disaster relief for areas that experience natural disasters. The Federal Emergency Management Agency (FEMA) is the agency responsible for coordinating relief efforts. The government's disaster relief funds provide money to rebuild homes and infrastructure.

The FRACC model includes governmental disaster relief. Relief is a function of the amount of storm damage (Equation 3.65). The government provides more relief after a Category 5 storm than a Category 1 storm, all else equal, because of more extensive damage. The relief flows to the community in the years following the storm, instead

of being injected immediately after the storm.

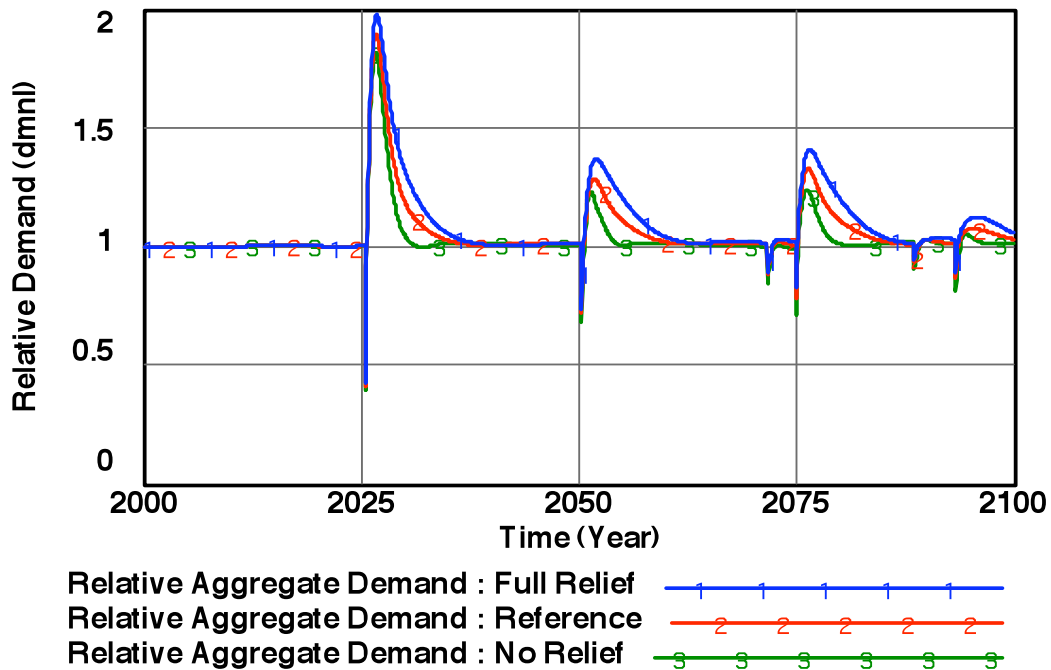
In the Reference scenario, the government provides relief for 50 percent of the damage not coverage by private insurance. To test the effects of disaster relief policy, two other policy scenarios are provided for comparison. The Full Relief scenario is the same as the Reference scenario, except that the governmental disaster relief is increased to 100 percent, meaning that all storm damage is covered by either private insurance or public funds. The No Relief scenario explores what would happen if the government decided it not to cover natural disasters with emergency funding. The percentage of government relief is reduced to zero percent.

## 7.2 Disaster relief scenario behavior

The sample storm pattern (Section 5.3.1) is used to illustrate the behavior of the three relief scenarios. The behavior is demonstrated for Miami-Dade, but the other communities are discussed in the economic growth rates section below.

The flow of relief monies from the government increases total economic demand in the community. Specifically, disaster relief increases the aggregate demand for goods in the local economy (Equation 3.58). Figure 7-1 illustrates that the *Relative Aggregate Demand* is correlated with the level of disaster relief. Higher levels of government assistance increase the demand for economic output. Importantly, demand is sustained at higher levels longer in the higher relief scenarios. Higher sustained economic demand causes the capital and labor adjustment mechanisms (Sections 3.5.2 and 3.5.4, respectively) to increase economic activity accordingly. For example, relief increases capital investment, as shown in Figure 7-2.

Capital investment and labor adjustments increase the capacity for economic output. The community's economy grows in the years after a storm for the Full and Reference scenarios. The economy under the No Relief scenario does not experience



**Figure 7-1:** Relative Aggregate Demand for the disaster relief scenarios. Behavior is for Miami-Dade County from 2000–2100, given three different levels of government disaster relief.

growth, and instead economic output declines over the century (Figure 7-3). The result points to the implications of disaster relief on economic recovery time, discussed further below.

The increase in economic activity also increases the exposure to storm damage. Figure 7-4 shows the increase in cumulative storm damage for the three scenarios. The Full Relief scenario has the most capital damage and the No Relief has the least.

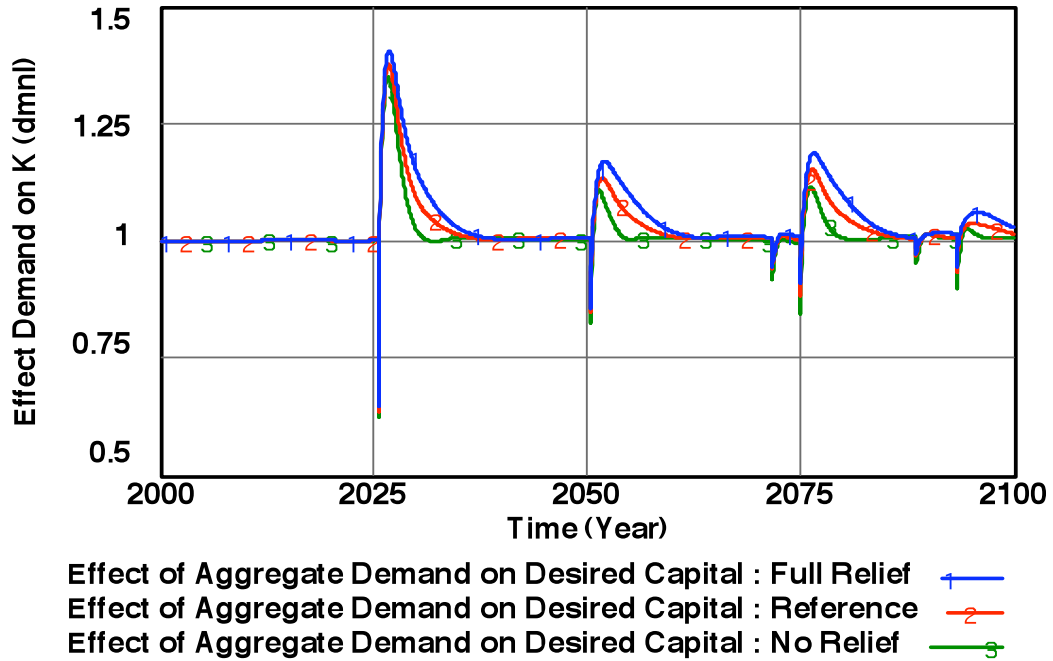


Figure 7-2: Effect of aggregate demand on capital investment, for the disaster relief scenarios. Behavior is for Miami-Dade County from 2000–2100, given three different levels of government disaster relief.

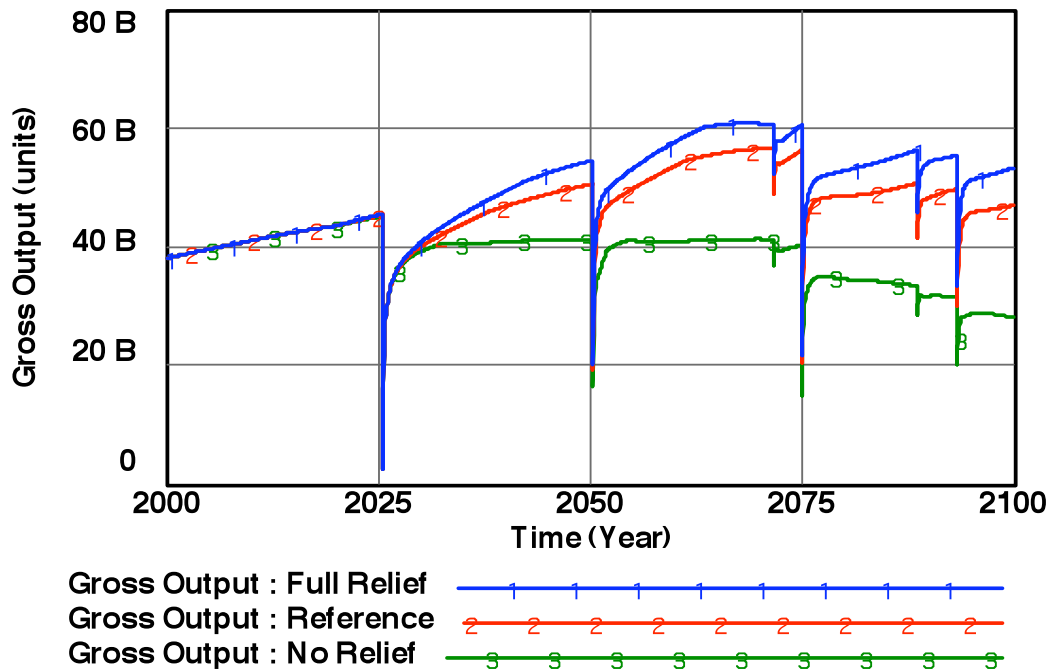
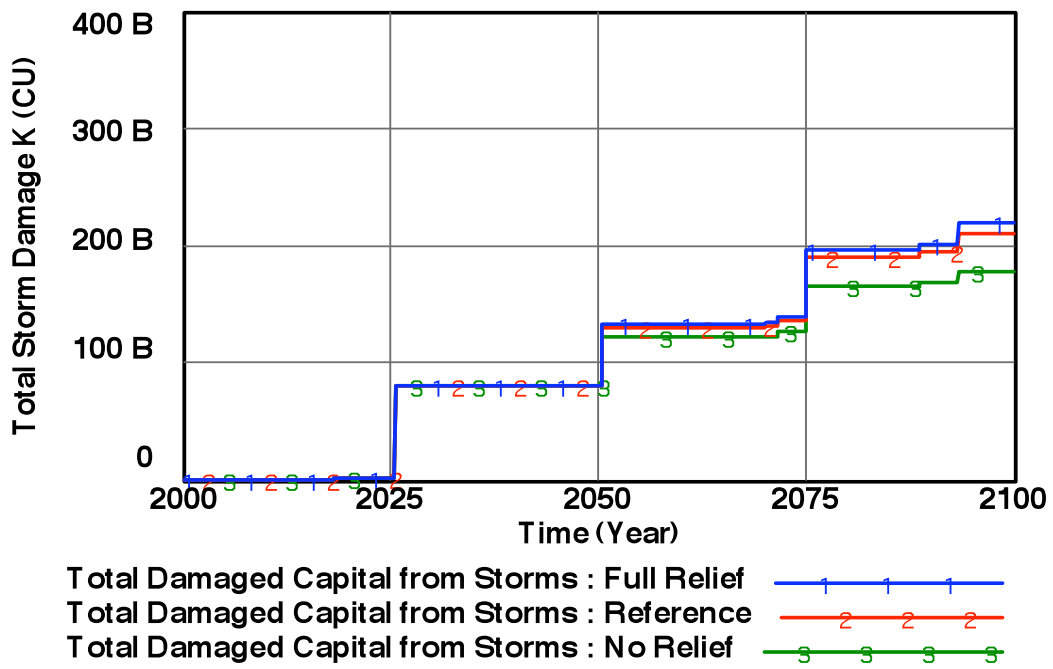


Figure 7-3: Gross output for the disaster relief scenarios. Behavior is for Miami-Dade County from 2000–2100, given three different levels of government disaster relief.





**Figure 7-4:** Cumulative storm damage for the disaster relief scenarios. Behavior is for Miami-Dade County from 2000–2100, given three different levels of government disaster relief.

### 7.3 Disaster Relief Monte Carlo Results

A Monte Carlo analysis was performed for the three relief scenarios. One thousand storm patterns were simulated for each of the three scenarios. The results were then analyzed for gross output, population, cumulative storm damage, and total evacuees. The differences between the three relief scenarios are statistically significant, with the p-value summarized in Table 7.1.

| Scenario           | Storm Damage | Total Evacuees | Gross Output | Population |
|--------------------|--------------|----------------|--------------|------------|
| Reference (50%)    | NA           | NA             | NA           | NA         |
| Full Relief (100%) | 3.1942E-190  | 3.7999E-247    | 0            | 0          |
| No Relief (0%)     | 3.2414E-211  | 1.1339E-243    | 0            | 0          |

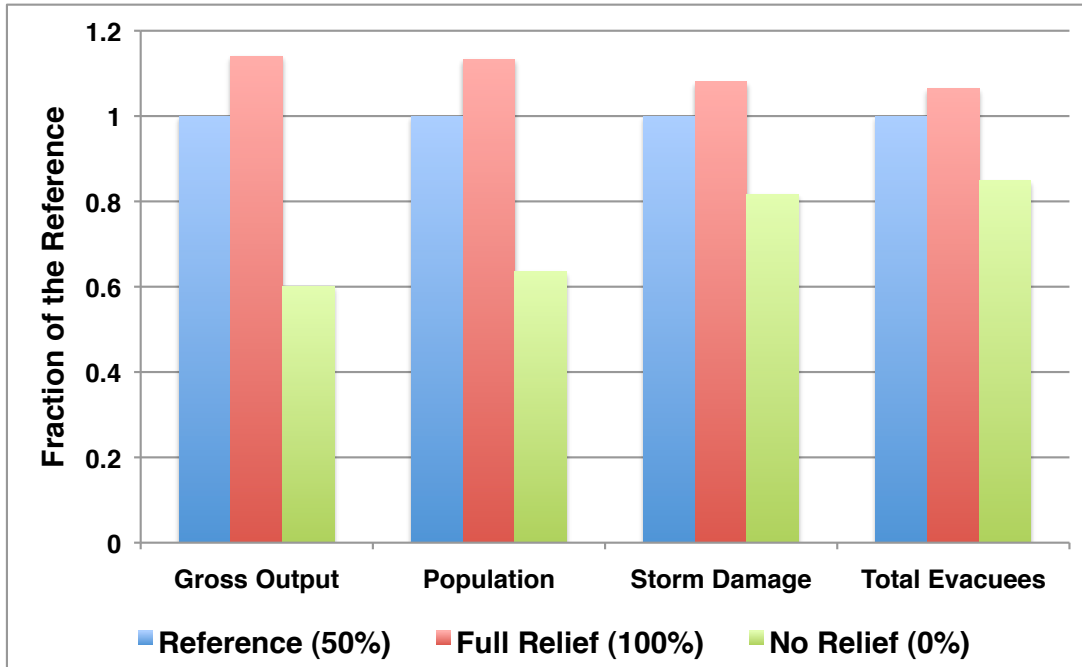
**Table 7.1:** Student’s t-test results. P-value results after comparing the Reference scenario (Half Relief) and other disaster relief scenarios, for each of the four metrics, for Miami-Dade County. Zero values are the result of Excel’s TTEST, representing highly significant values that require many decimals for precision and cannot otherwise be computed.

The Monte Carlo results are shown in Figure 7-5. For the Full Relief scenario, average economic output increases 14 percent while the average storm damage increases 8 percent. Economic output is decreased by 40 percent while damage drops 18 percent for the No Relief scenario.

The reasoning for the results is similar as described for the sample pattern above. Relief boosts economic demand, inducing economic growth. A relief policy provides funds for rebuilding, which increases economic activity, on average.

The larger economy increases the exposure of the community. More infrastructure and a large population mean that storms cause more total damage and drive more people to evacuate during the century. Overall though, the community could be thought to be better off because of the higher economic output.

Relief policies increase exposure to climatic risks, which means that they might not be socially optimal public policies. Relief policies might increase in the total



**Figure 7-5:** Comparison of the three disaster relief scenarios for Miami-Dade County. Plotted are the Monte Carlo means in 2100, normalized to the Reference scenario.

government outlays, more than society benefits from the overall economic growth of the community. Optimal policy analysis is beyond the scope of this work, but an important consideration when designing appropriate adaptation policies.

## 7.4 Disaster relief and economic growth rates

Disaster relief scenarios were simulated in all three communities to understand the effects on economic growth rates. One thousand storm patterns were simulated for each of the communities, followed by a calculation of the average annual economic growth rates from 2010–2100.

As might be expected, higher levels of disaster relief increase economic growth rates. Table 7.2 shows that Full disaster relief improves average annual economic growth for all communities. Contrarily, No Relief decreases economic growth rates.

|                        | Ref Half 50%         | Full 100%            |                             | No Relief 0%         |                             |
|------------------------|----------------------|----------------------|-----------------------------|----------------------|-----------------------------|
|                        | Mean Rate<br>(StDev) | Mean Rate<br>(StDev) | Change<br>from<br>Reference | Mean Rate<br>(StDev) | Change<br>from<br>Reference |
| <b>Cape Cod</b>        | 0.0026               | 0.0029               | 0.0003                      | 0.0021               | -0.0005                     |
|                        | (.003)               | (.0026)              | 11.4%                       | (.0034)              | -18.6%                      |
| <b>Miami-Dade</b>      | 0.0005               | 0.0021               | 0.0016                      | -0.0058              | -0.0063                     |
|                        | (.003)               | (.0025)              | 301.2%                      | (.005)               | -1195.7%                    |
| <b>St. Mary Parish</b> | 0.0035               | 0.0047               | 0.0012                      | 0.0009               | -0.0026                     |
|                        | (.004)               | (.0036)              | 34.2%                       | (.0054)              | -74.8%                      |

**Table 7.2:** Annual economic growth rates for the disaster relief scenarios, from 2010-2100 for Cape Cod, Miami-Dade, and St. Mary Parish. Annual rates are the mean of the Monte Carlo simulations. Percentage change values are the absolute change from Reference divided by the Reference growth rate.

The community most affected by disaster relief policies was Miami-Dade. Miami-Dade experiences a higher frequency of storms, along with stronger storms. The high frequency means that the community benefits more often from a disaster relief policy. Additionally, strong storms cause more damage, which means disaster relief payments would be larger. Miami-Dade is a community whose economic growth depends on a strong reconstruction policy.

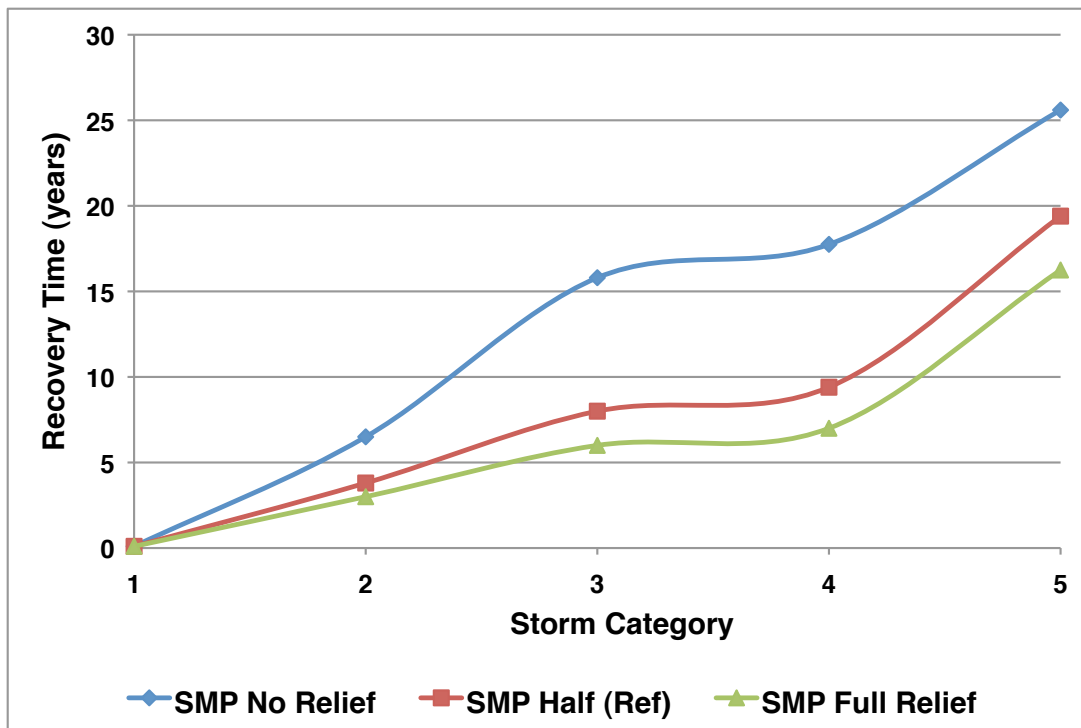
## 7.5 Disaster relief and economic recovery time

Similar to Section 5.5.2, economic recovery times were calculated for the disaster relief scenarios for each community. Overall, disaster relief improves the economic recovery in each of the communities, shown by the decreasing values between, left to right, in Table 7.3.

St. Mary Parish demonstrates the clearest influence of disaster relief on economic recovery time. Recovery time increases as a function of storm intensity independent of the disaster relief scenario (Figure 7-6). The recovery time is least under the Full Relief scenario. Recovery times lengthen as the amount of disaster relief is lowered.

| Community       | Storm Category | Years to Reach Pre-Storm GDP |             |             |
|-----------------|----------------|------------------------------|-------------|-------------|
|                 |                | No Relief                    | Half Relief | Full Relief |
| Cape Cod        | 1              | --                           | --          | --          |
|                 | 2              | --                           | --          | --          |
|                 | 3              | --                           | --          | 48.3        |
|                 | 4              | --                           | --          | 46          |
|                 | 5              | --                           | --          | --          |
| Miami-Dade      | 1              | 2                            | 1.75        | 1.6         |
|                 | 2              | --                           | 4.25        | 3.1         |
|                 | 3              | --                           | 3           | 2.25        |
|                 | 4              | --                           | 3.5         | 3           |
|                 | 5              | 15                           | 6           | 5           |
| St. Mary Parish | 1              | 0.1                          | 0.1         | 0.1         |
|                 | 2              | 6.5                          | 3.8         | 3           |
|                 | 3              | 15.8                         | 8           | 6           |
|                 | 4              | 17.75                        | 9.4         | 7           |
|                 | 5              | 25.6                         | 19.4        | 16.25       |

**Table 7.3:** Time for the disaster relief scenario simulations to recover to the pre-storm level of economic output, after an exogenous storm of a particular intensity was imposed in 2050.



**Figure 7-6:** Recovery Time for disaster relief scenarios for St. Mary Parish. Time to recover to the pre-storm level of economic output, after an exogenous storm of a particular intensity was imposed in 2050.

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# Chapter 8

## Discussion and Conclusion

As the world continues to warm, coastal communities around the world will contend with rising sea levels and changes in storm intensity and frequency. Key stakeholders will be faced with tough decisions: coastal managers will choose whether and how to protect their coastlines; investors will evaluate whether it is safe to build capital infrastructure; and policymakers will continue to set climate mitigation policies. To make these choices, decision makers will rely on the results of climate change adaptation studies.

This research evaluates the importance of including behavioral decision making and expanded system boundaries in climate change adaptation studies. Previous coastal adaptation studies typically assumed rational decision making and risk perception. Additionally, previous studies also simplified the representation of storms, investment decisions, population dynamics, and adaptation options.

The Feedback-Rich Adaptation to Climate Change (FRACC) model examines the effects of a broader system boundary and the relaxation of rationality assumptions. FRACC is a disequilibrium simulation model with explicit representation of storm events (using tropical storms as the example). The model is based on economic theory, field interviews, and psychological, natural disaster, climate change, and engineering literature. The FRACC model parameterizes the rationality assumptions of residents

and investors, and can be used to test different methodological assumptions and coastal adaptation policies.

The two foci for this research were 1) the importance of explicit storm representation for community dynamics, and 2) the implications of rationality assumptions on coastal adaptation studies. The findings in these two areas are discussed below, along with some additional findings and areas for future research.

## **8.1 Importance of Stochastic Storms**

The FRACC model includes a stochastic storm arrival model that can be initialized for the present climate as well as hypothetical future climates. The inclusion of stochastic storms differs from many previous coastal adaptation studies, which usually adjust economic output by the likely annual storm damage.

### **8.1.1 Storms increase economic growth rate variance**

The inclusion of explicit storms generated a new finding—coastal communities could experience significant changes in average annual economic growth rates, all other parameters held constant. Depending on the sequence of storms, some simulations (of a Monte Carlo analysis) had higher economic growth rates while others were lower.

Previous studies typically use likely annual storm damage instead of explicitly representing storm arrival. Likely annual storm damage reduces a community's economic growth rate compare to a no storm scenario because capital stock is damaged. Overall, economic growth is smooth and, for a given set of input parameters, there is no variance in the economic growth rate projection. Using likely annual damage provides a single estimate of economic growth, all else equal.

The FRACC model can estimate average annual economic growth rates along with the standard deviation. Storms arrive randomly and impact the community's econ-



omy differently, depending endogenous factors such as the timing of public protection and perceived risk of recent storm activity. In this study, storms can decrease economic growth by up to 63 percent (Table 5.6). Importantly, the standard deviations around growth rates are significant. It was found that the standard deviation could be large relative to the mean (e.g., Cape Cod has mean 0.0026 with standard deviation of 0.0029). The standard deviation can be particularly important for communities that might experience low economic growth even in the absence of storms, such as Miami-Dade. For low-growth communities, the standard deviation is an order of magnitude larger than the mean.

Likely annual storm damage methods do not have explicit storm events. Instead, the cumulative likely damage from various storm sizes (1 in 10, 1 in 100, etc.) reduces economic activity. The likely, or probable, annual damage is removed every year, rather than as a discrete loss when a specific storm occurs. Studies utilizing this method do not show the same community dynamics as the FRACC model and cannot be used to study the extent storm activity causes variability in a community's long-term economic growth. The inclusion of stochastic storms allows for more realistic studies of economic variability in coastal communities.

### **8.1.2 Storms allow for recovery time studies**

The inclusion of stochastic storms also allows for a community's economic recovery time to be examined. Economic recovery time is the length of time after a storm required for a community to return to pre-storm economic activity.

Economic recovery time captures a sense of a community's resiliency to storms. Communities that recover more quickly can be considered more resilient to storm activity. Resilient communities can recover from storm damage because of their economic base and the policies in place to rebuild after a storm. Adaptation policies, such as disaster relief, can be evaluated as to how they affect recovery time and community resiliency.

### 8.1.3 Storms generate important economic dynamics

Besides the quantification of long-term economic growth rates, explicit storm events allow the study of the economic dynamics in the aftermath. As stated above, most previous coastal adaptation studies model storm damage using the likely annual damage. Because there is not an explicit storm event, economic output of these models tends to be smooth over time, possibly with a lower growth rate.

The output of a particular simulation for the FRACC model illustrates the impact of a storm pattern on the community. Capital and housing are damaged, people evacuate, and economic output declines steeply. Instead of continuing smoothly from year to year, the community is shocked out of equilibrium. The community may recover over time, but the labor and capital markets do not instantaneously adjust. Instead, the community remains out of a steady-state growth path as adjustment mechanisms bring the system back into balance.

A recent storm example is Hurricane Katrina in New Orleans. The storm caused severe damage to the community's infrastructure and displaced thousands of residents. Since the storm, federal disaster relief monies have funded reconstruction and approximately three-quarters of the residents have returned. The dynamics of reconstruction after of a storm are important to understanding the impact of storms on coastal communities.

When the economic dynamics are more explicitly modeled, points of policy intervention can be identified. Policies could be implemented (e.g., elevating houses) to reduce the magnitude of the short-term economic decline or to decrease the duration of the decline (e.g., increase insurance participation). One key point of intervention is found to be government disaster relief, which is discussed below.

#### **8.1.4 Storms change development patterns**

In the FRACC model, land availability can restrict infrastructure investment and, therefore, economic growth. When infrastructure is retired or is damaged, land is cleared and can be developed again.

Some communities, such as Miami-Dade County, have built infrastructure on a significant fraction of their developable land. When a storm strikes these communities, infrastructure is damaged. Some of the damaged infrastructure is rebuilt and the remainder is discarded sooner than it otherwise would have been. These early discards free up land, so investment might be less restricted than before the storm.

Demand for infrastructure has to be present for the increased land availability to translate into increased investment. If demand for economic output and housing falls, investment will likely decline even though it could be higher than the pre-storm levels. Demand might fall after a storm if residents choose to relocate to other communities because of perceived storm risk, the lack of jobs, or the lack of available housing.

In general, urban development and related urban density changes are an important limitation of the FRACC model. The limitation is discussed further below.

#### **8.1.5 Storm frequency and intensity interact**

Both the frequency and intensity of storms significantly affect the economic conditions of a community. A higher storm frequency leads to higher storm damage and lower economic growth, all else equal. If the distribution of storm intensities shifts such that stronger storms are more likely, storm damage increases and economic growth falls, all else equal. In reality, these two storm parameters will likely both change.

The interaction of frequency and intensity changes a community's economic growth rates. Four different storm scenarios were examined to explore the impact on growth.

The parameters of the four scenarios were outputs of a physics-based hurricane model driven by four different global climate conditions (Section 4.5.3).

In one scenario, St. Mary Parish experienced similar storm intensities but with twice the frequency. The economic growth rate dropped from 0.0019 to -0.0064 because of the increase in storm activity. Economic growth was faster for Miami-Dade (increasing from 0.0005 to 0.0025) when storm intensities weakened, but arrived with approximately the same frequency.

Comparisons of both frequency and intensity change are more difficult. A response surface for a community might be possible, though it would be community specific.

Storm frequency and intensity were highly sensitive parameters in this research, as shown by the economic growth rate results. Coastal managers would like to have useful and reliable climate projections to make decisions. The variation of GCM storm projections for a given community and the high sensitivity of the FRACC model to these parameters make precise projections difficult. Instead of specific predictions, it will be important to provide tools to understand relative risk and analyze the uncertainty, until regional storm projections can be improved.

### **8.1.6 Storms are more important than SLR**

Separate sensitivity analyses of storms and SLR show that, for the cases analyzed here, results are more sensitive to changes in storm characteristics (frequency and intensity) than to changes in the magnitude of future SLR. In particular, shifts in storm patterns change economic growth rates more than any of the global SLR scenarios tested (comparing Tables 6.6 and 6.10).

Larger amounts of SLR did reduce average economic growth rates. The higher SLR scenarios had higher floodwater height during a storm, resulting in more damage. Additionally, if a community did not choose to hold back the sea, higher amounts of SLR permanently inundated more land, possibly reducing infrastructure investment.

Overall, though, storm characteristics influence long-term growth rates more than SLR. For Cape Cod, for instance, SLR impacted economic growth rates from -9.2 percent to 14.1 percent, over the range of five SLR scenarios (0.18–1.5 m by 2100). Storms changed Cape Cod’s economic growth rates from -300 percent to -75 percent between 2010–2100. Aggregating the results for the three communities, changes in SLR varied economic annual growths rates between 2010–2100 from -9.2 percent to 14.1 percent, while storms varied growth rates from -300 percent to 540 percent. In general, storms have a much stronger impact on growth rates, independent of the community.

SLR has been the climatic driver included most in coastal adaptation studies. This dissertation shows that it is important to include storm dynamics in future coastal adaptation studies because storms can change economic projections significantly. While a disequilibrium economic model, such as FRACC, is important to understanding economic adjustments after a storm, stochastic storms could be added to more traditional coastal adaptation models. Damage caused by stochastic storms would replace the likely annual damage formulation currently used in these models.

## **8.2 Implications of Bounded Rationality**

The second important research question involves relaxing the traditional assumptions of rational expectations and perfect foresight. Many previous economic analyses of coastal adaptation use classical economic assumptions. Decision makers in such models act with perfect understanding of future climatic risks. Applied to storms, investors make infrastructure decisions knowing the future likelihood of storm events. Their decisions would correctly take into account changes in storm frequency or intensity.

Bounded rationality provides an alternative to rational decision making theory, one that better reflects real-world conditions. The FRACC model implements a boundedly rational representation of storm risk perception. When storms occur, investors perceive the frequency to rise above their pre-storm expectation. In periods

of inactivity, investors' perception of storm frequency falls, possibly below the actual storm frequency.

### **8.2.1 Rationality and adaptation studies**

The implications of rationality assumptions for model results are significant. Model simulations that utilized rational risk perception projected economic output to be 28 percent higher, on average, than boundedly rational simulations. The additional economic activity also means that the community had a larger population, more total storm damage, and a larger number of cumulative evacuees. Correspondingly, boundedly rational simulations had less total storm damage because the economy was smaller.

The rationality assumptions of adaptation models can change the outcome of vulnerability and economic cost studies. Vulnerability studies may estimate a larger number of people and capital at risk if they use traditional rational assumptions. Boundedly rational risk perception leads to lower community growth on average, leading to lower estimates of vulnerability. After reading a rational-based study, policymakers might make coastal adaptation decisions to protect communities that are projected to be large, when they might actually be smaller.

Rational-based adaptation studies that performed benefit-cost analysis for public adaptation might be estimating higher levels of protection than would be suggested by boundedly rational models. Rational assumptions lead to higher economic growth and installed infrastructure, making levees and beach nourishment projects appear more beneficial. Boundedly rational models might suggest levels of protection that are lower. Note that this research cannot support this finding directly, because the three case study communities either protected or did not, regardless of the rationality assumption.

### **8.2.2 Rationality and economic growth rates**

Relaxing the rationality assumption also has important implications for long-term economic growth. For the three case studies, communities with boundedly rational actors had lower average economic growth rates. Conversely, St. Mary Parish and Cape Cod had growth rates that were almost 123 percent and 75 percent higher, respectively, with rational actors. Miami-Dade's average growth rate was 560 percent higher under rational instead of bounded rational assumptions.

Economic recovery times were also affected by rationality assumptions. Cape Cod recovered to pre-storm economic output under rational assumptions but did not recover under bounded rational assumptions. The higher economic growth rates of rational assumptions improve the recovery time for communities.

The boundedly rational risk perception formulation allows for people to overreact to storm activity. If two storms happen in a relatively short time, perception of storm risk can become irrationally high. A high perceived storm risk drives people to lower their rate of investment and slows population growth, which will lower future demand for economic output and lower long-term economic growth, all else equal.

The possibility of overreaction, because of higher-than-real perceived risk, creates a more fragile economy. Infrastructure investment depends on investors' expectations of their expected to return on new investment. If they perceive the risk of storm damage to be high, they expect the lifetime of capital to shorten, decreasing the time to realize a return. The result is a decline in investment and slower economic growth overall.

### **8.2.3 Optimistic rationality assumptions**

While I relax rationality assumptions regarding perceived storm frequency in the FRACC model, I make other assumptions that embody rationality. These assumptions are likely to prove optimistic with regard to community adaptation to climate

change.

### **High level of maintenance performed**

The first optimistic assumption is a high-level of preventive maintenance to public protection structures. By default, I assume that 90 percent of annual maintenance is performed. While it is hard to quantify the exact level of maintenance performed to existing structures, budget pressures and schedule delays lower the level of maintenance performed from the optimal. Levee failures in New Orleans after Hurricane Katrina have been attributed both to a lack of maintenance and delays in upgrading the level of protection (USACE, 2009).

Maintenance requires consistent annual funding, sustained for the life of the structure. In the US, levee maintenance is typically the responsibility of the local government, not the federal government (which may help fund construction). Local politicians face pressures to reduce property taxes and increase funding for local programs like education. Sustaining funding for levee projects is difficult given budget crunches and competing priorities, especially during lulls in storm activity.

Local and federal governments typically fund beach nourishment jointly over the life of the project. Each regular “renourishment” is a process that has to be approved and funded by both governments. Again, budget and political priorities may compete preventing optimal maintenance.

Adaptation studies like Fankhauser (1995) assume that public protection functions as designed for the entire simulation, which assumes perfect maintenance from 2000–2100. A lower level of maintenance will degrade the performance of a structure, increasing the likelihood of breaching and flood damage. Assuming perfect maintenance is an optimal assumption that decreases damage estimates and can change the economic projections of integrated assessment models.



## **Coastal managers protect with perfect foresight**

The second rationality assumption is 50 years of foresight and performance of coastal zone managers. There are three problems regarding the assumption: 1) uncertainty in RSLR projections, 2) constructing protection for 50 years from now today, and 3) regular maintenance is properly funded and implemented for the life of the structure.

RSLR projections are uncertain today. Coastal managers will need to estimate the appropriate height of protection given today's estimate of RSLR 50 years from now. In the FRACC model, coastal zone managers predicted future RSLR with certainty. The level of protection was always adequate and never over- or under-estimated. In the real world, projections will likely have some degree of error. For example, protection that would have been built based on global SLR projections in the 1990's would likely be inadequate for 2040, given recent higher estimates of global SLR today.

Along with issues of certainty in RSLR projections, coastal zone managers are assumed to get adequate funding today for protection appropriate for 50 years from now. There may be budget realities that may prevent such costly construction. Funding is also an issue for regular maintenance and upkeep. Hurricane Katrina showed that funding and poor maintenance is a real-world phenomenon that decreases the performance of the protection.

In the FRACC model, building with 50 years foresight creates another optimistic result: at any given moment the level of protection is always built for the design storm that would occur 50 year in the future. Protection is built continuously for the storm 50 years from present, adjusting for recent RSLR estimates. The assumption provides an extra level of protection to the community at all times during a simulation.

In Section 6.2, I demonstrate that FRACC model results are sensitive to these coastal manager assumptions. Specifically, lower levels of maintenance and foresight increase damages 12 times increase of demographic and economic conditions. The

results has important implications for all integrated assessment models. Adaptation studies should represent maintenance, planning, and coastal protection decisions in a more behaviorally realistic fashion. Failure to relax these assumptions results in an underestimation of storm and SLR damage by an order of magnitude.

A more realistic assumption might be a reactionary construction policy. Protection would be built with 50-year foresight after a triggering event, such as a large storm. No further construction would occur until another triggering event. Formulating protection construction as such would mean the relative level of protection would fall because of RSLR, until the next triggering event.

### **Near-miss storms not affect community**

In the FRACC model, boundedly rational investors and residents react only to storms that actually make landfall in the community. Additionally, residents are only evacuated for storms that make landfall. Neither investment decisions nor evacuation are affected by “near-miss” storms, or storms that approach the community but make landfall elsewhere.

Near-miss storms pose a problem for coastal communities. While they don’t cause as much storm damage (some wind damage may occur), they still disrupt economic activity. In reality, government officials may evacuate residents as the storm approaches the coast. Evacuation and the potential for damage makes the threat of storms more tangible for residents and investors.

Near-misses could be included in the FRACC model by having two different storm frequencies. The first storm frequency would be for storms that make landfall, similar to the current frequency. A second storm frequency could be for storms that make landfall within fixed range (e.g., 100 km) of the community. The frequencies may be the same for a small region, in which only one frequency is needed. Two random numbers could be drawn to evaluate whether a landfall and/or near-miss storm arrives. If a landfall storm arrives, then the model behaves as currently formulated. If a storm

does not make landfall but a near-miss occurs, then investors and residents react marginally to the threat. Evacuation and economic disruption occurs, but perceived storm frequency may not rise as much as it would for landfall storm.

The exclusion of near-miss storms makes the projections presented in this dissertation more optimistic. Near-miss storms would increase the perceived risk of storms marginally. The corresponding decrease in investment (which would decrease less than a landfall storm) would not be offset by an influx in disaster relief because no damage occurred. Near-miss storms would likely lower economic growth rates further than presented in the results chapters.

### **8.3 Disaster Relief and Economic Growth Rates**

The FRACC model can be used to test public policy options. Government disaster relief was chosen as a demonstration policy in Chapter 7. Three different scenarios for relief were simulated: full, half, and no relief.

Disaster relief increases economic output after a storm—the more disaster relief, the higher the economic output. Economic output is spurred by increasing the demand for economic production. For example, government assistance increases the demand for construction materials required to rebuild infrastructure. Without governmental financial assistance, funding reconstruction becomes more difficult.

Higher levels of disaster relief increase the average annual economic growth rate. All three communities had higher growth rates under the Full Relief scenario than either of the other two scenarios.

Higher levels of disaster relief reduces the economic recovery time of a community. When a community is compensated for storm damage, economic output rises to the pre-storm levels faster. Recovery time was shortest with the highest levels of disaster relief.

As a policy lever, disaster relief appears to play an important role in community resiliency. Other policy options, such as mandatory flood insurance or stricter building codes, might have similar effects. These alternative policies may be less costly than long-term public funding of reconstruction.

Disaster relief also increased average storm damage in a community. After a storm, the community rebuilds using disaster aid. Once rebuilt, subsequent storms damage both the new and old infrastructure, increasing the average damage relative to scenarios with no disaster relief. The socially optimal level of relief may be different from today's levels. Defining the precise level of disaster relief is beyond the scope of my dissertation.

The FRACC model can test coastal zone management policies. Along with disaster relief, FRACC can evaluate policies regarding flood insurance (e.g., mandatory option), physical mitigation of infrastructure (e.g., enforcement of existing FEMA policies to elevate houses), public protection maintenance, changes in the design storm for public protection, and moral hazard issues of public protection. The effect of these policies can be explored in future work.

## **8.4 Generalizing Insights**

Insights from the FRACC model could be applied to different regions of the world and integrated into different adaptation models. Some of the issues and pitfalls are discussed below.

### **8.4.1 Application to communities in other regions**

The FRACC model framework provides a solid base for extension to non-US geographies. The interaction between the climate, economic and adaptation components would largely remain unchanged. These component feedbacks are fundamental to most societies and economies. For example, capital investment in many economies

depends on expected return on the investment. In more planned economies, such as China, the structure of the model would need to change to represent the less market-driven incentives and decision making.

Model initialization for a new community is the fundamental chore of adapting the FRACC model. The data detailed in Chapter 4, such as coastal slope, population, wetland area, and storm distributions, would have to be gathered. Data for some communities might be harder to gather than others—a difficulty faced by other adaptation studies as well. Data is likely available for European communities, which would be a logical first choice when trying to extend the model outside the United States.

Adaptation responses will differ depending on societal preference and readily available options. In the US, levees and beach nourishment are likely public responses. Even so, the three case studies (Chapter 4) show that different regions of the US respond differently (i.e., levees in St. Mary Parish, beach nourishment in Miami-Dade, and no large-scale protection in Cape Cod). In part, community preference determines the nature of the response. Miami-Dade has a strong preference for usable beaches, while St. Mary Parish has a history of levee protection. Additionally, the availability of sand and other construction resources may restrict adaptation options in a community.

Outside the US, communities may have different adaptation preferences. The Netherlands has a history of both levees (there termed dikes) and beach nourishment. The Dutch manage flood risk more extensively than most societies, with detailed plans to reduce long-term risk. Other societies, possibly in developing countries, might not have a history of managing floods and may be more inclined to retreat. Adaptation options will have to be parameterized accordingly when transferring the model outside the US.

Consistent global data sets could provide a means for both studying communities outside the US, as well as aggregating and scaling up regional studies. The DIVA

coastal database could be used as a first approximation. The database includes economic, coastal morphology, and wetland data for the world's shoreline (Vafeidis et al., 2008), and is being actively developed and updated. The database could be supplemented by other global databases, such as the Nordhaus' geo-economic database (Nordhaus, 2006). The combination of different global data sets should improve adaptation estimates.

### **8.4.2 Application to different adaptation models**

A key insight of the FRACC model is the importance of the stochastic storm component. The inclusion of stochastic storm events allows for the study of economic dynamics including growth and recovery time. Relaxed rationality assumptions, the other fundamental insight, could also be included in non-FRACC models, allowing for the study of behavioral-based adaptation responses.

Other adaptation models, such as FUND or the full DIVA model, could represent storms explicitly. Storm distributions could be defined in a similar fashion to the FRACC model, including both frequency and intensity. Storm arrivals could be included as a Poisson process, as in this research. However, the time step of adaptation models would likely need to be reduced to increase the temporal resolution around storm arrival.

The impacts of storms in other models would differ from that of the FRACC model because many of the other models include an exogenous economic growth rate. If the economic growth rate is exogenous, studies of community resiliency and long-term economic growth rates become difficult. Additionally, other models have simplified capital accumulation formulations, in which future capital depends primarily on current capital. These models do not have adjustment mechanisms for return on capital, for instance. The inclusion of storms might allow for different economic outcomes, such as a wider range of economic estimates, but the study of adjustment dynamics would be limited.

Adaptation models should also include boundedly rational perception of risk. The addition of different risk formulations would mainly be important if stochastic storms were also included. Investment decisions could then be modified to use perceived risk, similar to this research. Without explicit storms, boundedly rational risk perception could be included with regard to public protection measures, such as levees. Investors in the FRACC model believe public protection is 100 percent effective against the design storm (Section 3.8.1). Models could include a similar formulation, instead of formulations that involve knowledge of the actual likelihood of failure.

Additionally, the FRACC model's results could be utilized in other economic and climate change models by generating response surfaces. The responses surface could vary several key parameters at once, including storm intensity and frequency, fraction of properties mitigated, and capital density. Other response surfaces could be generated, such as a surface describing economic growth rates, that depend on governmental disaster relief, insurance payments, and climatic forcings.

### **8.4.3 Aggregating to the nation-scale**

Applying the insights of this dissertation to other models most likely involves a change of regional scale. Many integrated assessment and adaptation models project outcomes for countries, not counties and communities like the FRACC model. Extending the FRACC model insights to countries involves changing some fundamental assumptions.

The FRACC model currently only includes one storm type: tropical storms. The inclusion of a single storm type may be reasonable for a single community, but probably unreasonable when considering storm activity for a country. The three communities chosen for this dissertation demonstrate the issue. Tropical storms are important weather events for Miami-Dade and St. Mary Parish, but not for Cape Cod where extra-tropical storms may be more important.

When scaling up, new storm types appropriate for various regions of a country should be included. For instance, when examine the US as a whole, nor'easters should be included for the Northeast and Pacific storms should be included for the West Coast. Emanuel's model can be used to estimate tropical storm characteristics for various regions of the US. I am unaware of equivalent storm models for extra-tropical storms.

When determining the storm characteristics for a country, a regional approach could be taken. Considering the US, coastal states could be regionalized into South-Atlantic, Mid-Atlantic, Northeast, etc. Storm models, such as the CHIPS model (Emanuel et al., 2008), could estimate storm frequency and intensities for a particular region. Hallegatte (2007) demonstrated the technique for the east coast of the US. Such an approach would limit the amount of storm data required for a nation-scale analysis.

The FRACC model assumes that the community is a small fraction of the larger national economy. As such, the economic changes in the community are compared to a national economy, which is assumed to be constant. When aggregating from a local community to the national scale, the assumption would be violated because multiple storms could occur in a year and impact the national economy. Also, a large storm, such as Hurricane Katrina, was found to impact national economic growth, and had international consequences via the regions influence on the global oil price.

A community in the FRACC model was small relative to the nation, so the community didn't have to worry about disaster relief funding. It was assumed that sufficient funding would be available from the federal government. When aggregating, different regions of a country would be competing for federal disaster relief. Additionally, regions struck by storms would also be competing with other natural disasters, like forest fires and earthquakes. Some representation of budget pressures will be important when aggregating to the national scale.



Aggregation may create data consistency issues. As stated above, it will be important to have consistent national or global data sets, such as DIVA, that can provide a reasonable level of resolution for a country.

Investors and residents in the FRACC model were boundedly rational with regard to storm frequency. Their perception of storm frequency was dependent on storm activity. When aggregating, it may be reasonable to have a formulation that considers storm activity of neighboring regions. For example, if a storm strikes South Carolina, North Carolina residents may take some precautions that they otherwise would not have done. Regions would no longer be isolated, as they are in FRACC.

The time step, or the temporal resolution of a model, may be particularly perplexing with regard to aggregation. National-scale models sometimes have long time steps (e.g., DIVA is five years) compared to the three-week time step of the FRACC model. Representing stochastic storms and their damage properly is problematic. If understanding storms is important to the modeling exercise, shortening the time step appears to be the best solution, which will increase run times and likely violate some current model assumptions.

Another problem with the longer time steps of other models are the relatively short time constants in the FRACC model. Of particular interest is the time for boundedly rational agents to forget, or become habituated, to storm risk. Investors and residents are assumed to forget about storms relatively quickly (constant = 10 years), and would need to be examined to make sure the behavior is correct.

#### **8.4.4 Integrating into a general equilibrium model**

The FRACC model is a disequilibrium economic model with boundedly rational investors. The following section explores some methods for integrating insights from this dissertation into a general equilibrium model. To be more concrete, the Emission Prediction and Policy Analysis (EPPA) model (Paltsev et al., 2005) from MIT's Joint

Program on the Science and Policy of Global Change is discussed.

The EPPA model is currently aggregated into sixteen world regions. I would relate a smaller geographic database to those regions, like Sugiyama et al. (2008) did with the DIVA database. The higher resolution data, based on linear coastal segments, would be the basis for coastal adaptation impacts (Vafeidis et al., 2008).

Segments would be assigned storm intensity and frequency depending on their geographic region. The regions would be sub-national, or at a scale appropriate for storm system modeling. Storm prediction models (e.g., CHIPS) would be run for these storm regions (see Hallegatte, 2007) to generate the storm frequency and intensity parameters.

For a first-order approximation, I would assume that the small segments would have full funding for adaptation measures and full disaster relief funding. As previously stated, this is an optimistic assumption. As EPPA is an equilibrium model, the money would be required to come from other sectors of the economy. A more complex decision rule regarding budget priorities could be developed, in which disaster funding competes with other economic priorities.

The above method does have limitations and many of the insights from this dissertation would be lost. In particular, because the social accounting matrix is still at the national level, it will be difficult to integrate the impact of boundedly rational investors in to the EPPA framework. A single storm in FRACC reduces investment, but it would likely not be appropriate to change the national investment rate.

## 8.5 Possible Research Extensions

As with any important topic, there are always more questions that could be answered and more work that could be done. This dissertation could be extended in several ways to provide more insight into coastal adaptation. The two high-priority

topics for future work are the urban development model and perceived storm risk formulation.

Current assumptions about the processes of land development are not very detailed. An urban development model that included processes such as “urban infill” and increasingly dense housing could improve the model results. The model currently uses the “floor area ratio” (FAR), a common urban planning and zoning guideline, to parameterize urban growth. FAR is constant in the model now, but could evolve over time. A likely outcome of this extension would be higher levels of long-term economic growth in already dense communities, because growth would not be restricted as tightly by land constraints. The land restriction is a sensitive variable, so improving the understanding and defining a range is important to bounding FRACC model output.

Perceived storm risk could be structured differently in future work. Currently a Category 1 storm increases perceived risk as much as a Category 5 storm. One alternative formulation is to make perceived risk a function of storm category. Category 1 storms might be forgotten quicker than larger events. Another formulation would make perceived risk a function of storm damage, in which extensive damage is remembered longer. These formulations appear to be reasonable alternatives, and would likely be better than the first-attempt presented in this dissertation.

Near-miss storms, as described above, should be included in future work. They would benefit from the change in perceived storm frequency structure. Near-miss storms, which cause little damage, would increase perceived storm frequency less than a Category 1 storm that makes landfall.

The performance of coastal defenses depends significantly on regular upkeep and maintenance. I include maintenance, but the budget pressures surrounding maintenance have been excluded. Deegan (2007) includes a model of public funding pressures for river levees. Deegan’s budget formulation could be applied to the FRACC model

because of its current regional focus. In the US, costs of constructing coastal levees and beach nourishment projects are typically shared between the federal and local governments. After construction, the local government is normally responsible for 100 percent of the maintenance costs. A model of public finance pressures could be used to regulate the amount of maintenance performed. A test of the importance of maintenance could be performed with the current version of FRACC . Varying the exogenous percentage of maintenance could provide upper and lower bounds for coastal protection performance.

Storm projections are also highly sensitive and poorly constrained. While not a direct improvement of the model presented in this research, improvements in regional climate projections and hurricane modeling would improve the storm data that drive the FRACC model.

In this dissertation, storm scenarios and SLR scenarios were developed independently. Future work could develop more consistent scenarios paring SLR and storms under future climates. For instance, for a particular atmospheric stabilization target (e.g., 350ppm), SLR and tropical storm parameters could be developed and tested in FRACC.

The storm damage function could also be improved. Storm damage depends on specifics such as construction materials of the community, characteristics of the storm (e.g., direction, surge), and topology of the land. The functional form could be changed to include more of these parameters. Damage functions are hard to determine because landfall events are relative rare, but new functional forms could be included to improve model response.

In the FRACC model, property owners purchased insurance or physically mitigated their property (e.g., elevate the building). These options were only partially endogenous in the model, driven by the perception of flood risk. The insurance sector, in particular, could be modeled with a price response and the interaction between

private insurance and the National Flood Insurance Program. Detailing the insurance sector could improve the model's insurance coverage response, particularly after storm events. I simplified the complexity of an evolving insurance market.

Previous studies have concluded the value of wetland acreage is important to public adaptation decisions. For instance, the decision to construct a levee would depend on the value of the nearby wetlands. I found that, in the United States, the economic value of wetlands is not often included in the decision to protect a community. More work could be done to value wetland ecosystem services. Wetland values could then be provided to the FRACC model to compare how it would impact the choices of coastal managers and communities.

Community attractiveness is comprised of three components in the current research: perceived storm risk, employment opportunities, and available housing. Community attractiveness may also include other factors. Two factors that could be included in future work are community services and local natural amenities. Community services, such as churches, post office, etc., provide an important social draw for residents. Gibbons and Nicholls (2006) found that these services might be important for communities, particularly isolated communities that cannot rely on the services of other cities and towns. Natural amenities, such as beaches, are important for some communities, along with a natural shoreline unobstructed by a levee.

Many of these additional work items depend on the scale and system boundaries of the desired study. When moving to a more global study, regional effects might have a net global effect. For instance, it is reasonable to assume that there is a fixed amount of tourism dollars worldwide each year. A beach nourishment project in Florida might bring more of these dollars to that community, but at a loss to another tourist destination. The global effect might net to zero. It is important to consider the scale of study and to ensure proper accounting.



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# Abbreviations

|              |   |
|--------------|---|
| <b>CHIPS</b> | Coupled <b>H</b> urricane <b>I</b> ntensity <b>P</b> rediction <b>S</b> ystem     |
| <b>DIVA</b>  | Dynamic <b>I</b> nteractive <b>V</b> ulnerability <b>A</b> ssessment model        |
| <b>FEMA</b>  | Federal <b>E</b> mergency <b>M</b> anagement <b>A</b> gency                       |
| <b>FRACC</b> | Feedback- <b>R</b> ich <b>A</b> daptation to <b>C</b> limate <b>C</b> hange model |
| <b>NFIP</b>  | National <b>F</b> lood <b>I</b> nsurance <b>P</b> rogram                          |
| <b>RSLR</b>  | Relative <b>S</b> ea- <b>L</b> evel <b>R</b> ise                                  |
| <b>SLR</b>   | Sea- <b>L</b> evel <b>R</b> ise   |

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# Glossary

**Adaptation** is society's response to changes in climate and climate variability, including both public and private adaptation.

**Coastal adaptation** is adaptation in communities that must respond to tropical storm and sea-level rise threats.

**Coastal protection** includes physical structures constructed to reduce the impacts of storms and sea-level rise. In this dissertation, structures include levees and beach nourishment projects.

**Mitigation** is a form of private adaptation that involves elevating property to reduce flood damage.

**Private adaptation** includes responses by property owners to reduce their risk to climate change; primarily flood mitigation and flood insurance.

**Protection** is short for "coastal protection."

**Public adaptation** is policies and actions taken by the public sector to respond to changes in climate. Primarily publicly financed coastal protection structures, including levees and beach nourishment, or "public coastal protection."

**Relative sea-level rise** is the effective sea-level rise experienced by a community. Relative sea-level rise is the global sea-level rise adjusted for local factors.

**Sea-level rise** is global sea-level rise, due to global trends including thermal expansion, and glacial and ice sheet melt.

**Storm or storm event** is a "tropical storm" that is categorized by the Saffir-Simpson scale.

**Storm frequency** the annual rate of storm arrival, measured in the number of storm events per year.

**Storm intensity** The size and force of a tropical storm. Storm intensity is classified according to wind speed using the Saffir-Simpson scale (e.g., Category 1, Category 2, etc).

**Tropical storm** Storms that form near the equator (~10 degrees North or South), in tropical air masses. Excluded are extratropical storms, such as nor'easters.

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# Appendices

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# Appendix A

## Storm Data Scripts

Kerry Emanuel provided three thousand storm tracks for each each GCM, each climate scenario, and each of the three regions (Miami-Dade County, Cape Cod, and St. Mary Parish). There were twelve storm sets, each with three thousand simulated storms, in total.

To ensure that the storms made landfall, following scripts were run on the storm sets. The first script filters the storm tracks by latitude and longitude. For storms that pass through a region, the maximum wind speed while in the region is save to a file. These storms, the subset that hit the region, were used to generate the storm intensity density functions.

The following script performs the filtering and data analysis:

---

```
#!/usr/bin/perl -w

# my $argc = 0;
# foreach my $arg (@ARGV) {
#   printf "Argument %2d: '%s'\n", ++ $argc, $arg;
# }

my $isSingleFile = 1;
if ( @ARGV > 0 ) {
#   print "Number of arguments: " . scalar @ARGV . "\n";
  $isSingleFile = 0;
} else {
  $hurr_file="/home/Desktop/Hurricane_Raw_Data_cp/gfdlcm20
/20th/1981_2000/CapeCod/AL/hurr/hurr10.out";
```

```

print "No arguments, so using $hurr_file.\n";
}

if ($isSingleFile == 1) {
ProcessHurrFile($hurr_file);
} else {
$dirtoget = $ARGV[0];
# print "$dirtoget\n";
opendir(HURRDIR, $dirtoget) || die("Cannot open directory");
@thefiles= readdir(HURRDIR);
closedir(HURRDIR);

foreach $f (@thefiles) {
unless ( ($f eq ".") || ($f eq "..") || ($f eq "poly.in") || ($f eq "latlongs.out")
|| ($f eq "stats.txt") )
{
print "$f\t";
ProcessHurrFile($dirtoget . $f);
}
}
}
exit 0;

#####
# Sub: ProcessHurrFile
#####
sub ProcessHurrFile {
# Get the passed path to the file
my $hurrFile=shift;

my $wcOutput = qx(wc $hurrFile);
my ($fileLineCount, $everythingelse) = split(' ', $wcOutput);

my $prevWindSpeed = 0;
my $twoWindSpeed = 0;
my $currWindSpeed = 0;
my $month = 0;
my $day = 0;
my $hour = 0;
my $lat = 0;
my $long = 0;
my $pressure = 0;
my $radius = 0;
my $vertWindShear = 0;
my $potentialIntensity = 777;
my $everythingElse = 0;
my $line =0;
my $numLandFalls = 0;
my $maxLandFalls = 0;
my $prevPotentialIntensity = 678;
my $maxWindSpeedInZone = 0;
my $inZone = 0;

# Open the HURR file
open HURRFILE, $hurrFile || die("Could not open file!");
while (<HURRFILE>)
{
$prevPotentialIntensity = "$potentialIntensity";

($month, $day, $hour, $lat, $long, $currWindSpeed, $pressure, $radius,
$vertWindShear, $potentialIntensity, $everythingElse) = split(' ', $_);

if ( $potentialIntensity == 0 && $prevPotentialIntensity > 0 ) {
$maxLandFalls++;
}
}
# print "$maxLandFalls\t";
close(HURRFILE);

```



```

# Open the HURR file
if ( $maxLandFalls > -678 ) {
$prevPotentialIntensity = 678;
$potentialIntensity = 777;

open HURRFILE, $hurrFile || die("Could not open file!");
while (<HURRFILE>)
{
$twoWindSpeed = "$prevWindSpeed";
$prevWindSpeed = "$currWindSpeed";
$prevPotentialIntensity = "$potentialIntensity";

($month, $day, $hour, $lat, $long, $currWindSpeed, $pressure, $radius,
$vertWindShear, $potentialIntensity, $everythingElse) = split(' ', $_);
$line++;

if ( $potentialIntensity == 0 && $prevPotentialIntensity > 0 ) {
$numLandFalls++;
}

$inZone = 0;
if ( ( ((29 < $lat) && ($lat < 30)) && ((268 < $long) && ($long < 270)) ) || # Atcha
( ((41.1 < $lat) && ($lat < 42.2)) && ((289.0 < $long) && ($long < 290.2)) ) || # Cape Cod
( ((25 < $lat) && ($lat < 26)) && ((279 < $long) && ($long < 280)) ) ) # Miami
{
$inZone = 1;
if ( $maxWindSpeedInZone < $currWindSpeed ) {
$maxWindSpeedInZone = $currWindSpeed;
}
# print "I'm inZone!\t$maxWindSpeedInZone\n";
}

# print "Final Max Wind:\t$maxWindSpeedInZone\n";
}
printf("%.2f\n", $maxWindSpeedInZone);
close(HURRFILE);
} else {
print "\n";
}
}

```

---

The following script calls the previous script twelve times, once for each storm data set:

```

#!/bin/sh

SCRIPT='./CollectLandfallWindSpeed_4.pl'
DATADIR='/home/Desktop/Hurricane_Raw_Data_cp'

mkdir -p output

# ECHAM 20th 1990
$SCRIPT $DATADIR/echam/20th/1981_2000/Atcha/AL/hurr/ > Atcha_1990_echam.txt
$SCRIPT $DATADIR/echam/20th/1981_2000/CapeCod/AL/hurr/ > Cape_1990_echam.txt
$SCRIPT $DATADIR/echam/20th/1981_2000/Miami/AL/hurr/ > Miami_1990_echam.txt

# ECHAM A1B 2190
$SCRIPT $DATADIR/echam/A1B/2181_2200/Atcha/AL/hurr/ > Atcha_2190_echam.txt
$SCRIPT $DATADIR/echam/A1B/2181_2200/CapeCod/AL/hurr/ > Cape_2190_echam.txt

```

```
$SCRIPT $DATADIR/echam/A1B/2181_2200/Miami/AL/hurr/ > Miami_2190_echam.txt

# GFDL 20th 1990
$SCRIPT $DATADIR/gfdlcm20/20th/1981_2000/Atcha/AL/hurr/ > Atcha_1990_gfdlcm20.txt
$SCRIPT $DATADIR/gfdlcm20/20th/1981_2000/CapeCod/AL/hurr/ > Cape_1990_gfdlcm20.txt
$SCRIPT $DATADIR/gfdlcm20/20th/1981_2000/Miami/AL/hurr/ > Miami_1990_gfdlcm20.txt

# GFDL A1B 2190
$SCRIPT $DATADIR/gfdlcm20/A1B/2181_2200/Atcha/AL/hurr/ > Atcha_2190_gfdlcm20.txt
$SCRIPT $DATADIR/gfdlcm20/A1B/2181_2200/CapeCod/AL/hurr/ > Cape_2190_gfdlcm20.txt
$SCRIPT $DATADIR/gfdlcm20/A1B/2181_2200/Miami/AL/hurr/ > Miami_2190_gfdlcm20.txt

exit
```

# Appendix B

## Interviews

To better understand the topics of this dissertation, interviews and fieldwork were conducted for the case studies. The interviews were performed with full consent of the interviewee according to MIT's COUHES guidelines. The interviews were semi-structured and notes were taken. Most of the interviews were about an hour long, depending the flow of conversation and the time constraints of the participant(s).

The following questions were used to as a guide for the semi-structured format. The first set of questions were discussed for most participants, no matter what there area of expertise. The second set of questions were more technical and posed to US Army Corps of Engineers in the New Orleans District offices and the Engineering Research and Development Center (ERDC) in Vicksburg, MS.

### B.1 General Questions

- How are community residents typically prepared for a storm event? How can they be better prepared?
- What incentives are effective in getting homeowners to take preparatory actions?
- How would you describe the flow of federal aid to the community?
- How do you feel the public perceives risk from SLR and tropical storms?

- Can you describe/characterize the social psyche of the area?
- In the face of SLR and storms, what do you think the likely course of action will be in the next 50 years?

## **B.2 Questions for the US Army Corps of Engineers**

- Could you please outline the process of protecting a portion of coast from flooding?
- What are the building standards for public protection projects? Are these often over- or underachieved? Margin of safety?
- Does the level or adequacy of private insurance figure into public protection planning?
- What are the road blocks to implementing a public protection project? How long does a roadblock typically delay a project?
- How are natural ecosystems incorporated into the planning process? How are natural ecosystems valued?
- How are zoning and other public policy measures included in the planning process?
- How are your estimates of future sea-level rise (SLR) derived? How are they updated? What assumptions do you make about the shape of the sea-level rise path?
- What role can private home improvements (e.g., stilts, storm shutters) play in developing a more resilient community? How do these improvements relate to larger public works projects? Are they important?
- How do public protection projects affect land-use and development of a coastal community? Is there a relationship between the adequacy of protection and development?
- What are the budget realities? Constraints? How hard is it to get funding to increase protection on an already existing project? Compared to a new project? Is there specification inertia?
- What is your coordination with FEMA, if any?

- What are you planning horizons? How far out are you designing for? What is taken into account, such as subsidence, SLR, etc?
- What is the typical maintenance associated with a levee? The cost structure (amount per year or one-off payments every 10 years, etc.)?
- My decision function is based on the dry land value and the cost of construction and the value of wetlands in the area. Is this close to right? What else is considered?
- How do you think about accommodation space for wetlands and protection options?
- How can I find the rates of beach nourishment for a given location?
- What are some standard planning times? Construction times? Does the Corps have guidelines for specifying projects? Are the retrospectives for evaluation and, if so, how do project fair?
- How do you estimate surge? Is there a reasonable assumption for a given?
- How do you allocate damage? Justify projects based on expected damage?

## B.3 Interviewees

The following people gave permission to be listed in this dissertation:

- Kathleen White; Civil Engineer; Cold Regions Research and Engineering Laboratory, USACE; Hanover, NH
- Lamar Hale; Senior Project Manager; Projects Branch, USACE; New Orleans, LA
- Stephen Faulkner; Wetland Ecologist, USGS; Baton Rouge, LA
- Amy Lesen; Assist. Professor in Biology; Dillard University; New Orleans, LA
- Timothy Axtman; Project Manager; Restoration Branch, USACE; New Orleans, LA
- William Curtis; Associate Technical Director; Coastal and Hydrology Laboratory, USACE; Vicksburg, MS
- Patrick Tassin; Maintenance Worker; Old River Control Structure, USACE; Vidalia, LA
- Edmond Russo, Jr.; Chief Coastal Engineering Branch; Coastal and Hydrology Laboratory, USACE; Vicksburg, MS
- Brian Harper; Economist; Institute for Water Resources, USACE; Alexandria, VA
- Kenneth Ned Mitchell; Engineer; Coastal and Hydrology Laboratory, USACE; Vicksburg, MS
- Nicole Elko; Coastal Coordinator; Pinellas County, FL; Clearwater, FL
- Gordon G. Thomson; P.E., Vice-President; Coastal Planning & Engineering, Inc.; Boca Raton, FL
- Joseph E. Pelczarski; Regional Planner; Executive Office of Energy and Environmental Affairs (CZM MA); Boston, MA
- Peter Slovinski; Coastal Geologist; State of Maine; Portland, ME
- Richard R. Zingarelli; Manager; Flood Hazard Management Program, Department of Conservation and Recreation; Boston, MA
- Daisy Sweeney; Regional Insurance Specialist; FEMA Region I; Boston, MA
- Frank McCune; Senior Planner; Planning and Zoning, Comprehensive Planning, Miami-Dade County; Miami, FL

- Frank Fink; Director of Economic Development; St. Mary Parish Government; Franklin, LA
- Bob Schwarzreich; Planning and Zoning Research; Miami-Dade County; Miami, FL
- Rebecca Haney; Coastal Geologist; State of Massachusetts; Boston, MA
- Daniel Dray; Administrator; Cape Cod Economic Development Council; Barnstable, MA

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# Appendix C

## Model Documentation

This draft was made with version FRACC v26.4.

Variables and equations to follow.

\*\*\*\*\*

.Aggregate Demand

\*\*\*\*\*

(001) Change in Expected income per capita = ( Output per Capita - Expected Income per Capita ) / Time to Adjust Expected Income

Units: units/(person\*Year\*Year)

The expected change in the real income per capita of the community given the current level of economic activity.

Used by: (010)Expected Income per Capita -

(002) Desired Consumption = Desired Consumption per Capita \* Population

Units: unit/Year

The total desired consumption in the community.

Used by: (005)Desired gross output -

(003) Desired Consumption per Capita = Marginal Propensity to Consume \* Expected Income per Capita

Units: units/(person\*Year)

The desired amount of consumption per person in the community, given their marginal consumption rate and their expected income level.

Used by: (002)Desired Consumption -

(004) Desired Government Services = ( Normal Government Spending + Direct Government Disaster Relief ) / Price of Output

Units: unit/Year

The desired rate of government service expenditures in the community.

Used by: (005)Desired gross output -

(005) Desired gross output = Desired Consumption + Desired Savings + Desired Government Services + External Demand + Insurance Claims Paid

Units: units/Year

The desired level of gross economic output of the community.  
Used by: (019)Relative Aggregate Demand -

(006) Desired Savings = Population \* Desired Savings per Capita  
Units: units/Year  
The desired amount of savings in the community.  
Used by: (005)Desired gross output -

(007) Desired Savings per Capita = ( 1 - Marginal Propensity to Consume ) \* Expected Income per Capita  
Units: unit/(person\*Year)  
The desired savings level per capita.  
Used by: (006)Desired Savings -

(008) Direct Government Disaster Relief = Switch Government Relief \* DELAY3 ( Damage not Covered by Insurance  
\* Fraction of Damage Covered by Govt Relief , Disaster Relief Delay )  
Units: \$/Year  
Direct government payments for storm and disaster relief.  
Used by: (004)Desired Government Services -

(009) Disaster Relief Delay = 5  
Units: years  
The average delay of disbursing governmental disaster relief  
funds.  
Used by: (008)Direct Government Disaster Relief -

(010) Expected Income per Capita = INTEG( Change in Expected income per capita , Initial Gross Output /  
Population )  
Units: units/(person\*Year)  
The expected amount of income per capita in the community.  
Used by: (001)Change in Expected income per capita -  
(003)Desired Consumption per Capita -  
(007)Desired Savings per Capita -

(011) External Demand = 0  
Units: unit/Year  
The rate of external demand by the community.  
Used by: (005)Desired gross output -

(012) Fraction of Damage Covered by Govt Relief = 0.5  
Units: dmn1  
The fraction of uninsured damages that will be covered by  
government disaster relief.  
Used by: (008)Direct Government Disaster Relief -

(013) Insurance Claims Delay = 2  
Units: years  
The average amount of time to received an insurance claim  
payment.  
Used by: (014)Insurance Claims Paid -

(014) Insurance Claims Paid = Switch Insurance \* DELAY3 ( Damage Covered by Insurance , Insurance Claims  
Delay ) / Price of Output  
Units: unit/Year  
Insurance claims coming to the community after a storm.  
Used by: (005)Desired gross output -

(015) Marginal Propensity to Consume = 0.8  
Units: dimensionless

The proportion of income that is typically consumed by the community.  
Used by: (003)Desired Consumption per Capita -  
(007)Desired Savings per Capita -

(016) Minimum Gross Output of Community =  $1e-007$   
Units: units/Year  
The minimum gross output of a community.  
Used by: (019)Relative Aggregate Demand -

(017) Normal Government Spending = 0  
Units: \$/Year  
Normal government expenditures in the community. Assumed to be zero because there taxes are fully recycled. Would be greater than zero if the government were deficit spending.  
Used by: (004)Desired Government Services -

(018) Output per Capita = Gross Output / Population  
Units: unit/(person\*Year)  
The economic output per capita for the community.  
Used by: (001)Change in Expected income per capita -

(019) Relative Aggregate Demand =  $XIDZ$  ( Desired gross output , Gross Output , Desired gross output / Minimum Gross Output of Community )  
Units: dimensionless  
The relatively pressure of aggregate demand on desired capital, as a ratio of desired output to actual output. Added Minimum Gross Output to fix units and a DIVO error.  
Used by: (086)Effect of Aggregate Demand on Desired Capital -  
(294)Effect of Aggregate Demand on Jobs -  
(436)Effect of Aggregate Demand on Output Price -

(020) Switch Government Relief = 1  
Units: dmn1  
Switch to activate governmental disaster relief. 0=off, 1=on  
Used by: (008)Direct Government Disaster Relief -

(021) Switch Insurance = 1  
Units: dmn1  
Switch to control the whether insurance payments are introduced.  
Used by: (014)Insurance Claims Paid -

(022) Time to Adjust Expected Income = 2  
Units: years  
The time required to adjust consumer expectations of income.  
Used by: (001)Change in Expected income per capita -

\*\*\*\*\*  
.Beach Nourishment  
\*\*\*\*\*

(023) Adjustment for BN Construction = ( Desired BN under Construction - Beach Nourishment under Construction ) / BN Construction Adjustment Time  
Units: meter\*meter\*meter/Year  
The adjustment to the desired number of new public protection project starts based on the number of projects currently under construction.  
Used by: (052)Desired BN Const Starts -

(024) Adjustment for BN in Planning = ( Desired BN in Planning - Beach Nourishment in Planning ) / BN Planning Adjustment Time  
Units: meter\*meter\*meter/Year  
The adjustment to the desired number of public protection projects in planning given the desired level and the current level.  
Used by: (054)Desired BN Start Rate -

(025) Adjustment for Completed BN = ( Desired Beach Nourishment Volume - Completed Beach Nourishment Protection ) / Beach Nourishment Completed Adjustment Time + Beach Erosion  
Units: meter\*meter\*meter/Year  
The adjustment to the desired number of public protection projects based on the number of currently completed projects.  
Used by: (051)Desired BN Completions -

(026) Annual Nourishment Costs = Cost per Cubic Meter of Sand \* Beach Nourishment Completion  
Units: \$/Year  
The annual costs of beach nourishment protection.  
Used by: (048)Cumulative Nourishment Costs -

(027) Beach Erosion = Beach Erosion Rate in Metric \* Segment Length  
Units: m\*m\*m/Year  
Beach erosion to the sand dunes.  
Used by: (039)Beach Nourishment under Construction -  
(045)Completed Beach Nourishment Protection -  
(025)Adjustment for Completed BN -  
(138)Estimated Beach Nourishment Maintenance Costs Per Year -

(028) Beach Erosion Rate = INITIAL( IF THEN ELSE ( Switch Segment Choice = 1, Beach Erosion Rate for Miami , IF THEN ELSE ( Switch Segment Choice = 2, Beach Erosion Rate for Cape Cod , IF THEN ELSE ( Switch Segment Choice = 3, Beach Erosion Rate for St Mary Parish , 0 ) ) ) )  
Units: cy/(Year\*ft)  
The annual volume of sand eroded from the dunes.  
Used by: (032)Beach Erosion Rate in Metric -

(029) Beach Erosion Rate for Cape Cod = 0  
Units: cy/(Year\*ft)  
The annual rate of sand erosion for Cape Cod. Future work: Find better source for erosion information. Difficult to get information from Woods Hole.  
Used by: (028)Beach Erosion Rate -

(030) Beach Erosion Rate for Miami = 3.5  
Units: cy/(Year\*ft)  
From Wiegel 1992 Miami Beach discussion. Within range of 3.1-3.75 for the southern beaches.  
Used by: (028)Beach Erosion Rate -

(031) Beach Erosion Rate for St Mary Parish = 3.5  
Units: cy/(Year\*ft)  
The annual rate of sand erosion for St. Mary Parish. The value is currently initialized to Miami's value and needs to be further researched. The model is doesn't not support a beach nourishment scenario for St. Mary Parish.  
Used by: (028)Beach Erosion Rate -

(032) Beach Erosion Rate in Metric = Beach Erosion Rate \* ( cubic meters in cubic yard \* feet in a kilometer )  
Units: m\*m\*m/(Year\*km)  
The annual volume of sand eroded per linear kilometer of beach.

Used by: (027)Beach Erosion -

(033) Beach Nourishment Area = Distance to depth of closure \* ( Length of beach nourishment \* meters in km )  
Units: m\*m  
The area of land that requires nourishment.  
Used by: (044)Completed Beach Nourishment Height -  
(050)Desired Beach Nourishment Volume -  
(062)Initial Volume of Beach Nourishment Protection -

(034) Beach Nourishment Completed Adjustment Time = 3  
Units: Year  
The time to adjust new public protection project starts given completed projects.  
Used by: (025)Adjustment for Completed BN -

(035) Beach Nourishment Completion = Beach Nourishment under Construction / BN Construction Delay  
Units: meter\*meter\*meter/Year  
The rate of public projects that finish construction per year.  
Used by: (037)Beach Nourishment in Planning -  
(039)Beach Nourishment under Construction -  
(045)Completed Beach Nourishment Protection -  
(026)Annual Nourishment Costs -

(036) Beach Nourishment Construction Starts = Beach Nourishment in Planning / BN Planning Delay  
Units: meter\*meter\*meter/Year  
The number of public projects whose construction has been started in a year.  
Used by: (037)Beach Nourishment in Planning -  
(039)Beach Nourishment under Construction -

(037) Beach Nourishment in Planning = INTEG( Beach Nourishment Planning Starts - Beach Nourishment Construction Starts , Beach Nourishment Completion \* BN Planning Delay )  
Units: m\*m\*m  
These are suggested public protection projects that are being planned by coastal managers.  
Used by: (024)Adjustment for BN in Planning -  
(036)Beach Nourishment Construction Starts -

(038) Beach Nourishment Planning Starts = Desired BN Start Rate  
Units: m\*m\*m/Year  
The number of new public protection projects that enter the planning process.  
Used by: (037)Beach Nourishment in Planning -

(039) Beach Nourishment under Construction = INTEG( Beach Nourishment Construction Starts - Beach Nourishment Completion , BN Construction Delay \* Beach Erosion )  
Units: m\*m\*m  
The amount of beach nourishment that is currently under construction.  
Used by: (023)Adjustment for BN Construction -  
(035)Beach Nourishment Completion -

(040) BN Construction Adjustment Time = 1  
Units: Year  
The time to adjust new public protection project starts given projects under construction.  
Used by: (023)Adjustment for BN Construction -

(041) BN Construction Delay = 1

Units: years  
The average time to finish construction of a beach nourishment project project.  
Used by: (039)Beach Nourishment under Construction -  
(035)Beach Nourishment Completion -  
(055)Desired BN under Construction -

(042) BN Planning Adjustment Time = 1  
Units: Year  
The time to adjust new public protection project starts given projects in planning.  
Used by: (024)Adjustment for BN in Planning -

(043) BN Planning Delay = 2  
Units: years  
The average length of time required to plan a public protection project.  
Used by: (037)Beach Nourishment in Planning -  
(036)Beach Nourishment Construction Starts -  
(053)Desired BN in Planning -

(044) Completed Beach Nourishment Height = Completed Beach Nourishment Protection / Beach Nourishment Area  
Units: meters  
The height of the finished beach nourishment project.  
Used by: (064)Beach Nourishment Exists -  
(069)Effective Height of Public Protection -  
(573)Height of Completed Public Protection -

(045) Completed Beach Nourishment Protection = INTEG( Beach Nourishment Completion - Beach Erosion , Initial Volume of Beach Nourishment Protection )  
Units: m\*m\*m  
The completed volume of sand protecting the community.  
Used by: (025)Adjustment for Completed BN -  
(044)Completed Beach Nourishment Height -

(046) Cost per Cubic Meter of Sand = Cost per Cubic Yard of Sand / cubic meters in cubic yard  
Units: \$/(m\*m\*m)  
The cost of sand used for beach nourishment.  
Used by: (026)Annual Nourishment Costs -  
(138)Estimated Beach Nourishment Maintenance Costs Per Year -  
(142)Estimated Initial Beach Nourishment Costs -

(047) Cost per Cubic Yard of Sand = 15  
Units: \$/cy  
The cost of sand used for beach nourishment. (\$15 per cubic yard; Elko, 2009)  
Used by: (046)Cost per Cubic Meter of Sand -

(048) Cumulative Nourishment Costs = INTEG( Annual Nourishment Costs , 0)  
Units: \$  
The cumulative actual costs of beach nourishment protection.

(049) Desired Beach Nourishment Height = IF THEN ELSE ( Time <= 2010, Initial Beach Nourishment Height ,  
IF THEN ELSE ( Public Protection Type and Height = 0, Initial Beach Nourishment Height ,  
IF THEN ELSE ( Public Protection Type and Height = 1, Initial Beach Nourishment Height ,  
IF THEN ELSE ( Public Protection Type and Height = 2 , Initial Beach Nourishment Height ,  
IF THEN ELSE ( Public Protection Type and Height = 3, Desired Public Protection Height , 0 ) ) ) ) )  
Units: meter  
The desired height of a beach nourishment project.  
Used by: (050)Desired Beach Nourishment Volume -

(050) Desired Beach Nourishment Volume = Beach Nourishment Area \* Desired Beach Nourishment Height  
Units: m\*m\*m  
The desired volume of sand for a given height of protection.  
Used by: (025)Adjustment for Completed BN -

(051) Desired BN Completions = Adjustment for Completed BN  
Units: meter\*meter\*meter/Year  
The desired rate of beach nourishment completion.  
Used by: (052)Desired BN Const Starts -  
(055)Desired BN under Construction -

(052) Desired BN Const Starts = Adjustment for BN Construction + Desired BN Completions  
Units: meter\*meter\*meter/Year  
The desired rate of construction starts for beach nourishment.  
Used by: (053)Desired BN in Planning -  
(054)Desired BN Start Rate -

(053) Desired BN in Planning = BN Planning Delay \* Desired BN Const Starts  
Units: meter\*meter\*meter  
The desired volume of sand in the planning phase.  
Used by: (024)Adjustment for BN in Planning -

(054) Desired BN Start Rate = Desired BN Const Starts + Adjustment for BN in Planning  
Units: meter\*meter\*meter/Year  
The desired number of new construction starts for public protection.  
Used by: (038)Beach Nourishment Planning Starts -

(055) Desired BN under Construction = BN Construction Delay \* Desired BN Completions  
Units: meter\*meter\*meter  
The desired volume of sand in the construction phase.  
Used by: (023)Adjustment for BN Construction -

(056) Distance to depth of closure = INITIAL( IF THEN ELSE ( Switch Segment Choice = 1, Distance to DoC for Miami ,  
IF THEN ELSE ( Switch Segment Choice = 2, Distance to DoC for Cape Cod ,  
IF THEN ELSE ( Switch Segment Choice = 3, Distance to DoC for St Mary Parish , 0) ) ) )  
Units: m  
The distance to depth of closure for the community.  
Used by: (033)Beach Nourishment Area -  
(137)Estimated amount of sand required -

(057) Distance to DoC for Cape Cod = 2406  
Units: m  
The distance to the depth of closure for Cape Cod. The depth of water is estimated at 25ft or 7.62m (Haney, 2009). Formula used is: 7.62/TAN(Coastal Slope for Cape Cod \* (ARCCOS(-1)/180) ).  
Used by: (056)Distance to depth of closure -

(058) Distance to DoC for Miami = 100  
Units: m  
The distance to the depth of closure for Miami (Robertson 2008).  
Used by: (056)Distance to depth of closure -

(059) Distance to DoC for St Mary Parish = 100  
Units: m  
The distance to the depth of closure for St. Mary Parish. The value is currently initialized to Miami's value and needs to be further researched. The model is doesn't not support a beach

nourishment scenario for St. Mary Parish.  
Used by: (056)Distance to depth of closure -

(060) Fraction suitable for beach nourishment = 1  
Units: dmn1  
The fraction of the community's coast that would be protected by beach nourishment. Other options could be levees or do nothing.  
Do Nothing needs to be thought through for damages.  
Used by: (063)Length of beach nourishment -

(061) Initial Beach Nourishment Height = 0  
Units: meters  
The initial height of the protective dune.  
Used by: (049)Desired Beach Nourishment Height -  
(062)Initial Volume of Beach Nourishment Protection -

(062) Initial Volume of Beach Nourishment Protection = INITIAL( Beach Nourishment Area \* Initial Beach Nourishment Height )  
Units: m\*m\*m  
The initial volume of sand currently in the protective dune.  
Used by: (045)Completed Beach Nourishment Protection -  
(137)Estimated amount of sand required -

(063) Length of beach nourishment = Fraction suitable for beach nourishment \* Segment Length  
Units: km  
The length of the beach nourishment protection in the community.  
Used by: (033)Beach Nourishment Area -  
(137)Estimated amount of sand required -

\*\*\*\*\*  
.Breaching  
\*\*\*\*\*

(064) Beach Nourishment Exists = IF THEN ELSE ( Completed Beach Nourishment Height > 0, 1, 0)  
Units: dmn1  
State variable on whether a beach nourishment project exists.  
Used by: (074)Public Protection Exists -

(065) Breach Count = INTEG( Increment Breach Count , 0)  
Units: dmn1  
The number of breaches that have occurred during the simulation.

(066) Breach Occurs = IF THEN ELSE ( Breaching Random Number Generator < Probability of Breach , 1, 0) \*  
Switch Breaching \* Public Protection Exists \* Storm Occurrence  
Units: dmn1  
A state variable indicating whether a levee or dune was breached.  
Used by: (564)Average Water Depth in Community -  
(155)Desired Reactionary Height -  
(070)Increment Breach Count -  
(574)Inland Distance Flooded During Storm -  
(581)Overtopping Breach Damage Multiplier -

(067) Breaching Random Number Generator = RANDOM UNIFORM ( 0, 1, Breaching Random Number Seed )  
Units: dmn1  
The random number generator for breaching.  
Used by: (066)Breach Occurs -

(068) Breaching Random Number Seed = 6  
Units: dmn1  
The random number seed to calculate a breach of coastal defenses.  
Used by: (067)Breaching Random Number Generator -



(069) Effective Height of Public Protection = IF THEN ELSE ( Public Protection Type and Height < 2, Effective Levee Protection , Completed Beach Nourishment Height )  
Units: meters  
The effective height of the current public protection structure.  
Used by: (073)Probability of Breach -

(070) Increment Breach Count = Breach Occurs / TIME STEP  
Units: 1/Year  
Increment the number of breaches that have occurred during the simulation.  
Used by: (065)Breach Count -

(071) Levee Exists = IF THEN ELSE ( Completed Levee Protection > 0, 1, 0)  
Units: dmn1  
State variable on whether a levee exists or not.  
Used by: (074)Public Protection Exists -

(072) "Median Saffir-Simpson Surges by Category"[StormCategory] = 1.37, 2.13 , 3.2, 4.72, 6.1  
Units: meters  
The mid-point of the surge ranges according the NOAA Saffir-Simpson scale. (4.5, 7, 10.5, 15.5, 20 feet)  
Used by: (551)Estimated Mitigated Floor Height -  
(554)Estimated Total Water Heights -  
(159)Height for Surge Protection -  
(580)Mitigated Floor Height -  
(076)Storm Surge Height -

(073) Probability of Breach = ( 1 / ( 1 + EXP ( Sensitivity of Breach to Overtopping \* ( Effective Height of Public Protection - Total Water Height - Reference Protection Height ) ) ) )  
Units: dmn1  
The probability that public protection will fail given a particular water height.  
Used by: (066)Breach Occurs -

(074) Public Protection Exists = IF THEN ELSE ( ( Beach Nourishment Exists + Levee Exists ) > 0, 1, 0)  
Units: dmn1  
State variable about whether any form of public protection exists.  
Used by: (066)Breach Occurs -  
(581)Overtopping Breach Damage Multiplier -  
(558)Perceived Level of Storm Protection -  
(504)Sea Level Rise before Construction -

(075) Sensitivity of Breach to Overtopping = 10  
Units: 1/meter  
The sensitivity of a public protection breach to the height of water and overtopping.  
Used by: (073)Probability of Breach -

(076) Storm Surge Height = IF THEN ELSE ( Storm Event with Strength = 0, 0,  
IF THEN ELSE ( Storm Event with Strength = 1, "Median Saffir-Simpson Surges by Category"[ Cat1] ,  
IF THEN ELSE ( Storm Event with Strength = 2, "Median Saffir-Simpson Surges by Category"[ Cat2] ,  
IF THEN ELSE ( Storm Event with Strength = 3, "Median Saffir-Simpson Surges by Category"[Cat3] ,  
IF THEN ELSE ( Storm Event with Strength = 4, "Median Saffir-Simpson Surges by Category"[ Cat4] ,  
IF THEN ELSE ( Storm Event with Strength = 5, "Median Saffir-Simpson Surges by Category"[ Cat5] , 0 ) ) ) ) ) ) ) )  
Units: meter  
The storm surge of a storm event.  
Used by: (078)Total Water Height -

(077) Switch Breaching = 1

Units: dmn1

Switch to turn on/off the possibility of levee failure. 0=off;  
1=possible.

Used by: (066)Breach Occurs -

(078) Total Water Height = Storm Surge Height + Sea Level Relative to Public Protection

Units: meters

The total sea level height including both long-term SLR and  
storm surge height.

Used by: (564)Average Water Depth in Community -

(574)Inland Distance Flooded During Storm -

(581)Overtopping Breach Damage Multiplier -

(073)Probability of Breach -

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.Capital Adjustment

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(079) Capital correction = ( Optimal Capital - Total Undamaged Capital ) / Capital correction time

Units: Capital Units/Year

The amount of new capital that should be constructed to  
satisfied expected returns on capital investment.

Used by: (085)Desired Net Change in Capital -

(080) Capital correction time = 4

Units: years

The time to correct of capital construction gaps.

Used by: (079)Capital correction -

(081) Capital Investment = MAX ( 0, Desired Capital Development Rate )

Units: Capital Units/Year

The rate of new capital stock construction in the community.

Used by: (115)New Mitigated Capital -

(116)New Unmitigated Capital -

(082) Cost of Capital = Interest Rate for Capital + ( 1 / Capital Lifetime ) + Perceived Fractional Damage  
from Storms

Units: 1/Year

The absolute cost of capital investment.

Used by: (091)Marginal Cost of Capital -

(083) Desired Capital Development Rate = IF THEN ELSE ( Switch Capital Growth = 0, Capital Discards ,  
Indicated Net Change in Capital + Capital Discards )

Units: Capital Units/Year

The amount of new capital that investors would like to build.

Used by: (081)Capital Investment -

(084) Desired Capital Growth = LR Expected Output Growth Rate \* Total Undamaged Capital

Units: Capital Units/Year

Capital adjustments due to expectations of long-run economic  
growth.

Used by: (085)Desired Net Change in Capital -

(085) Desired Net Change in Capital = Desired Capital Growth + Capital correction

Units: Capital Unit/Year

The desired capital adjustments given the optimal capital level  
and an adjustment for long-run economic growth.

Used by: (089)Indicated Net Change in Capital -

(086) Effect of Aggregate Demand on Desired Capital = Relative Aggregate Demand  $\wedge$  Sensitivity of Desired Capital to Aggregate Demand  
Units: dimensionless  
The effect of aggregate demand on the desired amount of capital investment.  
Used by: (093)Optimal Capital -

(087) Effect of Relative Return on Capital Investment = Perceived Relative Return to Capital  $\wedge$  Sensitivity of Desired Capital to Relative Return  
Units: dmnl  
The effect of relative return of capital investment on desired capital demand.  
Used by: (093)Optimal Capital -

(088) Factor Investment Return Perception Time = 2  
Units: years  
Time to perceive relative return on investment in production factors. The same is assumed for both labor and capital.  
Used by: (319)Perceived Relative Labor Return -  
(094)Perceived Relative Return to Capital -  
(252)Perceived Relative Return to Housing -

(089) Indicated Net Change in Capital = IF THEN ELSE ( Desired Net Change in Capital > 0, Effect of Land Availability on Investment \* Desired Net Change in Capital , Desired Net Change in Capital ) \* Switch Land Availability + ( 1 - Switch Land Availability ) \* Desired Net Change in Capital  
Units: Capital Unit/Year  
The amount of capital adjustment as constrain by developable land.  
Used by: (083)Desired Capital Development Rate -

(090) Interest Rate for Capital = Risk Free Interest Rate + Risk Premium for Capital Investment  
Units: 1/Year  
The interest rate for investments in capital is the risk free rate plus a risk premium set to the risk of capital development in the region.  
Used by: (082)Cost of Capital -

(091) Marginal Cost of Capital = Unit Price of Capital \* Cost of Capital  
Units: \$/(Year\*Capital Unit)  
The marginal cost of an additional unit of capital in the community.  
Used by: (110)Initial Capital Stock -  
(095)Relative Return to Capital -  
(443)Unit Costs -

(092) Marginal Return of Capital = Price of Output \* Marginal Productivity of Capital  
Units: \$/(Year\*Capital Unit)  
The marginal return of an additional unit of capital.  
Used by: (095)Relative Return to Capital -

(093) Optimal Capital = Total Undamaged Capital \* Effect of Relative Return on Capital Investment \* Effect of Aggregate Demand on Desired Capital  
Units: Capital Units  
The desired growth in capital based on expected returns to investment and aggregate demand.  
Used by: (079)Capital correction -

(094) Perceived Relative Return to Capital = SMOOTHI ( Relative Return to Capital , Factor Investment Return Perception Time , 1)

Units: dmn1

The perceived relative return on capital investment.

Used by: (087)Effect of Relative Return on Capital Investment -  
(109)Effect of Relative Return on Capital Rebuilding -

(095) Relative Return to Capital = Marginal Return of Capital / Marginal Cost of Capital

Units: dimensionless

The relative return of an additional unit of capital given the marginal cost of the unit.

Used by: (094)Perceived Relative Return to Capital -

(096) Risk Free Interest Rate = 0.03

Units: 1/Year

The risk-free interest rate of financing investment.

Used by: (090)Interest Rate for Capital -  
(248)Interest Rate for Housing -

(097) Risk Premium for Capital Investment = 0.02

Units: 1/years

The risk premium for financing capital investment.

Used by: (090)Interest Rate for Capital -

(098) Sensitivity of Desired Capital to Aggregate Demand = 0.5

Units: dimensionless

Coefficient of effect for the aggregate economic demand on desired capital demand.

Used by: (086)Effect of Aggregate Demand on Desired Capital -

(099) Sensitivity of Desired Capital to Relative Return = 0.5

Units: dmn1

Coefficient of effect of relative return of capital investment on desired capital demand.

Used by: (087)Effect of Relative Return on Capital Investment -

(100) Switch Capital Growth = 1

Units: dmn1

0 = Constant (discards only), 1 = Endog based on desired

Used by: (083)Desired Capital Development Rate -

(101) Total Undamaged Capital = Mitigated Undamaged Capital + Unmitigated Undamaged Capital

Units: Capital Units

The total undamaged capital stock in the community.

Used by: (129)Annual Value of Avoided Storm Damage -  
(130)Annual Value of Dryland -  
(079)Capital correction -  
(084)Desired Capital Growth -  
(225)Gross Output -  
(227)Marginal Productivity of Capital -  
(093)Optimal Capital -  
(443)Unit Costs -

(102) Unit Price of Capital = 1

Units: \$/Capital Unit

The price of a unit of capital.

Used by: (091)Marginal Cost of Capital -  
(215)Value of Capital Storm Damage -

\*\*\*\*\*  
.Capital Stock  
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(103) Capital Discards = Mitigated Capital Discards + Unmitigated Capital Discards  
Units: Capital Units/Year  
The discards of undamaged capital.  
Used by: (083)Desired Capital Development Rate -

(104) Capital Lifetime = 30  
Units: years  
The average lifetime of a unit of capital stock.  
Used by: (082)Cost of Capital -  
(111)Mitigated Capital Discards -  
(123)Unmitigated Capital Discards -

(105) Damage to Mitigated Capital = Total Fractional Damage to Mitigated Infrastructure \* Mitigated Undamaged Capital  
Units: Capital Units/Year  
The damage to mitigated capital during a storm.  
Used by: (112)Mitigated Damaged Capital -  
(114)Mitigated Undamaged Capital -  
(565)Damage to Capital from Storms -

(106) Damage to Unmitigated Capital = Total Fractional Damage to Unmitigated Infrastructure \* Unmitigated Undamaged Capital  
Units: Capital Units/Year  
To damage to unmitigated capital during a storm event.  
Used by: (124)Unmitigated Damaged Capital -  
(126)Unmitigated Undamaged Capital -  
(565)Damage to Capital from Storms -

(107) Damaged Mitigated Discards = Mitigated Damaged Capital / Mitigated Damaged Capital Lifetime  
Units: Capital Units/Year  
The discards of damaged mitigated capital.  
Used by: (112)Mitigated Damaged Capital -

(108) Damaged Unmitigated Discards = Unmitigated Damaged Capital / Unmitigated Damaged Capital Lifetime  
Units: Capital Units/Year  
The discards of damaged unmitigated capital.  
Used by: (124)Unmitigated Damaged Capital -

(109) Effect of Relative Return on Capital Rebuilding = Perceived Relative Return to Capital ^ Sensitivity of Capital Relative Return on Rebuilding  
Units: dmn1  
The effect of relative return to capital investment on capital construction.  
Used by: (118)Rebuilding of Mitigated Capital -  
(119)Rebuilding of Unmitigated Capital -

(110) Initial Capital Stock = INITIAL( Price of Output \* ( 1 - Share of labor ) \* Initial Gross Output / Marginal Cost of Capital )  
Units: Capital Units  
The initial capital stock of the community.  
Used by: (114)Mitigated Undamaged Capital -  
(126)Unmitigated Undamaged Capital -  
(225)Gross Output -  
(369)Land Occupied per Capital Unit -

(111) Mitigated Capital Discards = Mitigated Undamaged Capital / Capital Lifetime

Units: Capital Units/Year  
The discard rate of the commercial capital stock.  
Used by: (114)Mitigated Undamaged Capital -  
(103)Capital Discards -

(112) Mitigated Damaged Capital = INTEG( Damage to Mitigated Capital - Damaged Mitigated Discards -  
Rebuilding of Mitigated Capital , 0)  
Units: Capital Units  
The amount of damaged mitigated capital.  
Used by: (107)Damaged Mitigated Discards -  
(118)Rebuilding of Mitigated Capital -  
(122)Total Capital Stock -  
(425)Total Mitigated Capital -

(113) Mitigated Damaged Capital Lifetime = 5  
Units: years  
The lifetime of damaged mitigated capital.  
Used by: (107)Damaged Mitigated Discards -

(114) Mitigated Undamaged Capital = INTEG( New Mitigated Capital + Rebuilding of Mitigated Capital +  
Retrofitting Capital - Damage to Mitigated Capital - Mitigated Capital Discards , Initial Capital Stock \*  
Initial Mitigation Fraction )  
Units: Capital Units  
Mitigated capital that is functiona and producing economic  
output.  
Used by: (105)Damage to Mitigated Capital -  
(111)Mitigated Capital Discards -  
(122)Total Capital Stock -  
(425)Total Mitigated Capital -  
(101)Total Undamaged Capital -

(115) New Mitigated Capital = New Construction NFIP Compliance \* Capital Investment  
Units: Capital Units/Year  
The rate of mitigated capital construction in the community.  
Used by: (114)Mitigated Undamaged Capital -

(116) New Unmitigated Capital = ( 1 - New Construction NFIP Compliance ) \* Capital Investment  
Units: Capital Units/Year  
The rate of unmitigated capital construction.  
Used by: (126)Unmitigated Undamaged Capital -

(117) Normal Rebuilding Time = 5  
Units: years  
The average time to rebuild properties in the community.  
Used by: (118)Rebuilding of Mitigated Capital -  
(283)Rebuilding of Mitigated Housing -  
(119)Rebuilding of Unmitigated Capital -  
(284)Rebuilding of Unmitigated Housing -

(118) Rebuilding of Mitigated Capital = ( Mitigated Damaged Capital / Normal Rebuilding Time ) \* Effect of  
Relative Return on Capital Rebuilding  
Units: Capital Unit/Year  
The rebuilding of damaged mitigated capital, making it undamaged  
capital.  
Used by: (112)Mitigated Damaged Capital -  
(114)Mitigated Undamaged Capital -

(119) Rebuilding of Unmitigated Capital = ( Unmitigated Damaged Capital / Normal Rebuilding Time ) \* Effect  
of Relative Return on Capital Rebuilding  
Units: Capital Units/Year

The reconstruction of unmitigated capital.  
Used by: (124)Unmitigated Damaged Capital -  
(126)Unmitigated Undamaged Capital -

(120) Retrofitting Capital = Fraction Retrofitting \* Unmitigated Undamaged Capital  
Units: Capital Unit/Year

The retrofitting of unmitigated capital, making it mitigated.  
Used by: (114)Mitigated Undamaged Capital -  
(126)Unmitigated Undamaged Capital -

(121) Sensitivity of Capital Relative Return on Rebuilding = 0.7  
Units: dmnl

The sensitivity of capital reconstruction to the relative return  
to capital investment.  
Used by: (109)Effect of Relative Return on Capital Rebuilding -

(122) Total Capital Stock = Mitigated Damaged Capital + Unmitigated Damaged Capital + Mitigated Undamaged  
Capital + Unmitigated Undamaged Capital  
Units: Capital Units

The total amount of capital in the community, including all  
damaged and all functional categories.  
Used by: (329)Average Capital per Area Land -  
(367)Land Occupied by Capital -

(123) Unmitigated Capital Discards = Unmitigated Undamaged Capital / Capital Lifetime  
Units: Capital Units/Year

The discards of undamaged, unmitigated capital.  
Used by: (126)Unmitigated Undamaged Capital -  
(103)Capital Discards -

(124) Unmitigated Damaged Capital = INTEG( Damage to Unmitigated Capital - Damaged Unmitigated Discards -  
Rebuilding of Unmitigated Capital , 0)  
Units: Capital Units

The amount of damaged unmitigated capital in the community.  
Used by: (108)Damaged Unmitigated Discards -  
(119)Rebuilding of Unmitigated Capital -  
(122)Total Capital Stock -  
(427)Total Unmitigated Capital -

(125) Unmitigated Damaged Capital Lifetime = 2  
Units: years

The average lifetime of damaged unmitigated capital.  
Used by: (108)Damaged Unmitigated Discards -

(126) Unmitigated Undamaged Capital = INTEG( New Unmitigated Capital + Rebuilding of Unmitigated Capital -  
Damage to Unmitigated Capital - Retrofitting Capital - Unmitigated Capital Discards , Initial Capital Stock \* ( 1 - Initial Mitigation Fraction ) )

Units: Capital Units  
Unmitigated capital that is functional and producing economic  
output.  
Used by: (106)Damage to Unmitigated Capital -  
(120)Retrofitting Capital -  
(122)Total Capital Stock -  
(101)Total Undamaged Capital -  
(427)Total Unmitigated Capital -  
(123)Unmitigated Capital Discards -

\*\*\*\*\*  
.Coastal Manager Benefit-Cost  
\*\*\*\*\*

(127) Annual Avoided Flooding Benefits If Protected = Annual Value of Avoided Storm Damage + Annual value of Land Threatened by SLR

Units: \$/Year

The annual benefits of constructing a coastal protection project.

Used by: (136)Estimate Discounted Public Protection Benefits -

(128) Annual Unit Value of Dry Land = Annual Value of Dryland / Community Area

Units: \$/(Year\*km\*km)

The value of a sq. kilometer of dry land.

Used by: (131)Annual value of Land Threatened by SLR -

(129) Annual Value of Avoided Storm Damage = CM's Estimated Avoided Fractional Annual Storm Damage \* ( Total Undamaged Capital \* Price of Output \* Marginal Productivity of Capital + Total Undamaged Housing \* Average Rent ) \* Time horizon to value capital for dryland valuation

Units: \$/Year

The estimated annual value of property that would be protected from storm damaged by coastal protection.

Used by: (127)Annual Avoided Flooding Benefits If Protected -

(130) Annual Value of Dryland = IF THEN ELSE ( Switch Land Valuation Means = 0, Gross Output \* Price of Output , ( Total Undamaged Capital \* Marginal Productivity of Capital \* Price of Output + Total Undamaged Housing \* Average Rent ) )

Units: \$/Year

The value of the community's dry land. Can be based on capital plus housing or economic output of the land.

Used by: (128)Annual Unit Value of Dry Land -

(131) Annual value of Land Threatened by SLR = ( Annual Unit Value of Dry Land \* Coastal Managers Projected Inundated Area )

Units: dollars/Year

The value of dryland that is at risk from long-term SLR.

Used by: (127)Annual Avoided Flooding Benefits If Protected -

(132) Coastal Manager's Project Time Horizon = 50

Units: years

The time horizon that coastal managers use for their planning decisions.

Used by: (156)End Year of Project -

(133) Coastal Managers Projected Inundated Area = IF THEN ELSE ( Coastal Manager's Cumulative RSLR Estimate > 0, ZIDZ ( ( ( Coastal Manager's Cumulative RSLR Estimate - Sea Level when Public Protection Built ) / meters in km ) , TAN ( Coastal Slope \* ( ARCCOS ( -1 ) / 180 ) ) ) , 0 ) \* Segment Length

Units: km\*km

The area of dryland that is estimated by coastal managers to be permanently lost by long-term SLR. The calculations are based on the present day shoreline, hence the subtraction of "SL when Built". ARCCOS/180 converts from degrees to radians.

Used by: (131)Annual value of Land Threatened by SLR -

(134) Coastal Managers Recommended Height of Protection = IF THEN ELSE ( ( Estimated Discounted Public Protection Costs + ( Discounted Value of Wetlands \* Switch Consider Wetland Value ) ) < Estimate Discounted Public Protection Benefits , Coastal Managers Desired Public Protection Height , 0 )

Units: meters

The desired height of public protection based on a cost-benefit analysis by coastal managers.

Used by: (155)Desired Reactionary Height -

(160)Indicated Public Protection Height -

(135) Discount Rate = 0.06



Units: 1/Year

The discount rate used to value public protection projects.  
(Powers, 2003)

Used by: (734)Discounted Value of Wetlands -  
(136)Estimate Discounted Public Protection Benefits -  
(139)Estimated Discounted Beach Nourishment Costs -  
(140)Estimated Discounted Levee Costs -

(136) Estimate Discounted Public Protection Benefits = Annual Avoided Flooding Benefits If Protected /  
Discount Rate

Units: \$

The estimated discounted benefits from avoided flood damages and  
dry land protection of a public protection project.

Used by: (134)Coastal Managers Recommended Height of Protection -

(137) Estimated amount of sand required = ( ( Coastal Managers Desired Public Protection Height \* Distance to  
depth of closure ) \* ( Length of beach nourishment \* meters in km ) ) - Initial Volume of Beach Nourishment  
Protection

Units: m\*m\*m

The estimated amount o sand required for a beach nourishment  
project.

Used by: (142)Estimated Initial Beach Nourishment Costs -

(138) Estimated Beach Nourishment Maintenance Costs Per Year = Beach Erosion \* Cost per Cubic Meter of Sand

Units: \$/Year

The estimated annual cost of maintaining a sand dune at a  
particular height.

Used by: (139)Estimated Discounted Beach Nourishment Costs -

(139) Estimated Discounted Beach Nourishment Costs = Estimated Initial Beach Nourishment Costs + ( Estimated  
Beach Nourishment Maintenance Costs Per Year / Discount Rate )

Units: \$

The estimated discounted costs of a beach nourishment project.

Used by: (141)Estimated Discounted Public Protection Costs -

(140) Estimated Discounted Levee Costs = Estimated Levee Construction Costs + ( Estimated Levee Maintenance  
Costs per Year / Discount Rate )

Units: \$

The estimate total cost of a levee protection project for the  
community.

Used by: (141)Estimated Discounted Public Protection Costs -

(141) Estimated Discounted Public Protection Costs = IF THEN ELSE ( Public Protection Type and Height < 2,  
Estimated Discounted Levee Costs , Estimated Discounted Beach Nourishment Costs )

Units: \$

The estimated total cost of the chosen public protecton type.

Used by: (134)Coastal Managers Recommended Height of Protection -

(142) Estimated Initial Beach Nourishment Costs = Cost per Cubic Meter of Sand \* Estimated amount of sand  
required

Units: \$

The estimated initial costs of a beach nourishment project.  
Costs to bring the beach up to the design specifications.

Used by: (139)Estimated Discounted Beach Nourishment Costs -

(143) Estimated Levee Construction Costs = Levee Construction Costs \* Length of Levee \* Coastal Managers  
Desired Public Protection Height

Units: \$

The estimated cost to construct levee protection for the  
community.

Used by: (140)Estimated Discounted Levee Costs -

(144) Estimated Levee Maintenance Costs per Year = ( Coastal Managers Desired Public Protection Height / Lifetime of Levees ) \* "Levee Maintenance Costs per meter-km" \* Length of Levee  
Units: \$/Year  
The estimated annual maintenance costs of levee protection.  
Used by: (140)Estimated Discounted Levee Costs -

(145) Switch Consider Wetland Value = 0  
Units: dmn1  
A switch to control whether or not wetland value is considered in the public protection decision process. 0=Not considered, 1=Considered.  
Used by: (134)Coastal Managers Recommended Height of Protection -

(146) Switch Land Valuation Means = 1  
Units: dmn1  
Switch to change the method of dryland valuation. 0=Gross Output, 1=Capital Stock  
Used by: (130)Annual Value of Dryland -

(147) Time horizon to value capital for dryland valuation = 1  
Units: Year  
The length of time to value capital over. Currently considered 1 year, but maybe should be the lifetime of capital, dividing the value of capital by its depreciation time.  
Used by: (129)Annual Value of Avoided Storm Damage -

\*\*\*\*\*  
.Coastal Manager Protection Calculations  
\*\*\*\*\*

(148) Change in Desired Public Protection Height = MAX ( 0, Gap in Desired Public Protection Height / TIME STEP )  
Units: meter/Year  
The change in the desired height of public protection.  
Used by: (154)Desired Public Protection Height -

(149) Coastal Manager's Cum Linear RSLR Estimate = Annual Relative SLR \* ( End Year of Project - INITIAL TIME )  
Units: meters  
The height of SLR at the end of a protection project given a linear extrapolation.  
Used by: (151)Coastal Manager's Cumulative RSLR Estimate -

(150) Coastal Manager's Cum Quadratic Global SLR Estimate = a2 \* ( End Year of Project - INITIAL TIME ) ^ 2 + a1 \* ( End Year of Project - INITIAL TIME ) + a0 - ( Annual Uplift \* ( End Year of Project - INITIAL TIME ) )  
Units: meters  
:MACRO: SLRQUADRATIC(coeff\_a2, coeff\_a1, coeff\_a0, currYear)  
SLRQUADRATIC=coeff\_a2 \* currTime^2 + coeff\_a1 \* currTime + coeff\_a0  
meters/year  
Another comment.  
currTime = (currYear - INTITIAL TIME\$)  
years  
Here is my comment  
:END OF MACRO:  
Used by: (151)Coastal Manager's Cumulative RSLR Estimate -

(151) Coastal Manager's Cumulative RSLR Estimate = IF THEN ELSE ( QUANTUM ( Switch SLR Scenario / 2, 1) = Switch SLR Scenario / 2, Coastal Manager's Cum Quadratic Global SLR Estimate , Coastal Manager's Cum Linear RSLR Estimate )

Units: meters

The coastal managers' estimate of cumulative SLR that will have occurred by the end of a public protection project.

Used by: (152)Coastal Managers Desired Public Protection Height -  
(133)Coastal Managers Projected Inundated Area -

(152) Coastal Managers Desired Public Protection Height = Coastal Manager's Cumulative RSLR Estimate + Height for Surge Protection - Sea Level when Public Protection Built

Units: meters

The desired height of public protection based on SLR estimates and surge estimates for a design storm.

Used by: (134)Coastal Managers Recommended Height of Protection -  
(137)Estimated amount of sand required -  
(143)Estimated Levee Construction Costs -  
(144)Estimated Levee Maintenance Costs per Year -

(153) Design Storm for Protection = 2

Units: dmnl

The design storm category for the coastal protection project.

Used by: (540)CM's Estimated Fractional Water Damage to Mitigated if Protected by Category -  
(541)CM's Estimated Fractional Water Damage to Unmitigated if Protected by Category -  
(159)Height for Surge Protection -  
(558)Perceived Level of Storm Protection -

(154) Desired Public Protection Height = INTEG( Change in Desired Public Protection Height , 0)

Units: meters

The desired height of public protection for the community.

Used by: (049)Desired Beach Nourishment Height -  
(389)Desired Height of Levee -  
(155)Desired Reactionary Height -  
(158)Gap in Desired Public Protection Height -

(155) Desired Reactionary Height = IF THEN ELSE ( Breach Occurs = 1, Coastal Managers Recommended Height of Protection ,

IF THEN ELSE ( Storm Occurrence = 1,

IF THEN ELSE ( Desired Public Protection Height = 0, Coastal Managers Recommended Height of Protection , 0) , 0 )

Units: meters

The desired height of public protection if society responds in a reactionary manner.

Used by: (160)Indicated Public Protection Height -

(156) End Year of Project = Coastal Manager's Project Time Horizon + Time

Units: Year

The last year of planning for the public protection project.

Used by: (149)Coastal Manager's Cum Linear RSLR Estimate -  
(150)Coastal Manager's Cum Quadratic Global SLR Estimate -

(157) Exogenous Public Protection Type Height = 1

Units: dmnl

0 = Levee Initial height (constant), 1= Levees Coastal Manager,  
2 = Beach Nourishment Initial, 3= Beach Nourishment Coastal  
Manager.

Used by: (161)Public Protection Type and Height -

(158) Gap in Desired Public Protection Height = Indicated Public Protection Height - Desired Public Protection Height

Units: meters

The gap between the desired height and the present height of public protection.  
Used by: (148)Change in Desired Public Protection Height -

(159) Height for Surge Protection = IF THEN ELSE ( Design Storm for Protection = 0, 0,  
IF THEN ELSE ( Design Storm for Protection = 1, "Median Saffir-Simpson Surges by Category"[ Cat1] ,  
IF THEN ELSE ( Design Storm for Protection = 2, "Median Saffir-Simpson Surges by Category"[ Cat2] ,  
IF THEN ELSE ( Design Storm for Protection = 3 , "Median Saffir-Simpson Surges by Category"[Cat3 ] ,  
IF THEN ELSE ( Design Storm for Protection = 4, "Median Saffir-Simpson Surges by Category"[ Cat4] ,  
IF THEN ELSE ( Design Storm for Protection = 5, "Median Saffir-Simpson Surges by Category"[ Cat5] , 0)  
)) ) )

Units: meters  
The additional height of the levee to protect against a particular category of storm.  
Used by: (152)Coastal Managers Desired Public Protection Height -

(160) Indicated Public Protection Height = ( 1 - Switch Reactionary Protection ) \* Coastal Managers Recommended Height of Protection + Switch Reactionary Protection \* Desired Reactionary Height  
Units: meters  
The desired height of public protection depending on whether society responds in a preemptive or reactive manner.  
Used by: (158)Gap in Desired Public Protection Height -

(161) Public Protection Type and Height = IF THEN ELSE ( Switch Segment Choice = 1, Public Protection Type for Miami ,  
IF THEN ELSE ( Switch Segment Choice = 2, Public Protection Type for Cape Cod ,  
IF THEN ELSE ( Switch Segment Choice = 3, Public Protection Type for St Mary Parish , 0 ) ) ) \* Switch Public Protection Type Height + ( 1 - Switch Public Protection Type Height ) \* Exogenous Public Protection Type Height  
Units: dmnl  
The type of public protection that the community will choose.  
Either levee or beach nourishment, initial or dynamic height.  
Used by: (049)Desired Beach Nourishment Height -  
(389)Desired Height of Levee -  
(069)Effective Height of Public Protection -  
(141)Estimated Discounted Public Protection Costs -

(162) Public Protection Type for Cape Cod = 3  
Units: dmnl  
0 = Levee Initial height (constant), 1= Levees Coastal Manager,  
2 = Beach Nourishment Initial, 3= Beach Nourishment Coastal Manager.  
Used by: (161)Public Protection Type and Height -

(163) Public Protection Type for Miami = 3  
Units: dmnl  
0 = Levee Initial height (constant), 1= Levees Coastal Manager,  
2 = Beach Nourishment Initial, 3= Beach Nourishment Coastal Manager.  
Used by: (161)Public Protection Type and Height -

(164) Public Protection Type for St Mary Parish = 1  
Units: dmnl  
0 = Levee Initial height (constant), 1= Levees Coastal Manager,  
2 = Beach Nourishment Initial, 3= Beach Nourishment Coastal Manager.  
Used by: (161)Public Protection Type and Height -

(165) Switch Public Protection Type Height = 1  
Units: dmnl  
Determine the type and height of public protection for a

segment. 0=exog, 1=endog (most likely type and BCA)  
Used by: (161)Public Protection Type and Height -

(166) Switch Reactionary Protection = 0  
Units: dmn1  
Switch to turn on/off reactionary public protection adjustments.  
0=off, 1=on (reactionary)  
Used by: (160)Indicated Public Protection Height -

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.Community Attractiveness  
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(167) Community Relative Attractiveness = Job Attractiveness Effect \* Storm Risk Attractiveness Effect \*  
Occupancy Attractiveness Effect  
Units: dmn1  
The attractiveness and draw of this segment over other segments,  
based on a variety of economic and social factors.  
Used by: (452)Evacuee Return -  
(458)Fractional Rate of Emigration -  
(459)Fractional Rate of Immigration -  
(467)Permanent Resettling -

(168) Initial Occupancy Fraction = INITIAL( Initial Population / Initial Number of Houses )  
Units: People/House  
The initial occupancy fraction of housing, measured by the  
average number of people living in a house.  
Used by: (172)Occupancy Attractiveness Effect -

(169) Job Attractiveness Effect = IF THEN ELSE ( Switch Job Attractiveness = 0, 1,  
IF THEN ELSE ( Switch Job Attractiveness = 1, Job Attractiveness Effect tf ( Labor Force to Jobs Ratio  
) , 0 )  
Units: dmn1  
The effect of jobs on the community's attractiveness.  
Used by: (167)Community Relative Attractiveness -

(170) Job Attractiveness Effect tf ( [(0,0)-(2,2)],(0,2),(0.2,1.95),(0.4,1.8)  
,(0.6,1.6),(0.8,1.35),(1,1),(1.2,0.5),(1.4,0.3),(1.6,0.2),(1.8,0.15) ,(2,0.1) )  
Units: dmn1  
Lookup table for the effect of jobs on the community's relative  
attractiveness. (Based off Intro Urban Dynamics)  
Used by: (169)Job Attractiveness Effect -

(171) Labor Force to Jobs Ratio = ( Labor Force \* ( 1 - Normal Unemployment Rate ) ) / Jobs  
Units: dmn1  
The ratio of the number of workers to the number of jobs in the  
community.  
Used by: (169)Job Attractiveness Effect -

(172) Occupancy Attractiveness Effect = IF THEN ELSE ( Switch Occupancy Feedback = 0, 1,  
IF THEN ELSE ( Switch Occupancy Feedback = 1, Occupancy Attractiveness Effect tf ( Occupancy Fraction /  
Initial Occupancy Fraction ) , 0 )  
Units: dmn1  
The effect of the occupancy fraction the attractiveness of the  
segment.  
Used by: (167)Community Relative Attractiveness -

(173) Occupancy Attractiveness Effect tf ( [(0,0)-(2,2)],(0,1.4),(0.2,1.4),  
(0.4,1.35),(0.6,1.3),(0.8,1.15),(1,1),(1.2,0.8),(1.4,0.65),(1.6,0.5) ,(1.8,0.42),(2,0.4) )  
Units: dmn1

The table function of the relationship between the occupancy fraction and community attractiveness. (Based off of Intro Urban Dynamics)  
Used by: (172)Occupancy Attractiveness Effect -

(174) Occupancy Fraction = Population / Total Livable Houses  
Units: People/House  
The occupancy fraction of housing for the segment.  
Used by: (172)Occupancy Attractiveness Effect -

(175) Storm Risk Attractiveness Effect = IF THEN ELSE ( Switch Storm Risk Attractiveness = 0, 1, IF THEN ELSE ( Switch Storm Risk Attractiveness = 1, Storm Risk Attractiveness Effect tf ( Relative Expected Damage from Storms ) , 0 ) )  
Units: dmn1  
The effect of perceived storm frequency on community attractiveness.  
Used by: (167)Community Relative Attractiveness -

(176) Storm Risk Attractiveness Effect tf ( [(0,0)-(10,2)],(0,1.2),(1,1),(2,0.8) ,(3,0.65),(4,0.55),(10,0.5) )  
Units: dmn1  
The table function for the effect of perceived storm frequency on community attractiveness.  
Used by: (175)Storm Risk Attractiveness Effect -

(177) Switch Job Attractiveness = 1  
Units: dmn1  
Switch to turn on job attractiveness. (0=off; 1 = feedback on)  
Used by: (169)Job Attractiveness Effect -

(178) Switch Occupancy Feedback = 1  
Units: dmn1  
0=No effect, 1=Crowding effect active  
Used by: (172)Occupancy Attractiveness Effect -

(179) Switch Storm Risk Attractiveness = 1  
Units: dmn1  
The switch to turn on/off the storm community attractiveness feedback. (0=off; 1=feedback on)  
Used by: (175)Storm Risk Attractiveness Effect -

(180) Total Livable Houses = Total Undamaged Housing / Average Living Area per House  
Units: House  
The total number of houses in the community.  
Used by: (174)Occupancy Fraction -

\*\*\*\*\*  
.Control  
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Simulation Control Parameters  
(181) FINAL TIME = 2100  
Units: Year  
The final time for the simulation.  
Used by: (509)a2 -  
(511)Annual Linear Global SLR -  
(515)Cum Linear Global SLR -

(182) INITIAL TIME = 2000

Units: Year

The initial time for the simulation.

Used by: (000)Time -

(509)a2 -

(511)Annual Linear Global SLR -

(512)Annual Quadratic Global SLR -

(149)Coastal Manager's Cum Linear RSLR Estimate -

(150)Coastal Manager's Cum Quadratic Global SLR Estimate -

(515)Cum Linear Global SLR -

(516)Cum Quadratic Global SLR -

(430)mean storms per year -

(183) SAVEPER = TIME STEP

Units: Year

The frequency with which output is stored.

(184) TIME STEP = 0.0625

Units: Year

The time step for the simulation.

Used by: (649)Annual Storm Frequency adjusted by TIMESTEP -

(148)Change in Desired Public Protection Height -

(200)Change in Flood Insurance Coverage -

(450)Evacuation Time -

(652)Exogenous Storm Event -

(415)Fraction Retrofitting -

(070)Increment Breach Count -

(594)New Storm -

(183)SAVEPER -

(431)storm -

(432)storm cat count -

(586)Total Fractional Damage to Mitigated Infrastructure -

(588)Total Fractional Damage to Unmitigated Infrastructure -

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.Econ Growth Trend

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(185) Change in perceived gross output trend = ( Indicated trend in gross output - Perceived Trend of Economic Output ) / Time to perceive Gross Output Trend

Units: 1/(Year\*Year)

Change in the expected trend of economic output.

Used by: (193)Perceived Trend of Economic Output -

(186) Change in PPC of Gross Output = ( Gross Output - Perceived Present Condition of Gross Output ) / Time to perceive Present Gross Output

Units: units/(Year\*Year)

The change of the perceived present condition of the economy in the community. Based on recent gross output.

Used by: (192)Perceived Present Condition of Gross Output -

(187) Change in Reference Condition = ( Perceived Present Condition of Gross Output - Reference Condition of gross output ) / Time horizon for reference condition of gross output

Units: units/(Year\*Year)

The change in the reference condition of long-term economic output.

Used by: (194)Reference Condition of gross output -

(188) "Exogenous Long-run Output Growth Rate" = 0

Units: 1/Year

A constant, exogenous expected economic growth rate.

Used by: (191)LR Expected Output Growth Rate -

(189) Hist Output Growth Rate = 0.01  
Units: 1/Year  
Historic growth rate of output and investment. First quarter of 2000 the US had a 1 percent growth rate (US Bureau of Economic Analysis). Future work: Initialize to community economic growth rate.  
Used by: (192)Perceived Present Condition of Gross Output -  
(193)Perceived Trend of Economic Output -  
(194)Reference Condition of gross output -

(190) Indicated trend in gross output = ( ( Perceived Present Condition of Gross Output - Reference Condition of gross output ) / Reference Condition of gross output ) / Time horizon for reference condition of gross output  
Units: 1/years  
Indicated trend of gross economic output of the community.  
Used by: (185)Change in perceived gross output trend -

(191) LR Expected Output Growth Rate = IF THEN ELSE ( "Switch Long-run Output Growth Rate trend" = 0, "Exogenous Long-run Output Growth Rate" ,  
IF THEN ELSE ( "Switch Long-run Output Growth Rate trend" = 1, Perceived Trend of Economic Output , 0 )  
)  
Units: 1/Year  
Perceived long run trend of economic output.  
Used by: (084)Desired Capital Growth -  
(297)Expected LR job growth -

(192) Perceived Present Condition of Gross Output = INTEG( Change in PPC of Gross Output , Initial Gross Output / ( 1 + Time to perceive Present Gross Output \* Hist Output Growth Rate ) )  
Units: units/Year  
Perceived present condition of the economic output of the community.  
Used by: (186)Change in PPC of Gross Output -  
(187)Change in Reference Condition -  
(190)Indicated trend in gross output -

(193) Perceived Trend of Economic Output = INTEG( Change in perceived gross output trend , Hist Output Growth Rate )  
Units: 1/years  
The perceived fractional growth rate of gross economic output.  
Used by: (185)Change in perceived gross output trend -  
(191)LR Expected Output Growth Rate -

(194) Reference Condition of gross output = INTEG( Change in Reference Condition , ( Initial Gross Output / ( 1 + Time to perceive Present Gross Output \* Hist Output Growth Rate ) ) / ( 1 + Time horizon for reference condition of gross output \* Hist Output Growth Rate ) )  
Units: units/Year  
Reference condition of gross economic output of the community.  
Used by: (187)Change in Reference Condition -  
(190)Indicated trend in gross output -

(195) "Switch Long-run Output Growth Rate trend" = 1  
Units: dmn1  
0=Exogenous, 1=BusDyn  
Used by: (191)LR Expected Output Growth Rate -

(196) Time horizon for reference condition of gross output = 3  
Units: years  
The time horizon to analyze the economic conditions of the community. This says that we evaluate economic trends based on three years worth of economic data.



Used by: (194)Reference Condition of gross output -  
(187)Change in Reference Condition -  
(190)Indicated trend in gross output -

(197) Time to perceive Gross Output Trend = 3  
Units: years  
The time for the community to change their expectations about  
the growth trends of economic output.  
Used by: (185)Change in perceived gross output trend -

(198) Time to perceive Present Gross Output = 1  
Units: Year  
Time required to report updates of the gross output of the  
community.  
Used by: (192)Perceived Present Condition of Gross Output -  
(194)Reference Condition of gross output -  
(186)Change in PPC of Gross Output -

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.Flood Insurance  
\*\*\*\*\*

(199) Average Memory of Storm Event for Insurance = 5  
Units: years  
The time delay for property owners to return their normal flood  
insurance behavior after a storm event.  
Used by: (208)Lapse of Insurance Coverage -

(200) Change in Flood Insurance Coverage = Storm Occurrence \* ( Max Insurance Coverage - Flood Insurance  
Coverage ) / TIME STEP  
Units: 1/Year  
The increase in insurance coverage because of a recent storm  
event.  
Used by: (205)Flood Insurance Coverage -

(201) Damage Covered by Insurance = Damage Covered by Wind Insurance + Damaged Covered by Flood Insurance  
Units: \$/Year  
The total amount of storm damage covered by insurance.  
Used by: (203)Damage not Covered by Insurance -  
(014)Insurance Claims Paid -

(202) Damage Covered by Wind Insurance = Fraction with Wind Insurance \* Total Value Damaged by Storm \*  
Fraction of Infrastructure Damaged by Wind  
Units: \$/Year  
The amount of wind damage covered by insurance.  
Used by: (201)Damage Covered by Insurance -

(203) Damage not Covered by Insurance = Total Value Damaged by Storm - Damage Covered by Insurance  
Units: \$/Year  
The total amount of storm damage not covered by insurance.  
Used by: (008)Direct Government Disaster Relief -

(204) Damaged Covered by Flood Insurance = ( Fraction of Unmitigated Infrastructure Damaged by Water +  
Fraction of Mitigated Infrastructure Damaged by Water ) \* Flood Insurance Coverage \* Total Value Damaged by  
Storm  
Units: \$/Year  
The amount of flood damage covered by insurance.  
Used by: (201)Damage Covered by Insurance -

(205) Flood Insurance Coverage = INTEG( Change in Flood Insurance Coverage - Lapse of Insurance Coverage , Normal Insurance Fraction )

Units: dmn1

The percentage of the community with flood insurance in the Special Flood Hazard Areas (SFHAs).

Used by: (200)Change in Flood Insurance Coverage -  
(204)Damaged Covered by Flood Insurance -  
(208)Lapse of Insurance Coverage -

(206) Fraction with Wind Insurance = 0.695

Units: dmn1

The fraction of property that is covered by wind insurance, through homeowners policy, etc. Pure average of renters and homeowners coverage. (Insurance Research Council, 2006)

Used by: (202)Damage Covered by Wind Insurance -

(207) Fractional Change of Coverage after Storm = 0.5

Units: dmn1

The response factor of insurance coverage to a recent storm event. Measured as a likelihood of buying insurance because of a recent storm. Example: 0.5 means 50% more likely to buy insurance.

Used by: (209)Max Insurance Coverage -

(208) Lapse of Insurance Coverage = ( Flood Insurance Coverage - Normal Insurance Fraction ) / Average Memory of Storm Event for Insurance

Units: 1/Year

The lapse of insurance coverage after a storm event.

Used by: (205)Flood Insurance Coverage -

(209) Max Insurance Coverage = Fractional Change of Coverage after Storm \* ( 1 - Normal Insurance Fraction ) + Normal Insurance Fraction

Units: dmn1

The maximum insurance coverage in the community due to recent storms.

Used by: (200)Change in Flood Insurance Coverage -

(210) Normal Insurance Fraction = INITIAL( IF THEN ELSE ( Switch Segment Choice = 1, Normal Insurance Fraction for Miami ,

IF THEN ELSE ( Switch Segment Choice = 2, Normal Insurance Fraction for Cape Cod ,

IF THEN ELSE ( Switch Segment Choice = 3, Normal Insurance Fraction for St Mary Parish , 0 ) ) )

Units: dmn1

The normal fraction of NFIP insurance coverage between storms.

Used by: (205)Flood Insurance Coverage -  
(208)Lapse of Insurance Coverage -  
(209)Max Insurance Coverage -

(211) Normal Insurance Fraction for Cape Cod = 0.28

Units: dmn1

The normal fraction of NFIP insurance coverage between storms for Cape Cod. For homes in the SFHA for the Northeast region (Table 4.1 in Dixon 2006).

Used by: (210)Normal Insurance Fraction -

(212) Normal Insurance Fraction for Miami = 0.61

Units: dmn1

The normal fraction of NFIP insurance coverage between storms for Miami. For homes in the SFHA for the South region (Table 4.1 in Dixon 2006).

Used by: (210)Normal Insurance Fraction -

(213) Normal Insurance Fraction for St Mary Parish = 0.61

Units: dmn1

The normal fraction of NFIP insurance coverage between storms for St Mary Parish. For homes in the SFHA for the South region (Table 4.1 in Dixon 2006).

Used by: (210)Normal Insurance Fraction -

(214) Total Value Damaged by Storm = Value of Capital Storm Damage + Value of Housing Storm Damage

Units: \$/Year

The total value of damage caused by a storm.

Used by: (202)Damage Covered by Wind Insurance -

(203)Damage not Covered by Insurance -

(204)Damaged Covered by Flood Insurance -

(215) Value of Capital Storm Damage = Damage to Capital from Storms \* Unit Price of Capital

Units: \$/Year

The value of capital damaged by a storm.

Used by: (214)Total Value Damaged by Storm -

(216) Value of Housing Storm Damage = Marginal Cost of Housing Construction \* Damage to Housing from Storms

Units: \$/Year

The value of housing damaged by a storm.

Used by: (214)Total Value Damaged by Storm -

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(217) cubic meters in cubic yard = 0.764555

Units: m\*m\*m/cy

Conversion factor for cubic meters in cubic yards.

Used by: (032)Beach Erosion Rate in Metric -

(046)Cost per Cubic Meter of Sand -

(218) feet in a kilometer = 3280.84

Units: ft/km

Conversion factor for feet in kilometer.

Used by: (032)Beach Erosion Rate in Metric -

(219) feet in meters = 0.3048

Units: ft/meter

Conversion factor for feet to meters.

Used by: (409)Levee Maintenance Costs per meter-km -

(220) kilometers in mile = 1.60934

Units: km/mile

Conversion factor for kilometers and miles.

Used by: (409)Levee Maintenance Costs per meter-km -

(221) "m\*m in km\*km" = 1e+006

Units: m\*m/(km\*km)

The number of square meters in a square kilometer.

Used by: (344)Developed Land -

(365)Initial Land Occupied by Housing -

(369)Land Occupied per Capital Unit -

(222) meters in km = 1000

Units: meters/km

Conversion factor between meters and kilometers.  
 Used by: (326)Annual Flooded Inland Distance -  
 (033)Beach Nourishment Area -  
 (133)Coastal Managers Projected Inundated Area -  
 (137)Estimated amount of sand required -  
 (548)Estimated Inland Distance Flooded During Storm -  
 (347)Flooded Inland Distance -  
 (574)Inland Distance Flooded During Storm -

(223) mm in m = 1000

Units: mm/meter

The conversion ratio for millimeters and meters.

Used by: (500)Annual Uplift -

(224) Switch Segment Choice = 1

Units: dmdl

1=Miami, 2=Cape Cod, 3= St Mary Parish

Used by: (665)Accommodation space of the segment -

- (620)Annual Storm Frequency in 1990 -
- (621)Annual Storm Frequency in 2190 -
- (259)Average Living Area per House -
- (028)Beach Erosion Rate -
- (331)Coastal Slope -
- (335)Coastal Uplift -
- (339)Community Area -
- (056)Distance to depth of closure -
- (349)Floor Area Ratio for Housing -
- (353)Fraction of Community Area Developable -
- (244)Initial Average Rent -
- (669)Initial Forested Wetland Area -
- (363)Initial Fraction of Land Developed -
- (673)Initial Freshmarsh Area -
- (303)Initial GDP per Capita -
- (677)Initial Mangrove Area -
- (416)Initial Mitigation Fraction -
- (272)Initial Number of Houses -
- (462)Initial Population -
- (681)Initial Saltmarsh Area -
- (695)Initial Unvegetated Area -
- (314)Labor Force Participation Fraction -
- (420)New Construction NFIP Compliance -
- (210)Normal Insurance Fraction -
- (161)Public Protection Type and Height -
- (622)Reference Perceived Storm Frequency -
- (699)Sediment supply of the segment -
- (370)Segment Length -
- (644)Storm Intensity 1990 -
- (645)Storm Intensity 2190 -
- (700)Tidal range of segment -
- (324)Working Age Fraction -

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.Gross Output

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(225) Gross Output = Initial Gross Output \* Total Factor Productivity \* ( Employed Labor / Initial Employment ) ^ ( Share of labor ) \* ( Total Undamaged Capital / Initial Capital Stock ) ^ ( 1 - Share of labor )

Units: units/Year

The total economic output of the segment.

- Used by: (130)Annual Value of Dryland -
- (186)Change in PPC of Gross Output -
  - (227)Marginal Productivity of Capital -
  - (228)Marginal Productivity of Labor -
  - (018)Output per Capita -
  - (019)Relative Aggregate Demand -

(443)Unit Costs -

(226) Initial Gross Output = INITIAL( Marginal Cost of Labor \* Initial Employment / ( Price of Output \* Share of labor ) )

Units: units/Year

The initial economic output for the region.

Used by: (010)Expected Income per Capita -  
(192)Perceived Present Condition of Gross Output -  
(194)Reference Condition of gross output -  
(225)Gross Output -  
(110)Initial Capital Stock -

(227) Marginal Productivity of Capital = ( 1 - Share of labor ) \* Gross Output / Total Undamaged Capital  
Units: units/(Year\*Capital Unit)

The marginal productivity an additional unit of capital to produce another unit of economic output.

Used by: (129)Annual Value of Avoided Storm Damage -  
(130)Annual Value of Dryland -  
(092)Marginal Return of Capital -

(228) Marginal Productivity of Labor = Share of labor \* Gross Output / Employed Labor  
Units: units/(FTE\*Year)

The marginal productivity of an additional unit of labor to produce another unit of economic output.

Used by: (320)Relative Return to Labor -

(229) Share of labor = 0.7

Units: dmn1

The Cobb-Douglas exponent for the labor share.

Used by: (225)Gross Output -  
(110)Initial Capital Stock -  
(226)Initial Gross Output -  
(227)Marginal Productivity of Capital -  
(228)Marginal Productivity of Labor -

(230) Total Factor Productivity = 1

Units: dmn1

The total factor productivity of economic resources.

Used by: (225)Gross Output -

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.Housing Adjustment

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(231) Adequacy of Housing Stock = Total Undamaged Housing / Indicated Housing Stock

Units: dimensionless

The relative adequacy of the housing stock. It is the ratio of livable housing to desired amount of housing given the community's population.

Used by: (237)Effect of Housing Adequacy on Housing -  
(493)Effect of Housing Adequacy on Rent -

(232) Average Living Area per Person = INITIAL( ( Initial Number of Houses \* Average Living Area per House ) / Population )

Units: m\*m/person

The average living area per person in the community.

Used by: (242)Indicated Housing Stock -

(233) Cost of Housing = Interest Rate for Housing + ( 1 / Housing Lifetime ) + Perceived Fractional Damage from Storms

Units: 1/Year  
The absolute cost of housing investment.  
Used by: (249)Marginal Cost of Housing -  
(250)Marginal Cost of Housing Construction -

(234) Desired Housing Development Rate = IF THEN ELSE ( Switch Housing Growth = 0, Housing Discards , Housing Discards + Indicated Net Change in Housing )  
Units: m\*m/Year  
The amount of new housing that investors would like to build.  
Used by: (241)Housing Investment -

(235) Desired Housing Growth = LR Expected Population Growth Rate \* Total Undamaged Housing  
Units: m\*m/Year  
The desired amount of housing adjustment giving expected population growth.  
Used by: (236)Desired Net Change in Housing -

(236) Desired Net Change in Housing = Desired Housing Growth + Housing Correction  
Units: m\*m/Year  
The desired change in housing considered the effects of adequacy and relative return, adjusted by expectations of long-run population growth.  
Used by: (243)Indicated Net Change in Housing -

(237) Effect of Housing Adequacy on Housing = Adequacy of Housing Stock ^ Sensitivity of Housing to Housing Adequacy  
Units: dmdl  
The effect of housing adequacy on the desired housing level in the community.  
Used by: (251)Optimal Housing -

(238) Effect of Relative Return on Housing = Perceived Relative Return to Housing ^ Sensitivity of Housing to Relative Return  
Units: dmdl  
The effect of relative return of capital investment on desired capital demand.  
Used by: (251)Optimal Housing -

(239) Housing Correction = ( Optimal Housing - Total Undamaged Housing ) / Housing Correction Time  
Units: m\*m/Year  
The amount of new capital that should be constructed to satisfied expected returns on capital investment.  
Used by: (236)Desired Net Change in Housing -

(240) Housing Correction Time = 4  
Units: years  
The time to correct of capital construction gaps.  
Used by: (239)Housing Correction -

(241) Housing Investment = MAX ( 0, Desired Housing Development Rate )  
Units: m\*m/Year  
The rate of new capital stock construction in the community.  
Used by: (281)New Mitigated Housing -  
(282)New Unmitigated Housing -

(242) Indicated Housing Stock = Population \* Average Living Area per Person  
Units: m\*m  
The housing stock desired for given the population of the community.

Used by: (231)Adequacy of Housing Stock -

(243) Indicated Net Change in Housing = IF THEN ELSE ( Desired Net Change in Housing > 0, Effect of Land Availability on Investment \* Desired Net Change in Housing , Desired Net Change in Housing ) \* Switch Land Availability + ( 1 - Switch Land Availability ) \* Desired Net Change in Housing

Units: meter\*meter/Year

The net change in housing given the amount of housing desired by the community, but restricted by the availability of land for construction.

Used by: (234)Desired Housing Development Rate -

(244) Initial Average Rent = INITIAL( IF THEN ELSE ( Switch Segment Choice = 1, Initial Rent in Miami , IF THEN ELSE ( Switch Segment Choice = 2, Initial Rent in Cape Cod , IF THEN ELSE ( Switch Segment Choice = 3, Initial Rent in St Mary Parish , 0 ) ) ) )

Units: \$/(Year\*meter\*meter)

The initial rent of living space in the community.

Used by: (491)Average Rent -

(245) Initial Rent in Cape Cod = 87.25

Units: \$/(m\*m\*Year)

The initial rental price on Cape Cod. The rental price from the three counties (city-data.com), weighted by number of housing units (census), divided by the national average for square footage (census 2000).

Used by: (244)Initial Average Rent -

(246) Initial Rent in Miami = 86.09

Units: \$/(m\*m\*Year)

The initial rent in Miami-Dade county. The rental price city-data.com for 3BR (most common unit) and the mean square footage from Census AHS for Miami.

Used by: (244)Initial Average Rent -

(247) Initial Rent in St Mary Parish = 46.46

Units: \$/(m\*m\*Year)

The initial rental price on St Mary Parish. The rental price (city-data.com) divided by the national average for square footage (census 2000).

Used by: (244)Initial Average Rent -

(248) Interest Rate for Housing = Risk Free Interest Rate + Risk Premium for Housing

Units: 1/years

The interest rate for investments in housing is the risk free rate plus a risk premium set to the risk of housing development in the region.

Used by: (233)Cost of Housing -

(249) Marginal Cost of Housing = Marginal Cost of Housing Construction \* Cost of Housing

Units: \$/(m\*m\*Year)

The marginal cost of an additional unit of housing in the community.

Used by: (494)Effect of Housing Costs on Rent -  
(253)Relative Return to Housing -

(250) Marginal Cost of Housing Construction = INITIAL( Average Rent / Cost of Housing )

Units: \$/(m\*m)

The marginal cost of constructing housing.

Used by: (249)Marginal Cost of Housing -  
(216)Value of Housing Storm Damage -

(251) Optimal Housing = Total Undamaged Housing \* Effect of Relative Return on Housing \* Effect of Housing Adequacy on Housing

Units: m\*m

The desired growth in capital based on expected returns to investment.

Used by: (239)Housing Correction -

(252) Perceived Relative Return to Housing = SMOOTHI ( Relative Return to Housing , Factor Investment Return Perception Time , 1)

Units: dmn1

The perceived relative return on capital investment.

Used by: (238)Effect of Relative Return on Housing -  
(265)Effect of Relative Return on Housing Rebuilding -

(253) Relative Return to Housing = Average Rent / Marginal Cost of Housing

Units: dimensionless

The relative return of an additional unit of capital given the marginal cost of the unit.

Used by: (252)Perceived Relative Return to Housing -

(254) Risk Premium for Housing = 0.03

Units: 1/years

The risk premium for loans on housing.

Used by: (248)Interest Rate for Housing -

(255) Sensitivity of Housing to Housing Adequacy = -1.5

Units: dmn1

The sensitivity of housing adjustments to the relative supply of housing in the community.

Used by: (237)Effect of Housing Adequacy on Housing -

(256) Sensitivity of Housing to Relative Return = 0.5

Units: dmn1

Coefficient of effect of relative return of capital investment on desired capital demand.

Used by: (238)Effect of Relative Return on Housing -

(257) Switch Housing Growth = 1

Units: dmn1

0 = Constant (discards only), 1 = Endog based on desired

Used by: (234)Desired Housing Development Rate -

(258) Total Undamaged Housing = Mitigated Undamaged Housing + Unmitigated Undamaged Housing

Units: m\*m

The total undamaged livable housing in the community.

Used by: (231)Adequacy of Housing Stock -  
(129)Annual Value of Avoided Storm Damage -  
(130)Annual Value of Dryland -  
(235)Desired Housing Growth -  
(239)Housing Correction -  
(251)Optimal Housing -  
(180)Total Livable Houses -

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.Housing Stock

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(259) Average Living Area per House = INITIAL( IF THEN ELSE ( Switch Segment Choice = 1, Average Living Area per House for Miami ,



IF THEN ELSE ( Switch Segment Choice = 2, Average Living Area per House for Cape Cod ,  
 IF THEN ELSE ( Switch Segment Choice = 3, Average Living Area per House for St Mary Parish , 0 ) ) )  
 Units: m\*m/House  
 The average living area of a home in the community.  
 Used by: (232)Average Living Area per Person -  
 (271)Initial Housing Stock -  
 (180)Total Livable Houses -

(260) Average Living Area per House for Cape Cod = 137.8  
 Units: m\*m/House  
 The median house size of home/condos/apartments for Cape Cod.  
 Data from the American Housing Survey for US (2001). Using  
 "Outside Metropolitan Statistical Areas Table 13-D."  
 Used by: (259)Average Living Area per House -

(261) Average Living Area per House for Miami = 168  
 Units: m\*m/House  
 The median house size of home/condos/apartments for Miami. Data  
 from the American Housing Survey for Miami-Ft. Lauderdale  
 (2002). (168 = 1808 sq ft)  
 Used by: (259)Average Living Area per House -

(262) Average Living Area per House for St Mary Parish = 167.8  
 Units: m\*m/House  
 The median house size of home/condos/apartments for St. Mary  
 Parish. Data from the American Housing Survey for US (2001).  
 Using "Suburbs Table 13-C."  
 Used by: (259)Average Living Area per House -

(263) Damage to Mitigated Housing = Total Fractional Damage to Mitigated Infrastructure \* Mitigated Undamaged  
 Housing  
 Units: meter\*meter/Year  
 The amount of mitigated housing capital damaged from by a storm.  
 Used by: (276)Mitigated Damaged Housing -  
 (280)Mitigated Undamaged Housing -  
 (566)Damage to Housing from Storms -

(264) Damage to Unmitigated Housing = Total Fractional Damage to Unmitigated Infrastructure \* Unmitigated  
 Undamaged Housing  
 Units: meter\*meter/Year  
 The amount of unmitigated housing capital damaged by a storm.  
 Used by: (288)Unmitigated Damaged Housing -  
 (292)Unmitigated Undamaged Housing -  
 (566)Damage to Housing from Storms -

(265) Effect of Relative Return on Housing Rebuilding = Perceived Relative Return to Housing ^ Sensitivity of  
 Housing Relative Return on Rebuilding  
 Units: dmn1  
 The effect of relative return on housing investment to housing  
 reconstruction.  
 Used by: (283)Rebuilding of Mitigated Housing -  
 (284)Rebuilding of Unmitigated Housing -

(266) Fraction of Housing Older than 1990 for Cape Cod = 0.8517  
 Units: dmn1  
 The fraction of housing units older than 1990. Weighted by  
 housing units for Cape Cod counties. (Census, 2000)  
 Used by: (417)Initial Mitigation Fraction for Cape Cod -

(267) Fraction of Housing Older than 1990 for Miami = 0.848

Units: dnnl  
The fraction of homes that were built before 1990 in Miami.  
(Census, 2000)  
Used by: (418)Initial Mitigation Fraction for Miami -

(268) Fraction of Housing Older than 1990 for St Mary Parish = 0.863  
Units: dnnl  
The fraction of housing units older than 1990 in St Mary Parish.  
(US Census, 2000)  
Used by: (419)Initial Mitigation Fraction for St Mary Parish -

(269) Housing Discards = Mitigated Housing Discards + Unmitigated Housing Discards  
Units: m\*m/Year  
The total rate of capital discards in the community, including  
both commercial and housing.  
Used by: (234)Desired Housing Development Rate -

(270) Housing Lifetime = 30  
Units: years  
The average lifetime of a unit of capital stock.  
Used by: (233)Cost of Housing -  
(279)Mitigated Housing Discards -  
(291)Unmitigated Housing Discards -

(271) Initial Housing Stock = INITIAL( Initial Number of Houses \* Average Living Area per House )  
Units: m\*m  
The initial area of the housing sector.  
Used by: (280)Mitigated Undamaged Housing -  
(292)Unmitigated Undamaged Housing -  
(365)Initial Land Occupied by Housing -

(272) Initial Number of Houses = INITIAL( IF THEN ELSE ( Switch Segment Choice = 1, Initial Number of Houses  
for Miami ,  
IF THEN ELSE ( Switch Segment Choice = 2, Initial Number of Houses for Cape Cod ,  
IF THEN ELSE ( Switch Segment Choice = 3, Initial Number of Houses for St Mary Parish , 0 ) ) ) )  
Units: Houses  
The initial number of housing in the community.  
Used by: (232)Average Living Area per Person -  
(271)Initial Housing Stock -  
(168)Initial Occupancy Fraction -

(273) Initial Number of Houses for Cape Cod = 171129  
Units: Houses  
The initial number of housing units in Cape Cod. (2000 Census  
data)  
Used by: (272)Initial Number of Houses -

(274) Initial Number of Houses for Miami = 852278  
Units: Houses  
The initial number of housing units in Miami. (2000 Census)  
Used by: (272)Initial Number of Houses -

(275) Initial Number of Houses for St Mary Parish = 21650  
Units: Houses  
The initial number of housing in St. Mary Parish. (2000 Census  
data)  
Used by: (272)Initial Number of Houses -

(276) Mitigated Damaged Housing = INTEG( Damage to Mitigated Housing - Mitigated Damaged Housing Discards -

Rebuilding of Mitigated Housing , 0)  
Units: m\*m  
The amount of damaged mitigated housing capital.  
Used by: (277)Mitigated Damaged Housing Discards -  
(283)Rebuilding of Mitigated Housing -  
(287)Total Housing Stock -  
(426)Total Mitigated Housing -

(277) Mitigated Damaged Housing Discards = Mitigated Damaged Housing / Mitigated Damaged Housing Lifetime  
Units: meter\*meter/Year  
The demolition rate of damaged mitigated housing.  
Used by: (276)Mitigated Damaged Housing -

(278) Mitigated Damaged Housing Lifetime = 2  
Units: years  
The time mitigated housing remains damaged before it is demolished.  
Used by: (277)Mitigated Damaged Housing Discards -

(279) Mitigated Housing Discards = Mitigated Undamaged Housing / Housing Lifetime  
Units: meter\*meter/Year  
The demolition rate of mitigated housing.  
Used by: (280)Mitigated Undamaged Housing -  
(269)Housing Discards -

(280) Mitigated Undamaged Housing = INTEG( New Mitigated Housing - Damage to Mitigated Housing - Mitigated Housing Discards + Retrofitting Housing + Rebuilding of Mitigated Housing , ( Initial Mitigation Fraction \* Initial Housing Stock ) )  
Units: m\*m  
The amount of mitigated housing that is livable.  
Used by: (263)Damage to Mitigated Housing -  
(279)Mitigated Housing Discards -  
(287)Total Housing Stock -  
(426)Total Mitigated Housing -  
(258)Total Undamaged Housing -

(281) New Mitigated Housing = New Construction NFIP Compliance \* Housing Investment  
Units: m\*m/Year  
Rate of new mitigated housing construction.  
Used by: (280)Mitigated Undamaged Housing -

(282) New Unmitigated Housing = ( 1 - New Construction NFIP Compliance ) \* Housing Investment  
Units: m\*m/Year  
Rate of new unmitigated housing stock.  
Used by: (292)Unmitigated Undamaged Housing -

(283) Rebuilding of Mitigated Housing = Effect of Relative Return on Housing Rebuilding \* ( Mitigated Damaged Housing / Normal Rebuilding Time )  
Units: meter\*meter/Year  
The rate which damaged mitigated housing capital is rebuilt.  
Used by: (276)Mitigated Damaged Housing -  
(280)Mitigated Undamaged Housing -

(284) Rebuilding of Unmitigated Housing = ( Unmitigated Damaged Housing / Normal Rebuilding Time ) \* Effect of Relative Return on Housing Rebuilding  
Units: meter\*meter/Year  
The rate of rebuilt unmitigated housing capital.  
Used by: (288)Unmitigated Damaged Housing -  
(292)Unmitigated Undamaged Housing -

(285) Retrofitting Housing = Unmitigated Undamaged Housing \* Fraction Retrofitting  
Units: meter\*meter/Year  
Rate of uninsured housing stock become insured housing stock.  
Used by: (280)Mitigated Undamaged Housing -  
(292)Unmitigated Undamaged Housing -

(286) Sensitivity of Housing Relative Return on Rebuilding = 0.7  
Units: dmn1  
The sensitivity of housing reconstruction to the relative return  
on housing investment.  
Used by: (265)Effect of Relative Return on Housing Rebuilding -

(287) Total Housing Stock = Unmitigated Damaged Housing + Mitigated Damaged Housing + Mitigated Undamaged  
Housing + Unmitigated Undamaged Housing  
Units: m\*m  
The total amount of living area in the housing sector.  
Used by: (330)Average Housing per Area Land -  
(368)Land Occupied by Housing -

(288) Unmitigated Damaged Housing = INTEG( Damage to Unmitigated Housing - Unmitigated Damaged Housing  
Discards - Rebuilding of Unmitigated Housing , 0)  
Units: m\*m  
The amount of damaged unmitigated housing capital.  
Used by: (284)Rebuilding of Unmitigated Housing -  
(287)Total Housing Stock -  
(428)Total Unmitigated Housing -  
(289)Unmitigated Damaged Housing Discards -

(289) Unmitigated Damaged Housing Discards = Unmitigated Damaged Housing / Unmitigated Damaged Housing  
Lifetime  
Units: meter\*meter/Year  
The demolition rate of damaged unmitigated housing.  
Used by: (288)Unmitigated Damaged Housing -

(290) Unmitigated Damaged Housing Lifetime = 1  
Units: years  
The time unmitigated housing remains damaged before it is  
demolished.  
Used by: (289)Unmitigated Damaged Housing Discards -

(291) Unmitigated Housing Discards = Unmitigated Undamaged Housing / Housing Lifetime  
Units: meter\*meter/Year  
The demolition rate of unmitigated housing.  
Used by: (292)Unmitigated Undamaged Housing -  
(269)Housing Discards -

(292) Unmitigated Undamaged Housing = INTEG( New Unmitigated Housing - Damage to Unmitigated Housing -  
Unmitigated Housing Discards - Retrofitting Housing + Rebuilding of Unmitigated Housing , ( 1 - Initial  
Mitigation Fraction ) \* Initial Housing Stock )  
Units: m\*m  
The amount of unmitigated housing in the community that is  
livable.  
Used by: (264)Damage to Unmitigated Housing -  
(285)Retrofitting Housing -  
(287)Total Housing Stock -  
(258)Total Undamaged Housing -  
(428)Total Unmitigated Housing -  
(291)Unmitigated Housing Discards -

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.Labor and Jobs  
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(293) Desired Change in Jobs = Expected LR job growth + Job Correction  
Units: FTE/Year  
The desired job growth rate in the community, given the long-run economic expectations and the demand for labor from industry and aggregate demand.  
Used by: (316)Net Job Change -

(294) Effect of Aggregate Demand on Jobs = Relative Aggregate Demand ^ Sensitivity of Jobs to Aggregate Demand  
Units: dimensionless  
The effect of aggregate demand relative to current output on the desired number of jobs in the community.  
Used by: (318)Optimal Jobs -

(295) Effect of Relative Return on Jobs = Perceived Relative Labor Return ^ Sensitivity of Jobs to Relative Return  
Units: dimensionless  
The effect of economic return of labor on job demand in the community.  
Used by: (318)Optimal Jobs -

(296) Employed Labor = MIN ( Jobs , Labor Force )  
Units: FTE  
The number of full-time equivalent jobs that the community is actually employing. This is either limited by the number of jobs or the number of workers.  
Used by: (225)Gross Output -  
(228)Marginal Productivity of Labor -  
(318)Optimal Jobs -  
(323)Unemployment Rate -  
(443)Unit Costs -

(297) Expected LR job growth = LR Expected Output Growth Rate \* Jobs  
Units: FTE/Year  
The amount of job growth expected by the community from the long-run economic growth rates.  
Used by: (293)Desired Change in Jobs -

(298) Fraction of Working Age for Cape Cod = 0.819  
Units: dmn1  
The fraction of people above 18 years old in Cape Cod, which is the age the US Census uses to determine work force participation. (US Census, 2006)  
Used by: (324)Working Age Fraction -

(299) Fraction of Working Age for Miami = 0.761  
Units: dmn1  
The fraction of people above 18 years old in Miami, which is the age the US Census uses to determine work force participation. (US Census, 2006)  
Used by: (324)Working Age Fraction -

(300) Fraction of Working Age for St Mary Parish = 0.727  
Units: dmn1  
The fraction of people above 18 years old in St Mary Parish, which is the age the US Census uses to determine work force participation. (US Census, 2006)

Used by: (324)Working Age Fraction -

(301) FTE per Person = 1  
Units: FTE/person  
The relationship between full-time equivalent jobs and persons.  
Used by: (315)Marginal Cost of Labor -

(302) Initial Employment = INITIAL( Labor Force \* ( 1 - Normal Unemployment Rate ) )  
Units: FTE  
The initial labor force of the community is the initial labor force less the normal number of unemployed.  
Used by: (309)Jobs -  
(225)Gross Output -  
(226)Initial Gross Output -

(303) Initial GDP per Capita = INITIAL( IF THEN ELSE ( Switch Segment Choice = 1, Initial per Capita Income for Miami ,  
IF THEN ELSE ( Switch Segment Choice = 2, Initial per Capita Income for Cape Cod ,  
IF THEN ELSE ( Switch Segment Choice = 3, Initial per Capita Income for St Mary Parish , 0 ) ) ) )  
Units: \$/(person\*Year)  
GDP per capita of the county. (US Census data, 2000)  
Used by: (315)Marginal Cost of Labor -

(304) Initial per Capita Income for Cape Cod = 25619  
Units: \$/(person\*Year)  
The initial income per capita for Cape Cod. (Census data)  
Used by: (303)Initial GDP per Capita -

(305) Initial per Capita Income for Miami = 18497  
Units: \$/(person\*Year)  
GDP per capita of the county from the US Census data (2000).  
Used by: (303)Initial GDP per Capita -

(306) Initial per Capita Income for St Mary Parish = 13399  
Units: \$/(person\*Year)  
The initial income per capita for St. Mary Parish. (Census data)  
Used by: (303)Initial GDP per Capita -

(307) Job Correction = ( Optimal Jobs - Jobs ) / Job Correction Time  
Units: FTE/Year  
The correction to the number of jobs in the community given the desired number and the current number of jobs.  
Used by: (293)Desired Change in Jobs -

(308) Job Correction Time = 1  
Units: Year  
The amount of time required to hire or fire employees.  
Used by: (307)Job Correction -

(309) Jobs = INTEG( Net Job Change , Initial Employment )  
Units: FTE  
The number of jobs in the community.  
Used by: (296)Employed Labor -  
(297)Expected LR job growth -  
(307)Job Correction -  
(171)Labor Force to Jobs Ratio -

(310) Labor Force = Labor Force Participation Fraction \* Population \* Working Age Fraction

Units: FTE  
 Labor force. Assumes invariable labor participation.  
 Used by: (296)Employed Labor -  
 (302)Initial Employment -  
 (171)Labor Force to Jobs Ratio -  
 (323)Unemployment Rate -

(311) Labor Force Participation for Cape Cod = 0.739  
 Units: FTE/person  
 The fraction of people 18 or older in Cape Cod that are in the work force. (US Census, Barnstable County.)  
 Used by: (314)Labor Force Participation Fraction -

(312) Labor Force Participation for Miami = 0.827  
 Units: FTE/person  
 The fraction of people above 18yo in Miami-Dade that are in the work force. (US Census)  
 Used by: (314)Labor Force Participation Fraction -

(313) Labor Force Participation for St Mary Parish = 0.733  
 Units: FTE/person  
 The fraction of people above 18yo in SMP that are in the work force. (US Census)  
 Used by: (314)Labor Force Participation Fraction -

(314) Labor Force Participation Fraction = INITIAL( IF THEN ELSE ( Switch Segment Choice = 1, Labor Force Participation for Miami ,  
 IF THEN ELSE ( Switch Segment Choice = 2, Labor Force Participation for Cape Cod ,  
 IF THEN ELSE ( Switch Segment Choice = 3, Labor Force Participation for St Mary Parish , 0 ) ) ) )  
 Units: FTE/person  
 The fraction of the community's population of working age and active in the wage labor force.  
 Used by: (310)Labor Force -

(315) Marginal Cost of Labor = Initial GDP per Capita / FTE per Person  
 Units: \$/(FTE\*Year)  
 The cost of a full-time equivalent worker per year.  
 Used by: (226)Initial Gross Output -  
 (320)Relative Return to Labor -  
 (443)Unit Costs -

(316) Net Job Change = Desired Change in Jobs  
 Units: FTE/Year  
 The rate of new job creation or job loss for the community.  
 Used by: (309)Jobs -

(317) Normal Unemployment Rate = 0.05  
 Units: dmn1  
 The normal rate of unemployment for the community. This is the long-term unemployment rate for the area.  
 Used by: (302)Initial Employment -  
 (171)Labor Force to Jobs Ratio -

(318) Optimal Jobs = Employed Labor \* Effect of Aggregate Demand on Jobs \* Effect of Relative Return on Jobs  
 Units: FTE  
 The desired number of jobs in the community given the effects of aggregate demand and the expected returns to labor.  
 Used by: (307)Job Correction -

(319) Perceived Relative Labor Return = SMOOTHI ( Relative Return to Labor , Factor Investment Return Perception Time , 1)

Units: dmn1

The perceived return to labor by industry, allowing for perception time to see the value.

Used by: (295)Effect of Relative Return on Jobs -

(320) Relative Return to Labor = Price of Output \* Marginal Productivity of Labor / Marginal Cost of Labor

Units: dmn1

The relative economic return of an additional unit of labor given its cost.

Used by: (319)Perceived Relative Labor Return -

(321) Sensitivity of Jobs to Aggregate Demand = 0.75

Units: dimensionless

Coefficient of effect for the aggregate economic demand on desired jobs.

Used by: (294)Effect of Aggregate Demand on Jobs -

(322) Sensitivity of Jobs to Relative Return = 0.75

Units: dimensionless

The sensitivity of jobs to the economic return of employed labor.

Used by: (295)Effect of Relative Return on Jobs -

(323) Unemployment Rate = 1 - Employed Labor / Labor Force

Units: dmn1

The unemployment rate in the community.

(324) Working Age Fraction = INITIAL( IF THEN ELSE ( Switch Segment Choice = 1, Fraction of Working Age for Miami ,

IF THEN ELSE ( Switch Segment Choice = 2, Fraction of Working Age for Cape Cod ,

IF THEN ELSE ( Switch Segment Choice = 3, Fraction of Working Age for St Mary Parish , 0 ) ) )

Units: dmn1

The fraction of people above 18 years old in the community, which is the age the US Census uses to determine work force participation.

Used by: (310)Labor Force -

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.Land

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(325) Annual Capital Lost to SLR = Average Capital per Area Land \* Land Loss Due to SLR

Units: Capital Unit/Year

The annual amount of capital lost to long-term SLR.

Used by: (377)Total Capital lost to SLR -

(326) Annual Flooded Inland Distance = IF THEN ELSE ( Annual Relative SLR > 0, ZIDZ ( ( Annual Relative SLR / meters in km ) , TAN ( Coastal Slope \* ( ARCCOS ( -1 ) / 180 ) ) ) , 0)

Units: km/Year

The new annual amount of coastal inundation from SLR,

IF no

protection. ARCCOS/180 converts from degrees to radians.

Used by: (328)Annual Inundated Area -

(327) Annual Housing Capital Lost to SLR = Land Loss Due to SLR \* Average Housing per Area Land

Units: m\*m/Year

The annual amount of housing area lost due to long-term SLR.

Used by: (378)Total Housing lost to SLR -

(328) Annual Inundated Area = Annual Flooded Inland Distance \* Segment Length



Units: km\*km/Year  
The newly flooded area by SLR,  
IF no protection.  
Used by: (366)Land Loss Due to SLR -

(329) Average Capital per Area Land = Total Capital Stock / Developable Land Area  
Units: Capital Units/(km\*km)  
The average number of capital units per square kilometer.  
Used by: (325)Annual Capital Lost to SLR -

(330) Average Housing per Area Land = Total Housing Stock / Developable Land Area  
Units: m\*m/(km\*km)  
The average amount of housing area per area of dry land.  
Used by: (327)Annual Housing Capital Lost to SLR -

(331) Coastal Slope = INITIAL( IF THEN ELSE ( Switch Segment Choice = 1, Coastal Slope for Miami ,  
IF THEN ELSE ( Switch Segment Choice = 2, Coastal Slope for Cape Cod ,  
IF THEN ELSE ( Switch Segment Choice = 3, Coastal Slope for St Mary Parish , 0 ) ) ) )  
Units: dmn1  
The slope of a segment in degrees. Measured in degrees.  
Used by: (326)Annual Flooded Inland Distance -  
(133)Coastal Managers Projected Inundated Area -  
(548)Estimated Inland Distance Flooded During Storm -  
(347)Flooded Inland Distance -  
(574)Inland Distance Flooded During Storm -

(332) Coastal Slope for Cape Cod = 0.181389  
Units: dmn1  
The coastal slope for Cape Cod. (DIVA data. Weighted average  
based on segment length. Measured in degrees.)  
Used by: (331)Coastal Slope -

(333) Coastal Slope for Miami = 0.0521631  
Units: dmn1  
The coastal slope for Miami. (DIVA data; Weighted average based  
on segment length. Measured in degrees.)  
Used by: (331)Coastal Slope -

(334) Coastal Slope for St Mary Parish = 0.062  
Units: dmn1  
The coastal slope for St. Mary Parish. (DIVA data. Measured in  
degrees.)  
Used by: (331)Coastal Slope -

(335) Coastal Uplift = INITIAL( IF THEN ELSE ( Switch Segment Choice = 1, Coastal Uplift for Miami ,  
IF THEN ELSE ( Switch Segment Choice = 2, Coastal Uplift for Cape Cod ,  
IF THEN ELSE ( Switch Segment Choice = 3, Coastal Uplift for St Mary Parish , 0 ) ) ) )  
Units: mm/Year  
The amount of geological uplift of a segment. Negative means  
subsidence.  
Used by: (500)Annual Uplift -

(336) Coastal Uplift for Cape Cod = -0.7  
Units: mm/Year  
The Local Change column of Table 1 from Nicholls and Leatherman  
(1995). Negative numbers mean subsidence. Location: Woods  
Hole, MA.  
Used by: (335)Coastal Uplift -

(337) Coastal Uplift for Miami = -0.6  
Units: mm/Year  
The Local Change column of Table 1 from Nicholls and Leatherman (1995). Negative numbers mean subsidence. Location: Miami Beach, FL.  
Used by: (335)Coastal Uplift -

(338) Coastal Uplift for St Mary Parish = -8.6  
Units: mm/Year  
The Local Change column of Table 1 from Nicholls and Leatherman (1995). Negative numbers mean subsidence. Location: Grand Isle, LA.  
Used by: (335)Coastal Uplift -

(339) Community Area = INITIAL( IF THEN ELSE ( Switch Segment Choice = 1, County Area for Miami , IF THEN ELSE ( Switch Segment Choice = 2, County Area for Cape Cod , IF THEN ELSE ( Switch Segment Choice = 3, County Area of St Mary Parish , 0 ) ) ) )  
Units: km\*km  
The total land area in the community.  
Used by: (128)Annual Unit Value of Dry Land -  
(543)Estimated Fraction of Community Flooded -  
(569)Fraction of Community Flooded -  
(361)Initial Developable Land Area -  
(694)Initial Undevelopable Area (Wetlands) -  
(366)Land Loss Due to SLR -

(340) County Area for Cape Cod = 1416.99  
Units: km\*km  
The summed area of Cape Cod counties. (Census data)  
Used by: (339)Community Area -

(341) County Area for Miami = 5040.27  
Units: km\*km  
The county area for Miami-Dade County. (Census data)  
Used by: (339)Community Area -

(342) County Area of St Mary Parish = 1587.12  
Units: km\*km  
The area of St. Mary Parish. (Census data)  
Used by: (339)Community Area -

(343) Developable Land Area = INTEG( - Land Loss Due to SLR , Initial Developable Land Area )  
Units: km\*km  
The amount of developable land in the community.  
Used by: (329)Average Capital per Area Land -  
(330)Average Housing per Area Land -  
(354)Fraction of Developable Land Occupied -  
(366)Land Loss Due to SLR -

(344) Developed Land = ( Land Occupied by Housing + Land Occupied by Capital ) / "m\*m in km\*km"  
Units: km\*km  
The total amount of developed land in the community, including both housing and capital.  
Used by: (354)Fraction of Developable Land Occupied -

(345) Effect of Land Availability on Investment = Effect of Land Availability on Investment tf ( Fraction of Developable Land Occupied )  
Units: dmnl  
The effect of land availability on investment.  
Used by: (089)Indicated Net Change in Capital -

(243) Indicated Net Change in Housing -

(346) Effect of Land Availability on Investment  $tf \left( \left[ (0,0)-(1,1) \right], (0,1), (0.1,1) \right)$   
 $(0.2,1), (0.3,1), (0.4,1), (0.5,0.97), (0.6,0.9), (0.7,0.8), (0.8,0.62), (0.9,0.35), (1,0)$   
Units: dmnl  
The relationship between the availability of developable land and the amount of construction that would take place.  
Used by: (345) Effect of Land Availability on Investment -

(347) Flooded Inland Distance = IF THEN ELSE ( Cumulative Relative SLR > 0, ZIDZ ( ( Cumulative Relative SLR / meters in km ) , TAN ( Coastal Slope \* ( ARCCOS ( -1 ) / 180 ) ) ) , 0)  
Units: km  
The horizontal distance inland of flooding. The perpendicular distance inland. ARCCOS/180 converts from degrees to radians.  
Used by: (379) Total Inundated Area -

(348) Floor Area Ratio for Cape Cod = 0.3  
Units: dmnl  
The ratio of inside floor area to the lot size for Cape Cod. Taken from city council hearings about zoning exceptions.  
Used by: (349) Floor Area Ratio for Housing -

(349) Floor Area Ratio for Housing = INITIAL( IF THEN ELSE ( Switch Segment Choice = 1, Floor Area Ratio for Miami ,  
IF THEN ELSE ( Switch Segment Choice = 2, Floor Area Ratio for Cape Cod ,  
IF THEN ELSE ( Switch Segment Choice = 3, Floor Area Ratio for St Mary Parish , 0 ) ) ) )  
Units: dmnl  
The ratio of the lot size to the living area size for the community.  
Used by: (365) Initial Land Occupied by Housing -  
(368) Land Occupied by Housing -

(350) Floor Area Ratio for Miami = 2  
Units: dmnl  
The ratio of inside floor area to the lot size for Miami. Mid-point of the FAR from the Comprehensive Development Master Plan for Miami.  
Used by: (349) Floor Area Ratio for Housing -

(351) Floor Area Ratio for St Mary Parish = 0.3  
Units: dmnl  
The ratio of inside floor area to the lot size for St Mary Parish. Matched to Cape Cod, no solid data.  
Used by: (349) Floor Area Ratio for Housing -

(352) Fraction Land Developable for Miami = 0.25  
Units: dmnl  
The fraction of the land area appropriate for development in Miami.  
Used by: (353) Fraction of Community Area Developable -

(353) Fraction of Community Area Developable = INITIAL( IF THEN ELSE ( Switch Segment Choice = 1, Fraction Land Developable for Miami ,  
IF THEN ELSE ( Switch Segment Choice = 2, Fraction of Land Developable for Cape Cod ,  
IF THEN ELSE ( Switch Segment Choice = 3, Fraction of Land Developable for St Mary Parish , 0 ) ) ) )  
Units: dmnl  
The fraction of the land area appropriate for development.  
Used by: (361) Initial Developable Land Area -  
(694) Initial Undevelopable Area (Wetlands) -

(354) Fraction of Developable Land Occupied = Developed Land / Developable Land Area  
Units: dmn1

The fraction of developable land that is already developed.  
Used by: (345)Effect of Land Availability on Investment -

(355) Fraction of Developed Area Occupied by Housing = ACTIVE INITIAL( Land Occupied by Housing / ( Land Occupied by Housing + Land Occupied by Capital ) , Initial Land Occupied by Housing / ( Initial Land Occupied by Housing + Initial Land Area Occupied by Capital ) )  
Units: dmn1

The fraction of the community's developed land that is occupied by housing.  
Used by: (424)Total Fraction of Infrastructure Mitigated -

(356) Fraction of Land Area Developed for Cape Cod = 0.5  
Units: dmn1

The initial fraction of all developable land that has been developed in the initial year for Cape Cod. (Dray, 2009)  
Used by: (363)Initial Fraction of Land Developed -

(357) Fraction of Land Area Developed for St Mary Parish = 0.2  
Units: dmn1

The initial fraction of all developable land that has been developed in the initial year for St. Mary's Parish. (Fink, 2009)  
Used by: (363)Initial Fraction of Land Developed -

(358) Fraction of Land Developable for Cape Cod = 0.67  
Units: dmn1

The fraction of the land area appropriate for development in Cape Cod. 1/3 of Barnstable County is open space preserves (parks, etc), so two-thirds is developable (Dray, 2009).  
Used by: (353)Fraction of Community Area Developable -

(359) Fraction of Land Developable for St Mary Parish = 0.8  
Units: dmn1

The fraction of the land area appropriate for development in St. Mary Parish. (Fink, 2009)  
Used by: (353)Fraction of Community Area Developable -

(360) Fraction of Land Developed for Miami = 0.6  
Units: dmn1

The initial fraction of all developable land that has been developed in the initial year for Miami.  
Used by: (363)Initial Fraction of Land Developed -

(361) Initial Developable Land Area = Fraction of Community Area Developable \* Community Area  
Units: km\*km

The initial amount of developable land in the community.  
Used by: (343)Developable Land Area -  
(362)Initial Developed Land Area -  
(366)Land Loss Due to SLR -

(362) Initial Developed Land Area = Initial Developable Land Area \* Initial Fraction of Land Developed  
Units: km\*km

The initial area of the community that has already been developed at the beginning of the simulation.  
Used by: (364)Initial Land Area Occupied by Capital -

(363) Initial Fraction of Land Developed = INITIAL( IF THEN ELSE ( Switch Segment Choice = 1, Fraction of

Land Developed for Miami ,  
 IF THEN ELSE ( Switch Segment Choice = 2, Fraction of Land Area Developed for Cape Cod ,  
 IF THEN ELSE ( Switch Segment Choice = 3, Fraction of Land Area Developed for St Mary Parish , 0 ) ) )  
 Units: dmm1  
 The initial fraction of all developable land that has been  
 developed in the initial year.  
 Used by: (362)Initial Developed Land Area -

(364) Initial Land Area Occupied by Capital = Initial Developed Land Area - Initial Land Occupied by Housing  
 Units: km\*km  
 The initial land area occupied by capital in the community.  
 Used by: (355)Fraction of Developed Area Occupied by Housing -  
 (369)Land Occupied per Capital Unit -

(365) Initial Land Occupied by Housing = ( Initial Housing Stock / "m\*m in km\*km" ) / Floor Area Ratio for  
 Housing  
 Units: km\*km  
 The initial area of land occupied by housing in the community.  
 Used by: (355)Fraction of Developed Area Occupied by Housing -  
 (364)Initial Land Area Occupied by Capital -

(366) Land Loss Due to SLR = Switch Land Loss from SLR \* IF THEN ELSE ( Cumulative Relative SLR > Height of  
 Completed Public Protection , MIN ( Annual Inundated Area \* ( Initial Developable Land Area / Community Area )  
 , Developable Land Area / Time for SLR Flooding ) , 0 )  
 Units: km\*km/Year  
 The area of developable land lost permanently to long-term SLR.  
 Used by: (343)Developable Land Area -  
 (325)Annual Capital Lost to SLR -  
 (327)Annual Housing Capital Lost to SLR -

(367) Land Occupied by Capital = Land Occupied per Capital Unit \* Total Capital Stock  
 Units: m\*m  
 The total amount of land occupied by capital.  
 Used by: (344)Developed Land -  
 (355)Fraction of Developed Area Occupied by Housing -

(368) Land Occupied by Housing = Total Housing Stock / Floor Area Ratio for Housing  
 Units: m\*m  
 The amount of land occupied by housing.  
 Used by: (344)Developed Land -  
 (355)Fraction of Developed Area Occupied by Housing -

(369) Land Occupied per Capital Unit = ( Initial Land Area Occupied by Capital / Initial Capital Stock ) \*  
 "m\*m in km\*km"  
 Units: m\*m/Capital Unit  
 The average amount of land occupied by a unit of capital.  
 Used by: (367)Land Occupied by Capital -

(370) Segment Length = INITIAL( IF THEN ELSE ( Switch Segment Choice = 1, Segment Length for Miami ,  
 IF THEN ELSE ( Switch Segment Choice = 2, Segment Length for Cape Cod ,  
 IF THEN ELSE ( Switch Segment Choice = 3, Segment Length for St Mary Parish , 0 ) ) ) )  
 Units: km  
 The length of a of coastline for the community.  
 Used by: (328)Annual Inundated Area -  
 (027)Beach Erosion -  
 (133)Coastal Managers Projected Inundated Area -  
 (553)Estimated Total Area Flooded -  
 (063)Length of beach nourishment -  
 (407)Length of Levee -  
 (583)Total Area Flooded -  
 (379)Total Inundated Area -

- (769)Wetland Length along Coast -
- (371) Segment Length for Cape Cod = 446.764  
 Units: km  
 The length of coastline for Cape Cod. (Sum of DIVA segment lengths)  
 Used by: (370)Segment Length -
- (372) Segment Length for Miami = 62.889  
 Units: km  
 From DIVA database. Currently doesn't include all the coastline of the Miami-Dade county. Mainly includes the developed portions of the coast, not the entire coastline of the county.  
 Used by: (370)Segment Length -
- (373) Segment Length for St Mary Parish = 80  
 Units: km  
 The length of coastline for St. Mary Parish. Estimated from Google Earth along the Gulf Coast. DIVA segment 1620 is too long.  
 Used by: (370)Segment Length -
- (374) Switch Land Availability = 1  
 Units: dmn1  
 Switch to turn on and off land availability considerations for construction of capital in the community. 0=off; 1=on.  
 Used by: (089)Indicated Net Change in Capital -  
 (243)Indicated Net Change in Housing -
- (375) Switch Land Loss from SLR = 1  
 Units: dmn1  
 Switch to turn on and off permanent land loss from long-term SLR. 0=off, 1=on.  
 Used by: (366)Land Loss Due to SLR -
- (376) Time for SLR Flooding = 1  
 Units: Year  
 The amount of time used to measure the loss of developable land.  
 Used by: (366)Land Loss Due to SLR -
- (377) Total Capital lost to SLR = INTEG( Annual Capital Lost to SLR , 0)  
 Units: Capital Unit  
 The total amount of capital permanently lost due to long-term SLR.
- (378) Total Housing lost to SLR = INTEG( Annual Housing Capital Lost to SLR , 0)  
 Units: m\*m  
 The total amount of housing permanently lost due to long-term SLR.
- (379) Total Inundated Area = Flooded Inland Distance \* Segment Length  
 Units: km\*km  
 The cumulative flooded area of the community by SLR,  
 IF no  
 protection.  
 \*\*\*\*\*  
 .Levee Construction  
 \*\*\*\*\*
- (380) Adjust for Levee in Planning = ( - Levee in Planning ) / Planning Adjustment Time  
 Units: meters/Year  
 The adjustment to the levee construction in planning given the desired level and the current level.  
 Used by: (390)Desired Levee Start Rate -

(381) Adjustment for Completed Levee = ( Desired Height of Levee - Completed Levee Protection ) / Completed Adjustment Time  
Units: meters/Year  
The adjustment to levee height based on the number of current height.  
Used by: (390)Desired Levee Start Rate -

(382) Adjustment for Levee Construction = ( - Levee under Construction ) / Construction Adjustment Time  
Units: meters/Year  
The adjustment to levee construction starts based on the amount of levee currently under construction.  
Used by: (390)Desired Levee Start Rate -

(383) Annual Levee Maintenance = Degradation of Levees \* Fraction of Levee Maintenance Performed  
Units: m/Year  
The standard amount of levee maintenance performed in the community.  
Used by: (403)Annual Levee Expenditures -  
(386)Completion of Effective Levee Protection -

(384) Completed Adjustment Time = 1  
Units: Year  
The time to adjust levee height given completed amount of levee.  
Used by: (381)Adjustment for Completed Levee -

(385) Completed Levee Protection = INTEG( Levee Completion , Initial Completed Levee )  
Units: meters  
The completed height of a levee.  
Used by: (381)Adjustment for Completed Levee -  
(573)Height of Completed Public Protection -  
(748)ifthen sdikehght -  
(071)Levee Exists -

(386) Completion of Effective Levee Protection = Levee Completion + Annual Levee Maintenance  
Units: m/Year  
The additional of effective levee protection.  
Used by: (391)Effective Levee Protection -  
(388)Degradation of Levees -

(387) Construction Adjustment Time = 1  
Units: Year  
The time to adjust levee construction starts given projects under construction.  
Used by: (382)Adjustment for Levee Construction -

(388) Degradation of Levees = DELAY3I ( Completion of Effective Levee Protection , Lifetime of Levees , Effective Levee Protection / Lifetime of Levees )  
Units: m/Year  
The degradation of levee effectiveness from the lack of maintenance.  
Used by: (391)Effective Levee Protection -  
(383)Annual Levee Maintenance -

(389) Desired Height of Levee = IF THEN ELSE ( Time <= 2010, Initial Completed Levee , IF THEN ELSE ( Public Protection Type and Height = 0, Initial Completed Levee , IF THEN ELSE ( Public Protection Type and Height = 1, Desired Public Protection Height , IF THEN ELSE ( Public Protection Type and Height = 2 , Initial Completed Levee , IF THEN ELSE ( Public Protection Type and Height = 3, Initial Completed Levee , 0 ) ) ) ) ) )

Units: meters  
 The desired height of the levee protection.  
 Used by: (381)Adjustment for Completed Levee -

(390) Desired Levee Start Rate = Adjust for Levee in Planning + Adjustment for Levee Construction +  
 Adjustment for Completed Levee  
 Units: meters/Year  
 The desired height of levee that should enter the construction  
 chain.  
 Used by: (399)Levee Planning Starts -

(391) Effective Levee Protection = INTEG( Completion of Effective Levee Protection - Degradation of Levees ,  
 Initial Completed Levee )  
 Units: meters  
 The effective level of levee protection.  
 Used by: (388)Degradation of Levees -  
 (069)Effective Height of Public Protection -

(392) Fraction of Levee Maintenance Performed = 0.9  
 Units: dmn1  
 The fraction of degraded levees are that repaired through a  
 regular maintenance program. Cannot perform more than 100% (1.0)  
 maintenance.  
 Used by: (383)Annual Levee Maintenance -

(393) Initial Completed Levee = 0  
 Units: meters  
 The initial height of levee protection already in place.  
 Used by: (385)Completed Levee Protection -  
 (391)Effective Levee Protection -  
 (389)Desired Height of Levee -

(394) Levee Completion = DELAY N ( Levee Construction Starts , Levee Construction Delay ,Levee under  
 Construction / Levee Construction Delay , 6)  
 Units: meters/Year  
 The completion rate of levee construction.  
 Used by: (385)Completed Levee Protection -  
 (400)Levee under Construction -  
 (386)Completion of Effective Levee Protection -

(395) Levee Construction Delay = 5  
 Units: years  
 The average time to finish construction of a levee.  
 Used by: (394)Levee Completion -

(396) Levee Construction Starts = DELAY N ( Levee Planning Starts , Levee Planning Delay ,Levee in Planning /  
 Levee Planning Delay , 6)  
 Units: meters/Year  
 The amount of levee construction started.  
 Used by: (394)Levee Completion -  
 (397)Levee in Planning -  
 (400)Levee under Construction -  
 (403)Annual Levee Expenditures -

(397) Levee in Planning = INTEG( Levee Planning Starts - Levee Construction Starts , 0)  
 Units: meters  
 These are suggested public protection projects that are being  
 planned by coastal managers.  
 Used by: (396)Levee Construction Starts -  
 (380)Adjust for Levee in Planning -



(398) Levee Planning Delay = 2

Units: years

The average length of time required to plan a public protection project.

Used by: (396)Levee Construction Starts -

(399) Levee Planning Starts = MAX ( 0, Desired Levee Start Rate )

Units: meters/Year

The amount of levee construction that enters the planning process.

Used by: (396)Levee Construction Starts -  
(397)Levee in Planning -

(400) Levee under Construction = INTEG( Levee Construction Starts - Levee Completion , 0)

Units: meters

The amount of levee already under construction.

Used by: (394)Levee Completion -  
(382)Adjustment for Levee Construction -

(401) Lifetime of Levees = 50

Units: years

The average lifetime of a levee protection project.

Used by: (388)Degradation of Levees -  
(144)Estimated Levee Maintenance Costs per Year -

(402) Planning Adjustment Time = 1

Units: Year

The time to adjust new levee construction starts given projects in planning.

Used by: (380)Adjust for Levee in Planning -

\*\*\*\*\*  
.Levee Costs  
\*\*\*\*\*

(403) Annual Levee Expenditures = ( Levee Construction Costs \* Levee Construction Starts \* Length of Levee )  
+ ( Annual Levee Maintenance \* "Levee Maintenance Costs per meter-km" \* Length of Levee )

Units: \$/Year

The annual expenditures on levees in the community.

Used by: (405)Cumulative Levee Expenditures -

(404) "Average Levee Maintenance Costs per Foot-Mile" = 4330

Units: \$(ft\*mile)

The cost of annual levee maintenance per foot height per mile length. Taken from Okita and Pritchard (2006) by averaging two levee projects there. Average was \$4330 per ft per mile.

Used by: (409)Levee Maintenance Costs per meter-km -

(405) Cumulative Levee Expenditures = INTEG( Annual Levee Expenditures , 0)

Units: \$

The cumulative money spent on levee construction and maintenance.

(406) Fraction Suitable for Levee Protection = 1

Units: dmnl

The fraction of the community's coast that would be protected by levees. Other options could be BN or do nothing. Do Nothing needs to be thought through for damages.

Used by: (407)Length of Levee -

(407) Length of Levee = Fraction Suitable for Levee Protection \* Segment Length

Units: km

The length of the levee in the community.

Used by: (403)Annual Levee Expenditures -

(143)Estimated Levee Construction Costs -

(144)Estimated Levee Maintenance Costs per Year -

(408) Levee Construction Costs =  $1.38 * 10^6$

Units: \$/(meter\*km)

Country-specific costs of raising a standard dike of one kilometer length by one meter (in million 1995\$ per meter per kilometer). DIVA data.

Used by: (403)Annual Levee Expenditures -

(143)Estimated Levee Construction Costs -

(409) "Levee Maintenance Costs per meter-km" = "Average Levee Maintenance Costs per Foot-Mile" / kilometers in mile \* feet in meters

Units: \$/(meter\*km)

The cost of annual levee maintenance per meter height per kilometer length.

Used by: (403)Annual Levee Expenditures -

(144)Estimated Levee Maintenance Costs per Year -

\*\*\*\*\*

.Mitigation

\*\*\*\*\*

(410) Fraction Capital Mitigated = ACTIVE INITIAL( Total Mitigated Capital / ( Total Mitigated Capital + Total Unmitigated Capital ) , Initial Mitigation Fraction )

Units: dmn1

The percentage of mitigated capital in the community.

Used by: (424)Total Fraction of Infrastructure Mitigated -

(411) Fraction Housing Mitigated = ACTIVE INITIAL( Total Mitigated Housing / ( Total Mitigated Housing + Total Unmitigated Housing ) , Initial Mitigation Fraction )

Units: dmn1

The percentage of total mitigated housing in the community.

Used by: (424)Total Fraction of Infrastructure Mitigated -

(412) Fraction of Older Housing Mitigated for Cape Cod = 0.5

Units: dmn1

The fraction of pre-1990 housing that complies with NFIP building standards in Cape Cod. (No source; Need better studies)

Used by: (417)Initial Mitigation Fraction for Cape Cod -

(413) Fraction of Older Housing Mitigated for Miami = 0.5

Units: dmn1

The fraction of pre-1990 housing that complies with NFIP building standards in Miami Dade. (No source; Need better studies)

Used by: (418)Initial Mitigation Fraction for Miami -

(414) Fraction of Older Housing Mitigated for St Mary Parish = 0.5

Units: dmn1

The fraction of pre-1990 housing that complies with NFIP building standards in St Mary Parish. (No source; Need better studies)

Used by: (419)Initial Mitigation Fraction for St Mary Parish -

(415) Fraction Retrofitting = ( Storm Occurrence \* New Construction NFIP Compliance \* Fraction of Community

Flooded ) / TIME STEP

Units: 1/Year

The fraction of existing capital that is retrofitted per year after a storm event.

Used by: (120)Retrofitting Capital -  
(285)Retrofitting Housing -

(416) Initial Mitigation Fraction = INITIAL( IF THEN ELSE ( Switch Segment Choice = 1, Initial Mitigation Fraction for Miami ,

IF THEN ELSE ( Switch Segment Choice = 2, Initial Mitigation Fraction for Cape Cod ,  
IF THEN ELSE ( Switch Segment Choice = 3, Initial Mitigation Fraction for St Mary Parish , 0 ) ) )

Units: dmn1

The initial fraction of property that is compliant with NFIP guidelines.

Used by: (114)Mitigated Undamaged Capital -  
(280)Mitigated Undamaged Housing -  
(126)Unmitigated Undamaged Capital -  
(292)Unmitigated Undamaged Housing -  
(410)Fraction Capital Mitigated -  
(411)Fraction Housing Mitigated -

(417) Initial Mitigation Fraction for Cape Cod = INITIAL( Fraction of Housing Older than 1990 for Cape Cod \* Fraction of Older Housing Mitigated for Cape Cod + ( 1 - Fraction of Housing Older than 1990 for Cape Cod ) \* New Construction NFIP Compliance for Cape Cod )

Units: dmn1

The initial fraction of property that is compliant with NFIP guidelines in Cape Cod.

Used by: (416)Initial Mitigation Fraction -

(418) Initial Mitigation Fraction for Miami = INITIAL( Fraction of Housing Older than 1990 for Miami \* Fraction of Older Housing Mitigated for Miami + ( 1 - Fraction of Housing Older than 1990 for Miami ) \* New Construction NFIP Compliance for Miami )

Units: dmn1

The initial fraction of property that is compliant with NFIP guidelines in Miami.

Used by: (416)Initial Mitigation Fraction -

(419) Initial Mitigation Fraction for St Mary Parish = INITIAL( Fraction of Housing Older than 1990 for St Mary Parish \* Fraction of Older Housing Mitigated for St Mary Parish + ( 1 - Fraction of Housing Older than 1990 for St Mary Parish ) \* New Construction NFIP Compliance for St Mary Parish )

Units: dmn1

The initial fraction of property that is compliant with NFIP guidelines in St Mary Parish.

Used by: (416)Initial Mitigation Fraction -

(420) New Construction NFIP Compliance = INITIAL( IF THEN ELSE ( Switch Segment Choice = 1, New Construction NFIP Compliance for Miami ,

IF THEN ELSE ( Switch Segment Choice = 2, New Construction NFIP Compliance for Cape Cod ,  
IF THEN ELSE ( Switch Segment Choice = 3, New Construction NFIP Compliance for St Mary Parish , 0 ) ) )

)

Units: dmn1

The fraction of new construction that is fully compliant with NFIP standards.

Used by: (415)Fraction Retrofitting -  
(115)New Mitigated Capital -  
(281)New Mitigated Housing -  
(116)New Unmitigated Capital -  
(282)New Unmitigated Housing -

(421) New Construction NFIP Compliance for Cape Cod = 0.587

Units: dmn1

The fraction of new construction that is fully compliant with

NFIP standards in Cape Cod. The closest region was "Mid-Atlantic" in Appendix B of Mathis 2006.  
Used by: (417)Initial Mitigation Fraction for Cape Cod -  
(420)New Construction NFIP Compliance -

(422) New Construction NFIP Compliance for Miami = 0.608

Units: dmnl  
The fraction of new construction that is fully compliant with NFIP standards in Miami. The value is "Florida West Coast" in Appendix B of Mathis 2006.  
Used by: (418)Initial Mitigation Fraction for Miami -  
(420)New Construction NFIP Compliance -

(423) New Construction NFIP Compliance for St Mary Parish = 0.661

Units: dmnl  
The fraction of new construction that is fully compliant with NFIP standards in St. Mary Parish. The region was "Louisiana" in Appendix B of Mathis 2006.  
Used by: (419)Initial Mitigation Fraction for St Mary Parish -  
(420)New Construction NFIP Compliance -

(424) Total Fraction of Infrastructure Mitigated = Fraction of Developed Area Occupied by Housing \* Fraction Housing Mitigated + ( 1 - Fraction of Developed Area Occupied by Housing ) \* Fraction Capital Mitigated

Units: dmnl  
The fraction of developed land has mitigated property. It is the land area weighted average.  
Used by: (530)CM's Estimated Fractional Damage by Storms if Protected -  
(531)CM's Estimated Fractional Damage by Storms if Unprotected -  
(544)Estimated Fraction of Infrastructure Damage by Category -

(425) Total Mitigated Capital = Mitigated Damaged Capital + Mitigated Undamaged Capital

Units: Capital Unit  
The total amount of mitigated capital in the community.  
Used by: (410)Fraction Capital Mitigated -

(426) Total Mitigated Housing = Mitigated Damaged Housing + Mitigated Undamaged Housing

Units: meter\*meter  
The total amount of mitigated housing area in the community.  
Used by: (411)Fraction Housing Mitigated -

(427) Total Unmitigated Capital = Unmitigated Damaged Capital + Unmitigated Undamaged Capital

Units: Capital Unit  
The total amount of unmitigated capital in the community.  
Used by: (410)Fraction Capital Mitigated -

(428) Total Unmitigated Housing = Unmitigated Damaged Housing + Unmitigated Undamaged Housing

Units: meter\*meter  
The total amount of unmitigated housing area in the community.  
Used by: (411)Fraction Housing Mitigated -

\*\*\*\*\*  
.Model Checks  
\*\*\*\*\*

(429) CHECK Sum Storm Prob = SUM ( Probability of Storm by Category[StormCategory! ] )

Units: dmnl  
Model Check: Make sure the probability of storm categories sums to 1.

(430) mean storms per year = ZIDZ ( storm count , Time - INITIAL TIME )

Units: 1/Year

Model Check: That is the simulated mean number of storms for a given run.

(431) storm = Storm Event Generator / TIME STEP  
 Units: 1/Year  
 A model check to see if the frequency of storms converges to a given annual frequency.  
 Used by: (433)storm count -

(432) storm cat count[Cat1] = IF THEN ELSE ( Storm Event with Strength = 1, 1 / TIME STEP , 0) storm cat count[Cat2] = IF THEN ELSE ( Storm Event with Strength = 2, 1 / TIME STEP , 0) storm cat count[Cat3] = IF THEN ELSE ( Storm Event with Strength = 3, 1 / TIME STEP , 0) storm cat count[Cat4] = IF THEN ELSE ( Storm Event with Strength = 4, 1 / TIME STEP , 0) storm cat count[Cat5] = IF THEN ELSE ( Storm Event with Strength = 5, 1 / TIME STEP , 0)  
 Units: 1/Year  
 Rate for building the storm intensity cdf.  
 Used by: (434)Storm Count by Category -

(433) storm count = INTEG( storm , 0)  
 Units: dmn1  
 A model check: count the number of storms to check the frequency of storms.  
 Used by: (430)mean storms per year -

(434) Storm Count by Category[StormCategory] = INTEG( storm cat count[StormCategory] , 0)  
 Units: dmn1  
 Count to verify the storm distribution.  
 \*\*\*\*\*  
 .Output Price  
 \*\*\*\*\*

(435) Change in Output Price = ( Optimal Price of Output - Price of Output ) / Time to Adjust Output Price  
 Units: \$/(Year\*unit)  
 The change of the actual unit price of output, in order to update to current economic conditions.  
 Used by: (439)Price of Output -

(436) Effect of Aggregate Demand on Output Price = Relative Aggregate Demand ^ Sensitivity of Output Price to Aggregate Demand  
 Units: dmn1  
 The effect of the demand and supply balance on the unit price of economic output.  
 Used by: (438)Optimal Price of Output -

(437) Effect of Costs on Output Price = 1 + Sensitivity of Output Price to Unit Costs \* ( ( Unit Costs / Price of Output ) - 1)  
 Units: dmn1  
 The effect of factor costs on the unit price of economic output.  
 Used by: (438)Optimal Price of Output -

(438) Optimal Price of Output = Price of Output \* Effect of Costs on Output Price \* Effect of Aggregate Demand on Output Price  
 Units: \$/unit  
 The price of a unit of gross economic output given the current market conditions.  
 Used by: (435)Change in Output Price -

(439) Price of Output = INTEG( Change in Output Price , 1)  
 Units: \$/unit  
 The price of the unit of gross economic output.  
 Used by: (129)Annual Value of Avoided Storm Damage -  
 (130)Annual Value of Dryland -

(435)Change in Output Price -  
(004)Desired Government Services -  
(437)Effect of Costs on Output Price -  
(110)Initial Capital Stock -  
(226)Initial Gross Output -  
(014)Insurance Claims Paid -  
(092)Marginal Return of Capital -  
(438)Optimal Price of Output -  
(320)Relative Return to Labor -

(440) Sensitivity of Output Price to Aggregate Demand = 0.25  
Units: dmn1  
The sensitivity of price to imbalances in the supply and demand.  
Used by: (436)Effect of Aggregate Demand on Output Price -

(441) Sensitivity of Output Price to Unit Costs = 1  
Units: dmn1  
The sensitivity of the price of economic output to the input  
factor costs.  
Used by: (437)Effect of Costs on Output Price -

(442) Time to Adjust Output Price = 1  
Units: Year  
The time it takes for the price of output to change from  
changing economic conditions.  
Used by: (435)Change in Output Price -

(443) Unit Costs = ( Marginal Cost of Labor \* Employed Labor + Marginal Cost of Capital \* Total Undamaged  
Capital ) / Gross Output  
Units: \$/unit  
The average cost of producing a unit of economic output.  
Used by: (437)Effect of Costs on Output Price -

\*\*\*\*\*  
.Population  
\*\*\*\*\*

(444) Additional Evacuees = Evacuation  
Units: person/Year  
People that have been evacuated because of a storm.  
Used by: (475)Total Number of Evacuees -

(445) Births = Fractional Birth Rate \* Community Population  
Units: persons/Year  
The additions to the segment population from births.  
Used by: (446)Community Population -

(446) Community Population = INTEG( Births + Immigration + Evacuee Return - Deaths - Evacuation - Emigration  
, Initial Population )  
Units: People  
The number of people that are currently living in the segment.  
Used by: (445)Births -  
(447)Deaths -  
(448)Emigration -  
(449)Evacuation -  
(460)Immigration -  
(468)Population -  
(476)Total Population including Evacuees -

(447) Deaths = Fractional Death Rate \* Community Population

Units: persons/Year  
The reduction in segment population from deaths.  
Used by: (446)Community Population -

(448) Emigration = Fractional Rate of Emigration \* Community Population  
Units: persons/Year  
The persons leaving the segment to live somewhere else.  
Used by: (446)Community Population -

(449) Evacuation = Storm Occurrence \* MAX ( 0, Community Population - Residents Remaining ) / Evacuation Time  
Units: person/Year  
The number of people who are evacuated because of a hurricane event.  
Used by: (446)Community Population -  
(451)Evacuee Population -  
(444)Additional Evacuees -

(450) Evacuation Time = TIME STEP  
Units: years  
The time it takes to evacuate and relocate people immediately after a storm event.  
Used by: (449)Evacuation -

(451) Evacuee Population = INTEG( Evacuation - Permanent Resettling - Evacuee Return , Initial Number of Evacuees )  
Units: People  
The number of displaced person from the segment.  
Used by: (452)Evacuee Return -  
(467)Permanent Resettling -  
(476)Total Population including Evacuees -

(452) Evacuee Return = ( Community Relative Attractiveness \* Evacuee Population ) / Returning Time  
Units: persons/Year  
The rate of returning displaced person to the segment.  
Used by: (446)Community Population -  
(451)Evacuee Population -

(453) Exogenous population = INITIAL( Initial Population )  
Units: persons  
A constant exogenous population.  
Used by: (468)Population -

(454) Fraction Willing to Evacuate = Fraction Willing to Evacuate tf ( Storm Event with Strength )  
Units: dmn1  
The fraction of the community that is willing to evacuate for the current category of storm.  
Used by: (471)Residents Remaining -

(455) Fraction Willing to Evacuate tf ( [(0,0)-(5,1)],(0,0),(1,0),(5,0.98) )  
Units: dmn1  
Table function of the fraction of the community that will evacuate for a given category of storm.  
Used by: (454)Fraction Willing to Evacuate -

(456) Fractional Birth Rate = 0.014  
Units: 1/Year  
The fractional birth rate of the segment. US national average crude birth rate for 2007, from CDC.  
Used by: (445)Births -

(457) Fractional Death Rate = 0.0081  
Units: 1/Year  
The fractional death rate of the segment. US national average  
crude death rate for 2006, from CDC.  
Used by: (447)Deaths -

(458) Fractional Rate of Emigration = ZIDZ ( 1, Community Relative Attractiveness ) \* Reference Fractional  
Rate of Emigration  
Units: 1/Year  
The fractional rate of outward migration for the segment.  
Used by: (448)Emigration -  
(466)Net Fractional Migration Rate -

(459) Fractional Rate of Immigration = Reference Fractional Rate of Immigration \* Community Relative  
Attractiveness  
Units: 1/Year  
The fractional rate of in migration per year.  
Used by: (460)Immigration -  
(466)Net Fractional Migration Rate -

(460) Immigration = Fractional Rate of Immigration \* Community Population  
Units: persons/Year  
Person moving into the segment from outside regions.  
Used by: (446)Community Population -

(461) Initial Number of Evacuees = 0  
Units: persons  
The initial number of displaced persons.  
Used by: (451)Evacuee Population -

(462) Initial Population = INITIAL( IF THEN ELSE ( Switch Segment Choice = 1, Initial Population of Miami ,  
IF THEN ELSE ( Switch Segment Choice = 2, Initial Population of Cape Cod ,  
IF THEN ELSE ( Switch Segment Choice = 3, Initial Population of St Mary Parish , 0 ) ) ) )  
Units: People  
The initial population of the community. (US Census data, 2000)  
Used by: (446)Community Population -  
(484)Perceived Present Condition of Population -  
(486)Reference Condition of Population -  
(453)Exogenous population -  
(168)Initial Occupancy Fraction -

(463) Initial Population of Cape Cod = 246737  
Units: People  
The initial population for the counties of Cape Cod and the  
Islands. (2000 Census data)  
Used by: (462)Initial Population -

(464) Initial Population of Miami = 2.40221e+006  
Units: People  
The initial population of the community. (US Census data, 2000)  
Used by: (462)Initial Population -

(465) Initial Population of St Mary Parish = 53500  
Units: People  
Population of St. Mary Parish. (2000 Census data)  
Used by: (462)Initial Population -



(466) Net Fractional Migration Rate = Fractional Rate of Immigration - Fractional Rate of Emigration  
Units: 1/Year  
The net population migration, taking into account the actual immigration and emigration rates.

(467) Permanent Resettling = ZIDZ ( 1, Community Relative Attractiveness ) \* Evacuee Population / Time for Evacuees to Resettle  
Units: persons/Year  
The rate of permanent resettling of displaced persons.  
Used by: (451)Evacuee Population -

(468) Population = IF THEN ELSE ( Switch Population models = 0, Exogenous population ,  
IF THEN ELSE ( Switch Population models = 1, Community Population , 0 ) )  
Units: persons  
The population in the segment.  
Used by: (010)Expected Income per Capita -  
(232)Average Living Area per Person -  
(478)Change in PPC of Population -  
(002)Desired Consumption -  
(006)Desired Savings -  
(242)Indicated Housing Stock -  
(310)Labor Force -  
(174)Occupancy Fraction -  
(018)Output per Capita -

(469) Reference Fractional Rate of Emigration = 0.02  
Units: 1/Year  
The average fraction of the population that emigrates during a year.  
Used by: (458)Fractional Rate of Emigration -

(470) Reference Fractional Rate of Immigration = 0.02  
Units: 1/Year  
The average fraction of the population that comes from immigration.  
Used by: (459)Fractional Rate of Immigration -

(471) Residents Remaining = Total Population including Evacuees \* ( 1 - Fraction Willing to Evacuate )  
Units: person  
The number of residents that are not going to leave for the given category of storm.  
Used by: (449)Evacuation -

(472) Returning Time = 0.5  
Units: years  
The time it takes to return to a damaged area after a storm event.  
Used by: (452)Evacuee Return -

(473) Switch Population models = 1  
Units: dmn1  
A switch to change the population model used. 0 = Exogenous, 1 = Migration model.  
Used by: (468)Population -

(474) Time for Evacuees to Resettle = 2  
Units: years  
The time it takes for people to permanently decide that they aren't returning to the segment after a storm event.  
Used by: (467)Permanent Resettling -

(475) Total Number of Evacuees = INTEG( Additional Evacuees , 0)  
Units: person  
The total number of people evacuated because of storms throughout the entire simulation.

(476) Total Population including Evacuees = Community Population + Evacuee Population  
Units: person  
The total number of people living in the city before a storm.  
Used by: (471)Residents Remaining -

\*\*\*\*\*  
.Population Trend  
\*\*\*\*\*

(477) Change in perceived Population Trend = ( Indicated trend in Population - Perceived Trend of Population Growth ) / Time to perceive Population Trend  
Units: 1/(Year\*Year)  
The change in the perceived population trend.  
Used by: (485)Perceived Trend of Population Growth -

(478) Change in PPC of Population = ( Population - Perceived Present Condition of Population ) / Time to Perceive Present Population  
Units: persons/Year  
The change of the perceived present condition of population size in the community.  
Used by: (484)Perceived Present Condition of Population -

(479) Change in Reference Condition of Population = ( Perceived Present Condition of Population - Reference Condition of Population ) / Time horizon for reference condition of Population  
Units: persons/Year  
The change in the reference condition of the population trend.  
Used by: (486)Reference Condition of Population -

(480) "Exogenous Expected Long-run Population Growth Rate" = 0.04  
Units: 1/Year  
An exogenous constant long-run population trend estimate.  
Used by: (483)LR Expected Population Growth Rate -

(481) Historical Population Growth Rate = 0.01  
Units: 1/Year  
The initialization for the population growth trend. Currently an estimate for US national average (US Census). Future work: initialize for community growth rate.  
Used by: (484)Perceived Present Condition of Population -  
(485)Perceived Trend of Population Growth -  
(486)Reference Condition of Population -

(482) Indicated trend in Population = ( ( Perceived Present Condition of Population - Reference Condition of Population ) / Reference Condition of Population ) / Time horizon for reference condition of Population  
Units: 1/years  
Indicated trend of gross economic output of the community.  
Used by: (477)Change in perceived Population Trend -

(483) LR Expected Population Growth Rate = IF THEN ELSE ( "Switch Long-run Population Rate Trend" = 0, "Exogenous Expected Long-run Population Growth Rate" , IF THEN ELSE ( "Switch Long-run Population Rate Trend" = 1, Perceived Trend of Population Growth , 0 ) )  
Units: 1/Year  
Perceived long run trend in population growth.  
Used by: (235)Desired Housing Growth -

(484) Perceived Present Condition of Population = INTEG( Change in PPC of Population , Initial Population / (

1 + Time to Perceive Present Population \* Historical Population Growth Rate ) )

Units: persons

Perceived present condition of the economic output of the community.

Used by: (478)Change in PPC of Population -  
(479)Change in Reference Condition of Population -  
(482)Indicated trend in Population -

(485) Perceived Trend of Population Growth = INTEG( Change in perceived Population Trend , Historical Population Growth Rate )

Units: 1/years

The perceived fractional growth rate of gross economic output.

Used by: (477)Change in perceived Population Trend -  
(483)LR Expected Population Growth Rate -

(486) Reference Condition of Population = INTEG( Change in Reference Condition of Population , ( Initial Population / ( 1 + Time to Perceive Present Population \* Historical Population Growth Rate ) ) / ( 1 + Time horizon for reference condition of Population \* Historical Population Growth Rate ) )

Units: persons

Reference condition of gross economic output of the community.

Used by: (479)Change in Reference Condition of Population -  
(482)Indicated trend in Population -

(487) "Switch Long-run Population Rate Trend" = 1

Units: dmdl

0=Exogenous, 1=BusDyn

Used by: (483)LR Expected Population Growth Rate -

(488) Time horizon for reference condition of Population = 3

Units: years

The time horizon to analyze the population of the community. This says that we evaluate population trends based on three years worth of data.

Used by: (486)Reference Condition of Population -  
(479)Change in Reference Condition of Population -  
(482)Indicated trend in Population -

(489) Time to perceive Population Trend = 1

Units: years

The time for the community to change their expectations about the growth trends of community population.

Used by: (477)Change in perceived Population Trend -

(490) Time to Perceive Present Population = 3

Units: Year

Time required to report updates of the gross output of the community.

Used by: (484)Perceived Present Condition of Population -  
(486)Reference Condition of Population -  
(478)Change in PPC of Population -

\*\*\*\*\*

.Rent Price

\*\*\*\*\*

(491) Average Rent = INTEG( Change in Rent , Initial Average Rent )

Units: \$(m\*m\*Year)

The price of the unit of gross economic output.

Used by: (129)Annual Value of Avoided Storm Damage -  
(130)Annual Value of Dryland -  
(492)Change in Rent -

(494)Effect of Housing Costs on Rent -  
(495)Indicated Rent -  
(250)Marginal Cost of Housing Construction -  
(253)Relative Return to Housing -

(492) Change in Rent = ( Indicated Rent - Average Rent ) / Time to Adjust Rent  
Units:  $\$/(\text{m}^*\text{m}*\text{Year}*\text{Year})$   
The change of the actual unit price of output, in order to  
update to current economic conditions.  
Used by: (491)Average Rent -

(493) Effect of Housing Adequacy on Rent = Adequacy of Housing Stock ^ Sensitivity of Rent Price to Housing  
Adequacy  
Units: dmn1  
The effect of housing adequacy on average housing rent. If  
there is inadequate housing, then rent will rise.  
Used by: (495)Indicated Rent -

(494) Effect of Housing Costs on Rent = 1 + Sensitivity of Rent to Housing Construction Cost \* ( ( Marginal  
Cost of Housing / Average Rent ) - 1)  
Units: dmn1  
The effect of housing construction costs on average rent in the  
community. If costs are higher than rent, then there is upward  
pressure on rent, and vice versa.  
Used by: (495)Indicated Rent -

(495) Indicated Rent = Average Rent \* Effect of Housing Adequacy on Rent \* Effect of Housing Costs on Rent  
Units:  $\$/(\text{m}^*\text{m}*\text{Year})$   
The indicated rent price. Renting price taking into account the  
effects.  
Used by: (492)Change in Rent -

(496) Sensitivity of Rent Price to Housing Adequacy = -0.5  
Units: dmn1  
The sensitivity of the price of economic output to the input  
factor costs.  
Used by: (493)Effect of Housing Adequacy on Rent -

(497) Sensitivity of Rent to Housing Construction Cost = 0.25  
Units: dmn1  
Factor to adjust how sensitive rent is the to the marginal cost  
of housing.  
Used by: (494)Effect of Housing Costs on Rent -

(498) Time to Adjust Rent = 1  
Units: Year  
The time it takes for housing rental costs to change housing  
conditions.  
Used by: (492)Change in Rent -

\*\*\*\*\*  
.RSLR  
\*\*\*\*\*

(499) Annual Relative SLR = Switch RSLR \* ( Annual Global SLR - Annual Uplift ) + ( 1 - Switch RSLR ) \*  
Exogenous RSLR  
Units: meters/Year  
The annual change in the relative sea-level for a given segment.  
Used by: (501)Cumulative Relative SLR -  
(326)Annual Flooded Inland Distance -

(149)Coastal Manager's Cum Linear RSLR Estimate -  
(733)deltaSLR -  
(504)Sea Level Rise before Construction -

(500) Annual Uplift = Coastal Uplift / mm in m  
Units: meter/Year  
The amount of uplift or subsidence (negative uplift) per year for community's coast.  
Used by: (499)Annual Relative SLR -  
(150)Coastal Manager's Cum Quadratic Global SLR Estimate -

(501) Cumulative Relative SLR = INTEG( Annual Relative SLR , 0)  
Units: meters  
The cumulative level of relative sea-level rise in the segments, including subsidence.  
Used by: (554)Estimated Total Water Heights -  
(347)Flooded Inland Distance -  
(366)Land Loss Due to SLR -  
(503)Sea Level Relative to Public Protection -

(502) Exogenous RSLR = 0  
Units: meters/Year  
An exogenous rate of relative sea-level rise.  
Used by: (499)Annual Relative SLR -

(503) Sea Level Relative to Public Protection = Cumulative Relative SLR - Sea Level when Public Protection Built  
Units: meter  
The sea level rise since the construction of a public protection structure.  
Used by: (078)Total Water Height -

(504) Sea Level Rise before Construction = ( 1 - Public Protection Exists ) \* Annual Relative SLR  
Units: meters/Year  
The change in sea level before a public protection structure is built.  
Used by: (505)Sea Level when Public Protection Built -

(505) Sea Level when Public Protection Built = INTEG( Sea Level Rise before Construction , 0)  
Units: meters  
The sea level height at the start of a public protection project.  
Used by: (152)Coastal Managers Desired Public Protection Height -  
(133)Coastal Managers Projected Inundated Area -  
(503)Sea Level Relative to Public Protection -

(506) Switch RSLR = 1  
Units: dmn1  
Switch to control the annual rate of relative SLR. 0 = Exog, 1 = Endog  
Used by: (499)Annual Relative SLR -

\*\*\*\*\*  
.SLR  
\*\*\*\*\*

(507) a0 = Global SLR Height in 2000  
Units: meters  
The coefficient representing the constant in the quadratic fit.  
Used by: (150)Coastal Manager's Cum Quadratic Global SLR Estimate -  
(516)Cum Quadratic Global SLR -

(508)  $a_1$  = Global SLR Rate in 2000  
Units: meters/Year  
The coefficient for the quadratic SLR fit.  
Used by: (509) $a_2$  -  
(512)Annual Quadratic Global SLR -  
(150)Coastal Manager's Cum Quadratic Global SLR Estimate -  
(516)Cum Quadratic Global SLR -

(509)  $a_2 = ( \text{Global SLR Height in 2100} - ( \text{FINAL TIME} - \text{INITIAL TIME} ) * a_1 ) / ( ( \text{FINAL TIME} - \text{INITIAL TIME} ) ^ 2 )$   
Units: meters/(Year\*Year)  
The coefficient of the squared term for the quadratic fit.  
Used by: (512)Annual Quadratic Global SLR -  
(150)Coastal Manager's Cum Quadratic Global SLR Estimate -  
(516)Cum Quadratic Global SLR -

(510) Annual Global SLR = IF THEN ELSE ( QUANTUM ( Switch SLR Scenario / 2, 1) = Switch SLR Scenario / 2, Annual Quadratic Global SLR , Annual Linear Global SLR )  
Units: meters/Year  
The annual rate of global SLR.  
Used by: (499)Annual Relative SLR -

(511) Annual Linear Global SLR = ( Global SLR Height in 2100 - Global SLR Height in 2000 ) / ( FINAL TIME - INITIAL TIME )  
Units: meters/Year  
The annual rate of global SLR for a linear fit.  
Used by: (510)Annual Global SLR -

(512) Annual Quadratic Global SLR =  $2 * a_2 * ( \text{Time} - \text{INITIAL TIME} ) + a_1$   
Units: meters/Year  
The annual rate of global SLR if quadratic fit.  
Used by: (510)Annual Global SLR -

(513) "Ave Annual Global SLR (1963-2003)" = 0.0018  
Units: meters/Year  
The average annual rate of SLR from 1963-2003. (AR4 Chapter 10)  
Used by: (521)Global SLR Rate in 2000 -

(514) "Ave Annual Global SLR (1993-2003)" = 0.0031  
Units: meters/Year  
The average annual rate of SLR from 1993-2003. (AR4 Chapter 10)  
Used by: (521)Global SLR Rate in 2000 -

(515) Cum Linear Global SLR = ( Global SLR Height in 2100 - Global SLR Height in 2000 ) / ( FINAL TIME - INITIAL TIME ) \* ( Time - INITIAL TIME )  
Units: meters  
The cumulative amount of global SLR if linear fit.  
Used by: (517)Cumulative Global SLR -

(516) Cum Quadratic Global SLR =  $a_2 * ( \text{Time} - \text{INITIAL TIME} ) ^ 2 + a_1 * ( \text{Time} - \text{INITIAL TIME} ) + a_0$   
Units: meters  
The cumulative global SLR if quadratic fit.  
Used by: (517)Cumulative Global SLR -

(517) Cumulative Global SLR = IF THEN ELSE ( QUANTUM ( Switch SLR Scenario / 2, 1) = Switch SLR Scenario / 2, Cum Quadratic Global SLR , Cum Linear Global SLR )  
Units: meters

The cumulative amount of global SLR.  
(518) Exogenous Global SLR 2100 = 1.5  
Units: meters  
The final amount of SLR in 2100, provided exogenously.  
Used by: (520)Global SLR Height in 2100 -

(519) Global SLR Height in 2000 = 0  
Units: meters  
The amount of SLR in 2000.  
Used by: (507)a0 -  
(511)Annual Linear Global SLR -  
(515)Cum Linear Global SLR -

(520) Global SLR Height in 2100 = IF THEN ELSE ( Switch SLR Scenario = 1, IPCC B1 Low SLR ,  
IF THEN ELSE ( Switch SLR Scenario = 2, IPCC B1 Low SLR ,  
IF THEN ELSE ( Switch SLR Scenario = 3, IPCC A1B Mid SLR ,  
IF THEN ELSE ( Switch SLR Scenario = 4, IPCC A1B Mid SLR ,  
IF THEN ELSE ( Switch SLR Scenario = 5, IPCC A1FI High SLR ,  
IF THEN ELSE ( Switch SLR Scenario = 6, IPCC A1FI High SLR ,  
IF THEN ELSE ( Switch SLR Scenario = 7, Exogenous Global SLR 2100 ,  
IF THEN ELSE ( Switch SLR Scenario = 8, Exogenous Global SLR 2100 , 0) ) ) ) ) ) ) ) ) )  
Units: meters  
The cumulative global SLR in 2100.  
Used by: (509)a2 -  
(511)Annual Linear Global SLR -  
(515)Cum Linear Global SLR -

(521) Global SLR Rate in 2000 = Switch Initial Global SLR rate \* "Ave Annual Global SLR (1963-2003)" + ( 1 -  
Switch Initial Global SLR rate ) \* "Ave Annual Global SLR (1993-2003)"  
Units: meter/Year  
The average rate of global SLR in 2000.  
Used by: (508)a1 -

(522) IPCC A1B Mid SLR = 0.495  
Units: meters  
This is mid point of A1B scenario, including the mid-points of  
both the SLR range (0.345) and the ice sheet addition range  
(0.15).  
Used by: (520)Global SLR Height in 2100 -

(523) IPCC A1FI High SLR = 0.59 + 0.2  
Units: meters  
The high range of the A1FI scenario. It is the sum of the A1FI  
95% confidence interval value (0.59) plus the high value of ice  
sheet additions (0.2).  
Used by: (520)Global SLR Height in 2100 -

(524) IPCC B1 Low SLR = 0.18  
Units: meters  
The lower range (5% confidence value) of the B1 scenario,  
excluding any ice sheet additions.  
Used by: (520)Global SLR Height in 2100 -

(525) Switch Initial Global SLR rate = 1  
Units: dmn1  
0= 1993 through 2003, 1= 1963 through 2003.  
Used by: (521)Global SLR Rate in 2000 -

(526) Switch SLR Scenario = 8  
Units: dmn1

Switch for the SLR scenario. Low=B1, Mid=A1B, High=A1FI.  
 1=Low, Linear; 2=Low, Quad; 3=Mid, Linear; 4=Mid, Quad; 5=High,  
 Linear; 6=High, Quad; 7=Exog, Linear; 8=Exog, Quad.  
 Used by: (510)Annual Global SLR -  
 (151)Coastal Manager's Cumulative RSLR Estimate -  
 (517)Cumulative Global SLR -  
 (520)Global SLR Height in 2100 -

\*\*\*\*\*  
 .Storm Damage Estimation  
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(527) CM's Estimated Avoided Fractional Annual Storm Damage = CM's Estimated Fractional Damage by Storms if Unprotected - CM's Estimated Fractional Damage by Storms if Protected  
 Units: 1/Year  
 The coastal managers' estimated avoided annual fractional storm damage to infrastructure if public protection were built to the design storm specification.  
 Used by: (129)Annual Value of Avoided Storm Damage -

(528) CM's Estimated Fraction of Mitigated Infrastructure Damaged by Water[ StormCategory] = Estimated Max Fraction of Mitigated Infrastructure Damaged by Water[ StormCategory] \* Estimated Fraction of Community Flooded[StormCategory ]  
 Units: dmn1  
 The coastal managers's estimated damage to mitigated infrastructure if there were no public protection.  
 Used by: (535)CM's Estimated Fractional Damage to Mitigated if Unprotected by Category -  
 (540)CM's Estimated Fractional Water Damage to Mitigated if Protected by Category -

(529) CM's Estimated Fraction of Unmitigated Infrastructure Damaged by Water[ StormCategory] = Estimated Max Fraction of Unmitigated Infrastructure Damaged by Water[ StormCategory] \* Estimated Fraction of Community Flooded[StormCategory ]  
 Units: dmn1  
 The coastal managers's estimated damage to unmitigated infrastructure if there were no public protection.  
 Used by: (539)CM's Estimated Fractional Damage to Unmitigated if Unprotected by Category -  
 (541)CM's Estimated Fractional Water Damage to Unmitigated if Protected by Category -

(530) CM's Estimated Fractional Damage by Storms if Protected = Total Fraction of Infrastructure Mitigated \* CM's Estimated Fractional Damage to Mitigated if Protected + ( 1 - Total Fraction of Infrastructure Mitigated ) \* CM's Estimated Fractional Damage to Unmitigated if Protected  
 Units: 1/Year  
 The coastal managers' estimated fractional infrastructure annual infrastructure damage if protection were built.  
 Used by: (527)CM's Estimated Avoided Fractional Annual Storm Damage -

(531) CM's Estimated Fractional Damage by Storms if Unprotected = Total Fraction of Infrastructure Mitigated \* CM's Estimated Fractional Damage to Mitigated if Unprotected + ( 1 - Total Fraction of Infrastructure Mitigated ) \* CM's Estimated Fractional Damage to Unmitigated if Unprotected  
 Units: 1/Year  
 The coastal manager's estimated fractional damage if there were no public protection.  
 Used by: (527)CM's Estimated Avoided Fractional Annual Storm Damage -

(532) CM's Estimated Fractional Damage to Mitigated if Protected = SUM ( CM's Estimated Fractional Damage to Mitigated if Protected by Category[ StormCategory!] )  
 Units: 1/Year  
 The estimated fractional amount of storm damage to mitigated property if protected, as estimated by coastal managers.  
 Used by: (530)CM's Estimated Fractional Damage by Storms if Protected -



(533) CM's Estimated Fractional Damage to Mitigated if Protected by Category[ StormCategory] = Annual Storm Frequency \* Probability of Storm by Category[ StormCategory] \* ( Estimated Fraction of Infrastructure Wind Damaged by Category[ StormCategory] + CM's Estimated Fractional Water Damage to Mitigated if Protected by Category[ StormCategory] )

Units: 1/Year

The coastal manager's estimated fractional damage to mitigated property if protected, given storm frequency and storm intensity, by category.

Used by: (532)CM's Estimated Fractional Damage to Mitigated if Protected -

(534) CM's Estimated Fractional Damage to Mitigated if Unprotected = SUM ( CM's Estimated Fractional Damage to Mitigated if Unprotected by Category[ StormCategory!] )

Units: 1/Year

The fractional damage to mitigated structures if there is no public protection, as estimated by the coastal managers.

Used by: (531)CM's Estimated Fractional Damage by Storms if Unprotected -

(535) CM's Estimated Fractional Damage to Mitigated if Unprotected by Category[ StormCategory] = Annual Storm Frequency \* Probability of Storm by Category[ StormCategory] \* ( CM's Estimated Fraction of Mitigated Infrastructure Damaged by Water[ StormCategory] + Estimated Fraction of Infrastructure Wind Damaged by Category[ StormCategory] )

Units: 1/Year

The coastal manager's estimated fractional damage to mitigated property if unprotected, given storm frequency and storm intensity, by category.

Used by: (534)CM's Estimated Fractional Damage to Mitigated if Unprotected -

(536) CM's Estimated Fractional Damage to Unmitigated if Protected = SUM ( CM's Estimated Fractional Damage to Unmitigated if Protected by Category[ StormCategory!] )

Units: 1/Year

The estimated fractional amount of storm damaged to unmitigated property if protected, as estimated by coastal managers.

Used by: (530)CM's Estimated Fractional Damage by Storms if Protected -

(537) CM's Estimated Fractional Damage to Unmitigated if Protected by Category[ StormCategory] = Annual Storm Frequency \* Probability of Storm by Category[ StormCategory] \* ( CM's Estimated Fractional Water Damage to Unmitigated if Protected by Category[ StormCategory] + Estimated Fraction of Infrastructure Wind Damaged by Category[ StormCategory] )

Units: 1/Year

The coastal manager's estimated fractional damage to unmitigated property if protected, given storm frequency and storm intensity, by category.

Used by: (536)CM's Estimated Fractional Damage to Unmitigated if Protected -

(538) CM's Estimated Fractional Damage to Unmitigated if Unprotected = SUM ( CM's Estimated Fractional Damage to Unmitigated if Unprotected by Category[ StormCategory!] )

Units: 1/Year

The fractional damage to unmitigated structures if there is no public protection, as estimated by the coastal managers.

Used by: (531)CM's Estimated Fractional Damage by Storms if Unprotected -

(539) CM's Estimated Fractional Damage to Unmitigated if Unprotected by Category[ StormCategory] = Annual Storm Frequency \* Probability of Storm by Category[ StormCategory] \* ( CM's Estimated Fraction of Unmitigated Infrastructure Damaged by Water[ StormCategory] + Estimated Fraction of Infrastructure Wind Damaged by Category[ StormCategory] )

Units: 1/Year

The coastal manager's estimated fractional damage to unmitigated property if unprotected, given storm frequency and storm intensity, by category.

Used by: (538)CM's Estimated Fractional Damage to Unmitigated if Unprotected -

(540) CM's Estimated Fractional Water Damage to Mitigated if Protected by Category[ Cat1] = IF THEN ELSE ( Design Storm for Protection >= 1, 0, CM's Estimated Fraction of Mitigated Infrastructure Damaged by Water[ Cat1] ) CM's Estimated Fractional Water Damage to Mitigated if Protected by Category[ Cat2] = IF THEN ELSE ( Design Storm for Protection >= 2, 0, CM's Estimated Fraction of Mitigated Infrastructure Damaged by Water[ Cat2] ) CM's Estimated Fractional Water Damage to Mitigated if Protected by Category[ Cat3] = IF THEN ELSE ( Design Storm for Protection >= 3, 0, CM's Estimated Fraction of Mitigated Infrastructure Damaged by Water[ Cat3] ) CM's Estimated Fractional Water Damage to Mitigated if Protected by Category[ Cat4] = IF THEN ELSE ( Design Storm for Protection >= 4, 0, CM's Estimated Fraction of Mitigated Infrastructure Damaged by Water[ Cat4] ) CM's Estimated Fractional Water Damage to Mitigated if Protected by Category[ Cat5] = IF THEN ELSE ( Design Storm for Protection = 5, 0, CM's Estimated Fraction of Mitigated Infrastructure Damaged by Water[ Cat5] )

Units: dmnl

The estimated fractional amount of damage to mitigated property by storm category, IF protected.

Used by: (533)CM's Estimated Fractional Damage to Mitigated if Protected by Category -

(541) CM's Estimated Fractional Water Damage to Unmitigated if Protected by Category[ Cat1] = IF THEN ELSE ( Design Storm for Protection >= 1, 0, CM's Estimated Fraction of Unmitigated Infrastructure Damaged by Water[ Cat1] ) CM's Estimated Fractional Water Damage to Unmitigated if Protected by Category[ Cat2] = IF THEN ELSE ( Design Storm for Protection >= 2, 0, CM's Estimated Fraction of Unmitigated Infrastructure Damaged by Water[ Cat2] ) CM's Estimated Fractional Water Damage to Unmitigated if Protected by Category[ Cat3] = IF THEN ELSE ( Design Storm for Protection >= 3, 0, CM's Estimated Fraction of Unmitigated Infrastructure Damaged by Water[ Cat3] ) CM's Estimated Fractional Water Damage to Unmitigated if Protected by Category[ Cat4] = IF THEN ELSE ( Design Storm for Protection >= 4, 0, CM's Estimated Fraction of Unmitigated Infrastructure Damaged by Water[ Cat4] ) CM's Estimated Fractional Water Damage to Unmitigated if Protected by Category[ Cat5] = IF THEN ELSE ( Design Storm for Protection = 5, 0, CM's Estimated Fraction of Unmitigated Infrastructure Damaged by Water[ Cat5] )

Units: dmnl

The estimated fractional amount of damage to unmitigated property by storm category, IF protected.

Used by: (537)CM's Estimated Fractional Damage to Unmitigated if Protected by Category -

(542) Estimated Average Water Depth in Community[StormCategory] = 1 / 2 \* Estimated Total Water Heights[ StormCategory]

Units: meters

The estimated average water depth in the community. Because of the linear assumptions of coastal slope, it is half the total water height.

Used by: (550)Estimated Max Fraction of Unmitigated Infrastructure Damaged by Water - (555)Estimated Water Depth in Mitigated Structures -

(543) Estimated Fraction of Community Flooded[StormCategory] = Estimated Total Area Flooded[ StormCategory] / Community Area

Units: dmnl

The estimated fraction of land that would be effected by water damage.

Used by: (528)CM's Estimated Fraction of Mitigated Infrastructure Damaged by Water - (529)CM's Estimated Fraction of Unmitigated Infrastructure Damaged by Water - (546)Estimated Fraction of Mitigated Infrastructure Damaged by Water - (547)Estimated Fraction of Unmitigated Infrastructure Damaged by Water -

(544) Estimated Fraction of Infrastructure Damage by Category[StormCategory] = Estimated Fraction of Infrastructure Wind Damaged by Category[StormCategory] + ( Estimated Fraction of Mitigated Infrastructure Damaged by Water[ StormCategory] \* Total Fraction of Infrastructure Mitigated ) + ( ( 1 - Total Fraction of Infrastructure Mitigated ) \* Estimated Fraction of Unmitigated Infrastructure Damaged by Water[ StormCategory] )

Units: dmnl

The estimated total storm to infrastructure given the coastal defenses and the amount of mitigated property.

Used by: (556)Perceived Fractional Damage by Category - (561)Reference Fractional Damage by Category -

(545) Estimated Fraction of Infrastructure Wind Damaged by Category[StormCategory] = ( Possible Storm Intensities[StormCategory] ^ Sensitivity of Damage to Wind ) / Maximum Wind Damage

Units: dmn1

The estimated fraction of infrastructure damaged by wind.

Used by: (533)CM's Estimated Fractional Damage to Mitigated if Protected by Category -  
(535)CM's Estimated Fractional Damage to Mitigated if Unprotected by Category -  
(537)CM's Estimated Fractional Damage to Unmitigated if Protected by Category -  
(539)CM's Estimated Fractional Damage to Unmitigated if Unprotected by Category -  
(544)Estimated Fraction of Infrastructure Damage by Category -

(546) Estimated Fraction of Mitigated Infrastructure Damaged by Water[StormCategory] = Estimated Overtopping Breach Damage Multiplier[StormCategory] \* Estimated Max Fraction of Mitigated Infrastructure Damaged by Water[StormCategory] \* Estimated Fraction of Community Flooded[StormCategory]

Units: dmn1

The estimated fraction of a mitigated structure that is damaged by water.

Used by: (544)Estimated Fraction of Infrastructure Damage by Category -

(547) Estimated Fraction of Unmitigated Infrastructure Damaged by Water[StormCategory] = Estimated Max Fraction of Unmitigated Infrastructure Damaged by Water[ StormCategory] \* Estimated Overtopping Breach Damage Multiplier[StormCategory] \* Estimated Fraction of Community Flooded[StormCategory]

Units: dmn1

The estimated fraction of unmitigated infrastructure damaged by water during a storm.

Used by: (544)Estimated Fraction of Infrastructure Damage by Category -

(548) Estimated Inland Distance Flooded During Storm[StormCategory] = ZIDZ ( ( Estimated Total Water Heights[StormCategory] / meters in km ) , TAN ( Coastal Slope \* ( ARCCOS ( -1 ) / 180 ) ) )

Units: km

The estimated distance inland that would be flooded during a storm. ARCCOS/180 converts from degrees to radians.

Used by: (553)Estimated Total Area Flooded -

(549) Estimated Max Fraction of Mitigated Infrastructure Damaged by Water[StormCategory] = Depth Damage Relationship tf ( Estimated Water Depth in Mitigated Structures[ StormCategory] / Unit of Depth )

Units: dmn1

The estimated maximum fraction of a mitigated structure that is damaged by water.

Used by: (528)CM's Estimated Fraction of Mitigated Infrastructure Damaged by Water -  
(546)Estimated Fraction of Mitigated Infrastructure Damaged by Water -

(550) Estimated Max Fraction of Unmitigated Infrastructure Damaged by Water[ StormCategory] = Depth Damage Relationship tf ( Estimated Average Water Depth in Community[ StormCategory] / Unit of Depth )

Units: dmn1

The estimated maximum fraction of unmitigated infrastructure damaged by water during a storm.

Used by: (529)CM's Estimated Fraction of Unmitigated Infrastructure Damaged by Water -  
(547)Estimated Fraction of Unmitigated Infrastructure Damaged by Water -

(551) Estimated Mitigated Floor Height = IF THEN ELSE ( Design Storm for Mitigated Floor Height = 0, 0, IF THEN ELSE ( Design Storm for Mitigated Floor Height = 1, "Median Saffir-Simpson Surges by Category"[Cat1] , IF THEN ELSE ( Design Storm for Mitigated Floor Height = 2, "Median Saffir-Simpson Surges by Category"[Cat2] , IF THEN ELSE ( Design Storm for Mitigated Floor Height = 3, "Median Saffir-Simpson Surges by Category"[Cat3] , IF THEN ELSE ( Design Storm for Mitigated Floor Height = 4, "Median Saffir-Simpson Surges by Category"[Cat4] , IF THEN ELSE ( Design Storm for Mitigated Floor Height = 5, "Median Saffir-Simpson Surges by Category"[Cat5] , 0 ) ) ) ) ) )

Units: meters

The height of the floor of a mitigated structure. By default, they are the height of the surge of a design storm, without taking into account SLR. In theory, this is because FEMA doesn't use SLR, and the design storm should be the 100-yr event.  
Used by: (555)Estimated Water Depth in Mitigated Structures -

(552) Estimated Overtopping Breach Damage Multiplier[Cat1] = IF THEN ELSE ( Perceived Level of Storm Protection < 1, 1, 0) Estimated Overtopping Breach Damage Multiplier[Cat2] = IF THEN ELSE ( Perceived Level of Storm Protection < 2, 1, 0) Estimated Overtopping Breach Damage Multiplier[Cat3] = IF THEN ELSE ( Perceived Level of Storm Protection < 3, 1, 0) Estimated Overtopping Breach Damage Multiplier[Cat4] = IF THEN ELSE ( Perceived Level of Storm Protection < 4, 1, 0) Estimated Overtopping Breach Damage Multiplier[Cat5] = IF THEN ELSE ( Perceived Level of Storm Protection < 5, 1, 0)

Units: dmn1

The multiplier for water damage protection. For damage estimations, it is assumed that people perceived 100% protection up to the design storm specification. Storms stronger than the design storm are perceived to cause full damage.

Used by: (546)Estimated Fraction of Mitigated Infrastructure Damaged by Water -  
(547)Estimated Fraction of Unmitigated Infrastructure Damaged by Water -

(553) Estimated Total Area Flooded[StormCategory] = Segment Length \* Estimated Inland Distance Flooded During Storm[ StormCategory]

Units: km\*km

The estimated total area flooded by SLR and storms.

Used by: (543)Estimated Fraction of Community Flooded -

(554) Estimated Total Water Heights[StormCategory] = "Median Saffir-Simpson Surges by Category"[ StormCategory] + Cumulative Relative SLR

Units: meters

Estimations of the sea level height including both water and storm surges

Used by: (542)Estimated Average Water Depth in Community -  
(548)Estimated Inland Distance Flooded During Storm -

(555) Estimated Water Depth in Mitigated Structures[StormCategory] = MAX ( 0, Estimated Average Water Depth in Community[StormCategory] - Estimated Mitigated Floor Height )

Units: meters

The estimated water depth in a mitigated structure.

Used by: (549)Estimated Max Fraction of Mitigated Infrastructure Damaged by Water -

(556) Perceived Fractional Damage by Category[StormCategory] = Perceived Frequency of Storms \* Estimated Fraction of Infrastructure Damage by Category[StormCategory] \* Probability of Storm by Category[StormCategory]

Units: 1/Year

The perceived amount of fractional damage caused by storm category.

Used by: (557)Perceived Fractional Damage from Storms -

(557) Perceived Fractional Damage from Storms = SUM ( Perceived Fractional Damage by Category[ StormCategory!] )

Units: 1/Year

The perceived amount of fractional damage caused by all storms.

Used by: (082)Cost of Capital -  
(233)Cost of Housing -  
(563)Relative Expected Damage from Storms -

(558) Perceived Level of Storm Protection = Design Storm for Protection \* Public Protection Exists

Units: dmn1

The category of storm protection that people perceive they are protected from.

Used by: (552)Estimated Overtopping Breach Damage Multiplier -

(559) Possible Storm Intensities[StormCategory] = 1, 2, 3, 4, 5  
Units: dmn1  
The possible intensities of storms.  
Used by: (545)Estimated Fraction of Infrastructure Wind Damaged by Category -

(560) Probability of Storm by Category[Cat1] = Distribution of Storm Intensities[ Cat1] - 0 Probability of Storm by Category[Cat2] = Distribution of Storm Intensities[ Cat2] - Distribution of Storm Intensities[Cat1]  
Probability of Storm by Category[Cat3] = Distribution of Storm Intensities[ Cat3] - Distribution of Storm Intensities[Cat2]  
Probability of Storm by Category[Cat4] = Distribution of Storm Intensities[ Cat4] - Distribution of Storm Intensities[Cat3]  
Probability of Storm by Category[Cat5] = Distribution of Storm Intensities[ Cat5] - Distribution of Storm Intensities[Cat4]  
Units: dmn1  
The probability of a storm being a particular category.  
Used by: (429)CHECK Sum Storm Prob -  
(533)CM's Estimated Fractional Damage to Mitigated if Protected by Category -  
(535)CM's Estimated Fractional Damage to Mitigated if Unprotected by Category -  
(537)CM's Estimated Fractional Damage to Unmitigated if Protected by Category -  
(539)CM's Estimated Fractional Damage to Unmitigated if Unprotected by Category -  
(556)Perceived Fractional Damage by Category -  
(561)Reference Fractional Damage by Category -

(561) Reference Fractional Damage by Category[StormCategory] = Reference Perceived Storm Frequency \* Estimated Fraction of Infrastructure Damage by Category[StormCategory] \* Probability of Storm by Category[StormCategory]  
Units: 1/Year  
The amount of fractional damage caused by storm category given the perceived historical frequency.  
Used by: (562)Reference Fractional Damage from Storms -

(562) Reference Fractional Damage from Storms = SUM ( Reference Fractional Damage by Category[ StormCategory!] )  
Units: 1/Year  
The actual amount of fractional damage caused by all storms.  
Used by: (563)Relative Expected Damage from Storms -

(563) Relative Expected Damage from Storms = Perceived Fractional Damage from Storms / Reference Fractional Damage from Storms  
Units: dmn1  
The relative expected damages due to the perception of storm frequency.  
Used by: (175)Storm Risk Attractiveness Effect -

\*\*\*\*\*  
.Storm Damages  
\*\*\*\*\*

(564) Average Water Depth in Community = IF THEN ELSE ( ( Storm Occurrence + Breach Occurs ) > 0, 1 / 2 \* Total Water Height , 0)  
Units: meters  
The average water depth in the community during a flood. Because of the linear assumptions of coastal slope, it is half the total water height.  
Used by: (577)Max Fraction of Unmitigated Infrastructure Damaged by Water -  
(591)Water Depth in Mitigated Structures -

(565) Damage to Capital from Storms = Damage to Mitigated Capital + Damage to Unmitigated Capital  
Units: Capital Unit/Year  
The total damage to capital during a storm.  
Used by: (584)Total Damaged Capital from Storms -  
(215)Value of Capital Storm Damage -

(566) Damage to Housing from Storms = Damage to Mitigated Housing + Damage to Unmitigated Housing  
Units: meter\*meter/Year

The total damage to housing during a storm.

Used by: (585)Total Damaged Housing from Storms -  
(216)Value of Housing Storm Damage -

(567) Depth Damage Relationship  $tf$  ( [(0,0)-(5,1)],(0,0),(1,0.5),(2,0.75),(3,0.875) ,(4,1),(5,1) )  
Units: dmn1

The fraction of capital damaged given a flooded depth above the first floor elevation. This is the depth-damage relationship used in the DIVA model. Input should be in meters. Reasoning: that most of the damage occurs in the first few feet of flooding (electrical, appliances, etc.). (Green, 1994)

Used by: (549)Estimated Max Fraction of Mitigated Infrastructure Damaged by Water -  
(550)Estimated Max Fraction of Unmitigated Infrastructure Damaged by Water -  
(576)Max Fraction of Mitigated Infrastructure Damaged by Water -  
(577)Max Fraction of Unmitigated Infrastructure Damaged by Water -

(568) Design Storm for Mitigated Floor Height = 1

Units: dmn1

The design storm used to set the standard for base floor elevation.

Used by: (551)Estimated Mitigated Floor Height -  
(580)Mitigated Floor Height -

(569) Fraction of Community Flooded = Total Area Flooded / Community Area

Units: dmn1

The fraction of land that would be effected by water damage.

Used by: (571)Fraction of Mitigated Infrastructure Damaged by Water -  
(572)Fraction of Unmitigated Infrastructure Damaged by Water -  
(415)Fraction Retrofitting -

(570) Fraction of Infrastructure Damaged by Wind = ( Storm Event with Strength  $\wedge$  Sensitivity of Damage to Wind ) / Maximum Wind Damage

Units: dmn1

The fraction of infrastructure damaged by wind.

Used by: (202)Damage Covered by Wind Insurance -  
(587)Total Fractional Damage to Mitigated Infrastructure by Stochastic Storm -  
(589)Total Fractional Damage to Unmitigated Infrastructure by Stochastic Storm -

(571) Fraction of Mitigated Infrastructure Damaged by Water = Overtopping Breach Damage Multiplier \* Max Fraction of Mitigated Infrastructure Damaged by Water \* Fraction of Community Flooded

Units: dmn1

The fraction of a mitigated structure that is damaged by water. The maximum damage by the area that is flooded, given the performance of public protection.

Used by: (204)Damaged Covered by Flood Insurance -  
(587)Total Fractional Damage to Mitigated Infrastructure by Stochastic Storm -

(572) Fraction of Unmitigated Infrastructure Damaged by Water = Max Fraction of Unmitigated Infrastructure Damaged by Water \* Overtopping Breach Damage Multiplier \* Fraction of Community Flooded

Units: dmn1

The fraction of unmitigated infrastructure damaged by water during a storm. The maximum damage by the area that is flooded, given the performance of public protection.

Used by: (204)Damaged Covered by Flood Insurance -  
(589)Total Fractional Damage to Unmitigated Infrastructure by Stochastic Storm -

(573) Height of Completed Public Protection = MAX ( Completed Beach Nourishment Height , Completed Levee Protection )

Units: meters  
The height of the completed public protection in the community.  
Assumes the community only is protecting by either nourishment  
or levees.  
Used by: (366)Land Loss Due to SLR -  
(581)Overtopping Breach Damage Multiplier -

(574) Inland Distance Flooded During Storm = IF THEN ELSE ( ( Storm Occurrence + Breach Occurs ) > 0, ZIDZ ( ( Total Water Height / meters in km ) , TAN ( Coastal Slope \* ( ARCCOS ( -1 ) / 180 ) ) ) , 0)  
Units: km  
The distance inland that would be flooded during a storm.  
ARCCOS/180 converts from degrees to radians.  
Used by: (583)Total Area Flooded -

(575) Max Damage from Wind = 0.5  
Units: dmn1  
The maximum fraction of infrastructure wind damage by storm of  
the maximum intensity.  
Used by: (579)Maximum Wind Damage -

(576) Max Fraction of Mitigated Infrastructure Damaged by Water = Depth Damage Relationship tf ( Water Depth  
in Mitigated Structures / Unit of Depth )  
Units: dmn1  
The maximum fraction of a mitigated structure that is damaged by  
water.  
Used by: (571)Fraction of Mitigated Infrastructure Damaged by Water -

(577) Max Fraction of Unmitigated Infrastructure Damaged by Water = Depth Damage Relationship tf ( Average  
Water Depth in Community / Unit of Depth )  
Units: dmn1  
The maximum fraction of unmitigated infrastructure damaged by  
water during a storm.  
Used by: (572)Fraction of Unmitigated Infrastructure Damaged by Water -

(578) Max Storm Wind Intensity = 5  
Units: dmn1  
The maximum wind strength of a storm event. In this case, it a  
Category 5.  
Used by: (579)Maximum Wind Damage -

(579) Maximum Wind Damage = ( Max Storm Wind Intensity ^ Sensitivity of Damage to Wind ) / Max Damage from  
Wind  
Units: dmn1  
The coefficient for the wind damage function. Assumes a  
quadratic form.  
Used by: (545)Estimated Fraction of Infrastructure Wind Damaged by Category -  
(570)Fraction of Infrastructure Damaged by Wind -

(580) Mitigated Floor Height = IF THEN ELSE ( Design Storm for Mitigated Floor Height = 0, 0,  
IF THEN ELSE ( Design Storm for Mitigated Floor Height = 1, "Median Saffir-Simpson Surges by  
Category" [Cat1] ,  
IF THEN ELSE ( Design Storm for Mitigated Floor Height = 2, "Median Saffir-Simpson Surges by  
Category" [Cat2] ,  
IF THEN ELSE ( Design Storm for Mitigated Floor Height = 3, "Median Saffir-Simpson Surges by Category" [Cat3] ,  
IF THEN ELSE ( Design Storm for Mitigated Floor Height = 4, "Median Saffir-Simpson Surges by Category" [Cat4] ,  
IF THEN ELSE ( Design Storm for Mitigated Floor Height = 5, "Median Saffir-Simpson Surges by Category" [Cat5] , 0 ) ) ) ) ) ) )  
Units: meters  
The height of the floor of a mitigated structure. By default,

they are the height of the surge of a design storm, without taking into account SLR. In theory, this is because FEMA doesn't use SLR, and the design storm should be the 100-yr event.  
Used by: (591)Water Depth in Mitigated Structures -

(581) Overtopping Breach Damage Multiplier = IF THEN ELSE ( Public Protection Exists = 0, 1, IF THEN ELSE ( Breach Occurs = 1, 1, IF THEN ELSE ( Total Water Height > Height of Completed Public Protection , 0.5, 0 ) ) )  
Units: dmn1

The multiplier for water damage protection. This formulation assumes that breaching is same as no protection (1=full damage), overtopping is half damage (0.5). Otherwise protection works and no damage.

Used by: (571)Fraction of Mitigated Infrastructure Damaged by Water -  
(572)Fraction of Unmitigated Infrastructure Damaged by Water -

(582) Sensitivity of Damage to Wind = 3  
Units: dmn1

The sensitivity of infrastructure damage to wind during a storm. Assumed to be a cubic relationship.

Used by: (545)Estimated Fraction of Infrastructure Wind Damaged by Category -  
(570)Fraction of Infrastructure Damaged by Wind -  
(579)Maximum Wind Damage -

(583) Total Area Flooded = Segment Length \* Inland Distance Flooded During Storm  
Units: km\*km

The total land area flood during a storm event, given SLR and surge, IF not protected.

Used by: (569)Fraction of Community Flooded -

(584) Total Damaged Capital from Storms = INTEG( Damage to Capital from Storms , 0)  
Units: Capital Unit

The cumulative damage to capital by storms.

(585) Total Damaged Housing from Storms = INTEG( Damage to Housing from Storms , 0)  
Units: meter\*meter

The cumulative damage to housing by storms.

(586) Total Fractional Damage to Mitigated Infrastructure = Total Fractional Damage to Mitigated Infrastructure by Stochastic Storm / TIME STEP  
Units: 1/Year

The total fractional damage to mitigated infrastructure caused by a storm event. Assumes that water and wind damage are independent until the entire structure is destroyed.

Used by: (105)Damage to Mitigated Capital -  
(263)Damage to Mitigated Housing -

(587) Total Fractional Damage to Mitigated Infrastructure by Stochastic Storm = MIN ( 1, Fraction of Infrastructure Damaged by Wind + Fraction of Mitigated Infrastructure Damaged by Water )  
Units: dmn1

The total fractional damage to mitigated infrastructure caused by a storm event. Assumes that water and wind damage are independent until the entire structure is destroyed.

Used by: (586)Total Fractional Damage to Mitigated Infrastructure -

(588) Total Fractional Damage to Unmitigated Infrastructure = Total Fractional Damage to Unmitigated Infrastructure by Stochastic Storm / TIME STEP  
Units: 1/Year

The total fractional damage to unmitigated infrastructure caused by a storm event. Assumes that water and wind damage are independent until the entire structure is destroyed.

Used by: (106)Damage to Unmitigated Capital -  
(264)Damage to Unmitigated Housing -



(589) Total Fractional Damage to Unmitigated Infrastructure by Stochastic Storm = MIN ( 1, Fraction of Infrastructure Damaged by Wind + Fraction of Unmitigated Infrastructure Damaged by Water )

Units: dmn1

The total fractional damage to unmitigated infrastructure caused by a storm event. Assumes that water and wind damage are independent until the entire structure is destroyed.

Used by: (588)Total Fractional Damage to Unmitigated Infrastructure -

(590) Unit of Depth = 1

Units: meter

The unit that flood depth is measured.

Used by: (549)Estimated Max Fraction of Mitigated Infrastructure Damaged by Water -

(550)Estimated Max Fraction of Unmitigated Infrastructure Damaged by Water -

(576)Max Fraction of Mitigated Infrastructure Damaged by Water -

(577)Max Fraction of Unmitigated Infrastructure Damaged by Water -

(591) Water Depth in Mitigated Structures = MAX ( 0, Average Water Depth in Community - Mitigated Floor Height )

Units: meters

The water depth in a mitigated structure.

Used by: (576)Max Fraction of Mitigated Infrastructure Damaged by Water -

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.Storm Freq Perception

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(592) Assessment Window Shift = Years of Storm Observation / Time Horizon for Storm Frequency Assessment

Units: years/Year

The shifting of the window of assessment.

Used by: (601)Years of Storm Observation -

(593) Exogenous Perc Storm Freq = 0.0925

Units: 1/Year

The exogenous Perceived Frequency of Storm events, mainly used for testing.

Used by: (596)Perceived Frequency of Storms -

(594) New Storm = IF THEN ELSE ( Time <= 2010, Annual Storm Frequency , Storm Occurrence / TIME STEP )

Units: 1/Year

The arrival of a new storm into the assessment window. The 2010 constraint is because stochastic storms aren't allowed before 2010.

Used by: (600)Total Number of Storms -

(595) New Year of Assessment = 1

Units: 1

New year of assessment.

Used by: (601)Years of Storm Observation -

(596) Perceived Frequency of Storms = IF THEN ELSE ( Switch Perc Storm Freq = 1, Total Number of Storms / Years of Storm Observation , Exogenous Perc Storm Freq )

Units: 1/Year

Investors' perceived frequency of storm events given recent storm events in their window of assessment.

Used by: (556)Perceived Fractional Damage by Category -

(597) Storms Leaving Window = Total Number of Storms / Time Horizon for Storm Frequency Assessment

Units: 1/Year

Storm leaving the window of assessment. Forgetting or habituation.  
Used by: (600)Total Number of Storms -

(598) Switch Perc Storm Freq = 1  
Units: dmnl  
Switch to control perceived storm frequency. Mainly used to test scenarios. 0=exog, 1=endog.  
Used by: (596)Perceived Frequency of Storms -

(599) Time Horizon for Storm Frequency Assessment = 10  
Units: years  
The time horizon of considering storm events.  
Used by: (600)Total Number of Storms -  
(601)Years of Storm Observation -  
(592)Assessment Window Shift -  
(597)Storms Leaving Window -

(600) Total Number of Storms = INTEG( New Storm - Storms Leaving Window , Annual Storm Frequency \* Time Horizon for Storm Frequency Assessment )  
Units: dmnl  
The number of storms stored in memory, and are currently being considered by investors and residents.  
Used by: (596)Perceived Frequency of Storms -  
(597)Storms Leaving Window -

(601) Years of Storm Observation = INTEG( New Year of Assessment - Assessment Window Shift , Time Horizon for Storm Frequency Assessment )  
Units: years  
The number of years in the in window of assessment.  
Used by: (592)Assessment Window Shift -  
(596)Perceived Frequency of Storms -

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.Storm Initialization  
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(602) Annual Storm Frequency for Cape Cod in 1990 = INITIAL( IF THEN ELSE ( Switch Storm Climate Model Choice = 1, "Annual Storm Frequency for Cape Cod in 1990 (GFDL)" , IF THEN ELSE ( Switch Storm Climate Model Choice = 2, "Annual Storm Frequency for Cape Cod in 1990 (echam)" , 0 ) ) )  
Units: 1/Year  
The annual storm frequency for Cape Cod from 1981-2000.  
Used by: (620)Annual Storm Frequency in 1990 -

(603) "Annual Storm Frequency for Cape Cod in 1990 (echam)" = 0.0195  
Units: 1/Year  
The annual storm frequency of Cape Cod from 1981-2000 as estimated by the ECHAM climate model.  
Used by: (602)Annual Storm Frequency for Cape Cod in 1990 -

(604) "Annual Storm Frequency for Cape Cod in 1990 (GFDL)" = 0.0108  
Units: 1/Year  
The annual storm frequency of Cape Cod from 1981-2000 as estimated by the GFDL climate model.  
Used by: (602)Annual Storm Frequency for Cape Cod in 1990 -

(605) Annual Storm Frequency for Cape Cod in 2190 = INITIAL( IF THEN ELSE ( Switch Storm Climate Model Choice = 1, "Annual Storm Frequency for Cape Cod in 2190 (GFDL)" , IF THEN ELSE ( Switch Storm Climate Model Choice = 2, "Annual Storm Frequency for Cape Cod in 2190

(echam)" , 0) ) )  
Units: 1/Year  
The annual storm frequency for Cape Cod from 2181-2200.  
Used by: (621)Annual Storm Frequency in 2190 -

(606) "Annual Storm Frequency for Cape Cod in 2190 (echam)" = 0.019  
Units: 1/Year  
The annual storm frequency of Cape Cod from 2181-2200 as  
estimated by the ECHAM climate model.  
Used by: (605)Annual Storm Frequency for Cape Cod in 2190 -

(607) "Annual Storm Frequency for Cape Cod in 2190 (GFDL)" = 0.0343  
Units: 1/Year  
The annual storm frequency of Cape Cod from 2181-2200 as  
estimated by the GFDL climate model.  
Used by: (605)Annual Storm Frequency for Cape Cod in 2190 -

(608) Annual Storm Frequency for Miami in 1990 = INITIAL( IF THEN ELSE ( Switch Storm Climate Model Choice =  
1, "Annual Storm Frequency for Miami in 1990 (GFDL)" ,  
IF THEN ELSE ( Switch Storm Climate Model Choice = 2, "Annual Storm Frequency for Miami in 1990  
(echam)" , 0) ) ) )  
Units: 1/Year  
The annual storm frequency for Miami from 1981-2000.  
Used by: (620)Annual Storm Frequency in 1990 -

(609) "Annual Storm Frequency for Miami in 1990 (echam)" = 0.1087  
Units: 1/Year  
The annual storm frequency of Miami from 1981-2000 as estimated  
by the ECHAM climate model.  
Used by: (608)Annual Storm Frequency for Miami in 1990 -

(610) "Annual Storm Frequency for Miami in 1990 (GFDL)" = 0.0925  
Units: 1/Year  
The annual storm frequency of Miami from 1981-2000 as estimated  
by the GFDL climate model.  
Used by: (608)Annual Storm Frequency for Miami in 1990 -

(611) Annual Storm Frequency for Miami in 2190 = INITIAL( IF THEN ELSE ( Switch Storm Climate Model Choice =  
1, "Annual Storm Frequency for Miami in 2190 (GFDL)" ,  
IF THEN ELSE ( Switch Storm Climate Model Choice = 2, "Annual Storm Frequency for Miami in 2190  
(echam)" , 0) ) ) )  
Units: 1/Year  
The annual storm frequency for Miami from 2181-2200.  
Used by: (621)Annual Storm Frequency in 2190 -

(612) "Annual Storm Frequency for Miami in 2190 (echam)" = 0.0514  
Units: 1/Year  
The annual storm frequency of Miami from 2181-2200 as estimated  
by the ECHAM climate model.  
Used by: (611)Annual Storm Frequency for Miami in 2190 -

(613) "Annual Storm Frequency for Miami in 2190 (GFDL)" = 0.0851  
Units: 1/Year  
The annual storm frequency of Miami from 2181-2200 as estimated  
by the GFDL climate model.  
Used by: (611)Annual Storm Frequency for Miami in 2190 -

(614) Annual Storm Frequency for St Mary Parish in 1990 = INITIAL( IF THEN ELSE ( Switch Storm Climate Model  
Choice = 1, "Annual Storm Frequency for St Mary Parish in 1990 (GFDL)" ,

IF THEN ELSE ( Switch Storm Climate Model Choice = 2, "Annual Storm Frequency for St Mary Parish in 1990 (echam)" , 0 ) )

Units: 1/Year

The annual storm frequency for St. Mary Parish from 1981-2000.

Used by: (620)Annual Storm Frequency in 1990 -

(615) "Annual Storm Frequency for St Mary Parish in 1990 (echam)" = 0.0402

Units: 1/Year

The annual storm frequency of St. Mary Parish from 1981-2000 as estimated by the ECHAM climate model.

Used by: (614)Annual Storm Frequency for St Mary Parish in 1990 -

(616) "Annual Storm Frequency for St Mary Parish in 1990 (GFDL)" = 0.0399

Units: 1/Year

The annual storm frequency of St. Mary Parish from 1981-2000 as estimated by the GFDL climate model.

Used by: (614)Annual Storm Frequency for St Mary Parish in 1990 -

(617) Annual Storm Frequency for St Mary Parish in 2190 = INITIAL( IF THEN ELSE ( Switch Storm Climate Model Choice = 1, "Annual Storm Frequency for St Mary Parish in 2190 (GFDL)" ,

IF THEN ELSE ( Switch Storm Climate Model Choice = 2, "Annual Storm Frequency for St Mary Parish in 2190 (echam)" , 0 ) )

Units: 1/Year

The annual storm frequency for St. Mary Parish from 2181-2200.

Used by: (621)Annual Storm Frequency in 2190 -

(618) "Annual Storm Frequency for St Mary Parish in 2190 (echam)" = 0.0441

Units: 1/Year

The annual storm frequency of St. Mary Parish from 2181-2200 as estimated by the ECHAM climate model.

Used by: (617)Annual Storm Frequency for St Mary Parish in 2190 -

(619) "Annual Storm Frequency for St Mary Parish in 2190 (GFDL)" = 0.0793

Units: 1/Year

The annual storm frequency of St. Mary Parish from 2181-2200 as estimated by the GFDL climate model.

Used by: (617)Annual Storm Frequency for St Mary Parish in 2190 -

(620) Annual Storm Frequency in 1990 = INITIAL( IF THEN ELSE ( Switch Segment Choice = 1, Annual Storm Frequency for Miami in 1990 ,

IF THEN ELSE ( Switch Segment Choice = 2, Annual Storm Frequency for Cape Cod in 1990 ,

IF THEN ELSE ( Switch Segment Choice = 3, Annual Storm Frequency for St Mary Parish in 1990 , 0 ) ) )

Units: 1/Year

The annual storm frequency of the community from 1981-2000.

Used by: (648)Annual Storm Frequency -

(621) Annual Storm Frequency in 2190 = INITIAL( IF THEN ELSE ( Switch Segment Choice = 1, Annual Storm Frequency for Miami in 2190 ,

IF THEN ELSE ( Switch Segment Choice = 2, Annual Storm Frequency for Cape Cod in 2190 ,

IF THEN ELSE ( Switch Segment Choice = 3, Annual Storm Frequency for St Mary Parish in 2190 , 0 ) ) )

Units: 1/Year

The annual storm frequency of the community from 2181-2200.

Used by: (648)Annual Storm Frequency -

(622) Reference Perceived Storm Frequency = IF THEN ELSE ( Switch Segment Choice = 1, Reference Storm Freq for Miami ,

IF THEN ELSE ( Switch Segment Choice = 2, Reference Storm Freq for Cape Cod ,

IF THEN ELSE ( Switch Segment Choice = 3, Reference Storm Freq for SMP , 0 ) ) )

Units: 1/Year

The perceived storm frequency of non-expert residents. Should be

a reference to the historical trend, which is Emanuel's model.  
Used by: (561)Reference Fractional Damage by Category -

(623) Reference Storm Freq for Cape Cod = 0.0108  
Units: 1/Year

The reference perceived storm frequency for Cape Cod. The perceived historical trend. Currently GFDL 1980-2000 frequency.  
Used by: (622)Reference Perceived Storm Frequency -

(624) Reference Storm Freq for Miami = 0.0925  
Units: 1/Year

The reference perceived storm frequency for Miami. The perceived historical trend. Currently GFDL 1980-2000 frequency.  
Used by: (622)Reference Perceived Storm Frequency -

(625) Reference Storm Freq for SMP = 0.0399  
Units: 1/Year

The reference perceived storm frequency for St. Mary Parish. The perceived historical trend. Currently GFDL 1980-2000 frequency.  
Used by: (622)Reference Perceived Storm Frequency -

(626) Storm Intensities for Cape Cod 1990[StormCategory] = INITIAL( IF THEN ELSE ( Switch Storm Climate Model Choice = 1, Storm Intensities for Cape Cod 1990 GFDL[ StormCategory] , IF THEN ELSE ( Switch Storm Climate Model Choice = 2, Storm Intensities for Cape Cod 1990 ECHAM[StormCategory ] , 0 ) ) )

Units: dmm1  
The distribution of storm intensities for Cape Cod under present climate conditions.  
Used by: (644)Storm Intensity 1990 -

(627) Storm Intensities for Cape Cod 1990 ECHAM[StormCategory] = 0.81, 0.93 , 0.98, 1, 1  
Units: dmm1

The CDF of Category 1-5 storms for Cape Cod with the climate from 1980-2000 using the ECHAM model.  
Used by: (626)Storm Intensities for Cape Cod 1990 -

(628) Storm Intensities for Cape Cod 1990 GFDL[StormCategory] = 0.79, 0.95, 0.99, 0.99, 1  
Units: dmm1

The CDF of Category 1-5 storms for Cape Cod with the climate from 1980-2000 using the GFDL model.  
Used by: (626)Storm Intensities for Cape Cod 1990 -

(629) Storm Intensities for Cape Cod 2190[StormCategory] = INITIAL( IF THEN ELSE ( Switch Storm Climate Model Choice = 1, Storm Intensities for Cape Cod 2190 GFDL[ StormCategory] , IF THEN ELSE ( Switch Storm Climate Model Choice = 2, Storm Intensities for Cape Cod 2190 ECHAM[StormCategory ] , 0 ) ) )

Units: dmm1  
The distribution of storm intensities for Cape Cod under future climate conditions.  
Used by: (645)Storm Intensity 2190 -

(630) Storm Intensities for Cape Cod 2190 ECHAM[StormCategory] = 0.87, 0.93 , 0.99, 1, 1  
Units: dmm1

The CDF of Category 1-5 storms for Cape Cod with the climate from 2180-2200 using the ECHAM model.  
Used by: (629)Storm Intensities for Cape Cod 2190 -

(631) Storm Intensities for Cape Cod 2190 GFDL[StormCategory] = 0.79, 0.95, 0.99, 0.99, 1  
Units: dmm1

The CDF of Category 1-5 storms for Cape Cod with the climate from 2180-2200 using the GFDL model.  
Used by: (629)Storm Intensities for Cape Cod 2190 -

(632) Storm Intensities for Miami 1990[StormCategory] = INITIAL( IF THEN ELSE ( Switch Storm Climate Model Choice = 1, Storm Intensities for Miami 1990 GFDL[ StormCategory] , IF THEN ELSE ( Switch Storm Climate Model Choice = 2, Storm Intensities for Miami 1990 ECHAM[StormCategory ] , 0 ) ) )  
Units: dmn1  
The distribution of storm intensities for Miami under present climate conditions.  
Used by: (644)Storm Intensity 1990 -

(633) Storm Intensities for Miami 1990 ECHAM[StormCategory] = 0.43, 0.66, 0.84 , 0.97, 1  
Units: dmn1  
The CDF of Category 1-5 storms for Miami with the climate from 1980-2000 using the ECHAM model.  
Used by: (632)Storm Intensities for Miami 1990 -

(634) Storm Intensities for Miami 1990 GFDL[StormCategory] = 0.34, 0.52, 0.7 , 0.91, 1  
Units: dmn1  
The CDF of Category 1-5 storms for Miami with the climate from 1980-2000 using the GFDL model.  
Used by: (632)Storm Intensities for Miami 1990 -

(635) Storm Intensities for Miami 2190[StormCategory] = INITIAL( IF THEN ELSE ( Switch Storm Climate Model Choice = 1, Storm Intensities for Miami 2190 GFDL[ StormCategory] , IF THEN ELSE ( Switch Storm Climate Model Choice = 2, Storm Intensities for Miami 2190 ECHAM[StormCategory ] , 0 ) ) )  
Units: dmn1  
The distribution of storm intensities for Miami under future climate conditions.  
Used by: (645)Storm Intensity 2190 -

(636) Storm Intensities for Miami 2190 ECHAM[StormCategory] = 0.45, 0.67, 0.86 , 0.97, 1  
Units: dmn1  
The CDF of Category 1-5 storms for Miami with the climate from 2180-2200 using the ECHAM model.  
Used by: (635)Storm Intensities for Miami 2190 -

(637) Storm Intensities for Miami 2190 GFDL[StormCategory] = 0.46, 0.69, 0.88 , 0.99, 1  
Units: dmn1  
The CDF of Category 1-5 storms for Miami with the climate from 2180-2200 using the GFDL model.  
Used by: (635)Storm Intensities for Miami 2190 -

(638) Storm Intensities for St Mary Parish 1990[StormCategory] = INITIAL( IF THEN ELSE ( Switch Storm Climate Model Choice = 1, Storm Intensities for St Mary Parish 1990 GFDL[ StormCategory] , IF THEN ELSE ( Switch Storm Climate Model Choice = 2, Storm Intensities for St Mary Parish 1990 ECHAM[StormCategory ] , 0 ) ) )  
Units: dmn1  
The distribution of storm intensities for St. Mary Parish under present climate conditions.  
Used by: (644)Storm Intensity 1990 -

(639) Storm Intensities for St Mary Parish 1990 ECHAM[StormCategory] = 0.51 , 0.73, 0.89, 0.98, 1  
Units: dmn1  
The CDF of Category 1-5 storms for St. Mary Parish with the climate from 1980-2000 using the ECHAM model.  
Used by: (638)Storm Intensities for St Mary Parish 1990 -

(640) Storm Intensities for St Mary Parish 1990 GFDL[StormCategory] = 0.41, 0.63, 0.84, 0.99, 1  
Units: dmm1  
The CDF of Category 1-5 storms for St. Mary Parish with the  
climate from 1980-2000 using the GFDL model.  
Used by: (638)Storm Intensities for St Mary Parish 1990 -

(641) Storm Intensities for St Mary Parish 2190[StormCategory] = INITIAL( IF THEN ELSE ( Switch Storm Climate  
Model Choice = 1, Storm Intensities for St Mary Parish 2190 GFDL[ StormCategory] ,  
IF THEN ELSE ( Switch Storm Climate Model Choice = 2, Storm Intensities for St Mary Parish 2190  
ECHAM[StormCategory ] , 0 ) ) )  
Units: dmm1  
The distribution of storm intensities for St. Mary Parish under  
future climate conditions.  
Used by: (645)Storm Intensity 2190 -

(642) Storm Intensities for St Mary Parish 2190 ECHAM[StormCategory] = 0.41 , 0.62, 0.81, 0.94, 1  
Units: dmm1  
The CDF of Category 1-5 storms for St. Mary Parish with the  
climate from 2180-2200 using the ECHAM model.  
Used by: (641)Storm Intensities for St Mary Parish 2190 -

(643) Storm Intensities for St Mary Parish 2190 GFDL[StormCategory] = 0.33, 0.55, 0.79, 0.98, 1  
Units: dmm1  
The CDF of Category 1-5 storms for St. Mary Parish with the  
climate from 2180-2200 using the GFDL model.  
Used by: (641)Storm Intensities for St Mary Parish 2190 -

(644) Storm Intensity 1990[StormCategory] = INITIAL( IF THEN ELSE ( Switch Segment Choice = 1, Storm  
Intensities for Miami 1990[StormCategory] ,  
IF THEN ELSE ( Switch Segment Choice = 2, Storm Intensities for Cape Cod 1990[ StormCategory] ,  
IF THEN ELSE ( Switch Segment Choice = 3, Storm Intensities for St Mary Parish 1990[ StormCategory] ,  
0 ) ) ) )  
Units: dmm1  
The storm distribution of storm intensities for the community  
under present climate conditions.  
Used by: (651)Distribution of Storm Intensities -

(645) Storm Intensity 2190[StormCategory] = INITIAL( IF THEN ELSE ( Switch Segment Choice = 1, Storm  
Intensities for Miami 2190[StormCategory] ,  
IF THEN ELSE ( Switch Segment Choice = 2, Storm Intensities for Cape Cod 2190[ StormCategory] ,  
IF THEN ELSE ( Switch Segment Choice = 3, Storm Intensities for St Mary Parish 2190[ StormCategory] ,  
0 ) ) ) )  
Units: dmm1  
The storm intensity distribution for the community under the A1B  
scenario.  
Used by: (651)Distribution of Storm Intensities -

(646) Switch Storm Century Distribution = 0  
Units: dmm1  
Switch to control whether the storms have the characteristics of  
the average from 1980-2000 or 2080-2100. 0=1990, 1=2090.  
Used by: (648)Annual Storm Frequency -  
(651)Distribution of Storm Intensities -

(647) Switch Storm Climate Model Choice = 1  
Units: dmm1  
Switch to control what climate model is used for storm  
statistics. 1=GFDL, 2=ECHAM.  
Used by: (602)Annual Storm Frequency for Cape Cod in 1990 -

(605)Annual Storm Frequency for Cape Cod in 2190 -  
 (608)Annual Storm Frequency for Miami in 1990 -  
 (611)Annual Storm Frequency for Miami in 2190 -  
 (614)Annual Storm Frequency for St Mary Parish in 1990 -  
 (617)Annual Storm Frequency for St Mary Parish in 2190 -  
 (626)Storm Intensities for Cape Cod 1990 -  
 (629)Storm Intensities for Cape Cod 2190 -  
 (632)Storm Intensities for Miami 1990 -  
 (635)Storm Intensities for Miami 2190 -  
 (638)Storm Intensities for St Mary Parish 1990 -  
 (641)Storm Intensities for St Mary Parish 2190 -

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 .Storms  
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(648) Annual Storm Frequency = INITIAL( ( 1 - Switch Storm Century Distribution ) \* Annual Storm Frequency in 1990 + Switch Storm Century Distribution \* Annual Storm Frequency in 2190 )  
 Units: 1/Year

The annual storm frequency of the community.  
 Used by: (600)Total Number of Storms -  
 (649)Annual Storm Frequency adjusted by TIMESTEP -  
 (533)CM's Estimated Fractional Damage to Mitigated if Protected by Category -  
 (535)CM's Estimated Fractional Damage to Mitigated if Unprotected by Category -  
 (537)CM's Estimated Fractional Damage to Unmitigated if Protected by Category -  
 (539)CM's Estimated Fractional Damage to Unmitigated if Unprotected by Category -  
 (594)New Storm -

(649) Annual Storm Frequency adjusted by TIMESTEP = Annual Storm Frequency \* TIME STEP  
 Units: dmn1

The frequency of the storm events for the community in a year,  
 mindful of the model's time step.  
 Used by: (656)Storm Event Generator -

(650) Category of Exogenous Storm = 5  
 Units: dmn1

The strength of the exogenous storm event. The Saffir-Simpson  
 category of the storm.  
 Used by: (652)Exogenous Storm Event -

(651) Distribution of Storm Intensities[StormCategory] = INITIAL( IF THEN ELSE ( Switch Storm Century Distribution = 0, Storm Intensity 1990[ StormCategory] , IF THEN ELSE ( Switch Storm Century Distribution = 1, Storm Intensity 2190[StormCategory] , 0) ) )  
 Units: dmn1

The distribution of storm intensities for the community.  
 Used by: (560)Probability of Storm by Category -  
 (654)Stochastic Storm Intensity -

(652) Exogenous Storm Event = Category of Exogenous Storm \* PULSE ( Year of Exogenous Storm , TIME STEP )  
 Units: dmn1

An exogenous storm event with strength information. Related to  
 Saffir-Simpson scale.  
 Used by: (658)Storm Event with Strength -

(653) Stochastic Storm Event = IF THEN ELSE ( Storm Event Generator > 0, Stochastic Storm Intensity , 0)  
 Units: dmn1

A stochastic storm event with strength information. Currently  
 relate to Saffir-Simpson scale.  
 Used by: (658)Storm Event with Strength -

(654) Stochastic Storm Intensity = IF THEN ELSE ( Stochastic Storm Intensity Generator < Distribution of



```

Storm Intensities[Cat1] , 1,
  IF THEN ELSE ( Stochastic Storm Intensity Generator < Distribution of Storm Intensities[Cat2] , 2,
  IF THEN ELSE ( Stochastic Storm Intensity Generator < Distribution of Storm Intensities[ Cat3] , 3,
  IF THEN ELSE ( Stochastic Storm Intensity Generator < Distribution of Storm Intensities[Cat4] , 4,
  IF THEN ELSE ( Stochastic Storm Intensity Generator < Distribution of Storm Intensities[ Cat5] , 5, 0)
) ) )

```

Units: dmn1

The storm intensity of a simulated stochastic storm event.

Used by: (653)Stochastic Storm Event -

```
(655) Stochastic Storm Intensity Generator = RANDOM UNIFORM ( 0, 1, Storm Intensity Random Number Seed )
```

Units: dmn1

A random number generator that picks the strength of a storm event,

IF it occurs.

Used by: (654)Stochastic Storm Intensity -

```
(656) Storm Event Generator = IF THEN ELSE ( Time > 2010, RANDOM POISSON ( 0, 1e+009, Annual Storm Frequency
adjusted by TIMESTEP , 0, 1, Storm Event Random Number Seed ) , 0)
```

Units: dmn1

A random number generator for whether or not a storm formed near the community.

Used by: (653)Stochastic Storm Event -

(431)storm -

```
(657) Storm Event Random Number Seed = 41750.6
```

Units: dmn1

A seed parameter for the storm arrival random number generator.

Can be varied for a sensitivity analysis.

Used by: (656)Storm Event Generator -

```
(658) Storm Event with Strength = GAME( Switch Storms * ( ( 1 - Switch Storm Frequency ) * Exogenous Storm
Event + Switch Storm Frequency * Stochastic Storm Event ) )
```

Units: dmn1

A storm event including information of the strength of the event.

Used by: (570)Fraction of Infrastructure Damaged by Wind -

(454)Fraction Willing to Evacuate -

(432)storm cat count -

(660)Storm Occurrence -

(076)Storm Surge Height -

```
(659) Storm Intensity Random Number Seed = 0
```

Units: dmn1

A seed parameter for the storm intensity random number generator. Can be varied for a sensitivity analysis.

Used by: (655)Stochastic Storm Intensity Generator -

```
(660) Storm Occurrence = IF THEN ELSE ( Storm Event with Strength > 0, 1, 0 )
```

Units: dmn1

State variable to record if a storm occurred in a particular time step. 0=No storm, 1=Storm.

Used by: (564)Average Water Depth in Community -

(066)Breach Occurs -

(200)Change in Flood Insurance Coverage -

(155)Desired Reactionary Height -

(449)Evacuation -

(415)Fraction Retrofitting -

(574)Inland Distance Flooded During Storm -

(594)New Storm -

```
(661) StormCategory : (Cat1-Cat5)
```

Subscript for the category of storms.

(662) Switch Storm Frequency = 1  
Units: dmn1  
Switch to control the frequency of storm events in the model.  
0=Single Exogenous storm, 1=Poisson storm arrivals.  
Used by: (658)Storm Event with Strength -

(663) Switch Storms = 1  
Units: dmn1  
A switch to activate or deactivate storm event(s). 0=Off, 1=On  
Used by: (658)Storm Event with Strength -

(664) Year of Exogenous Storm = 2050  
Units: Year  
The year of the exogenous storm event occurrence.  
Used by: (652)Exogenous Storm Event -

\*\*\*\*\*  
.Wetland Initialization  
\*\*\*\*\*

(665) Accommodation space of the segment = INITIAL( IF THEN ELSE ( Switch Segment Choice = 1, Initial accommodation space of Miami ,  
IF THEN ELSE ( Switch Segment Choice = 2, Initial accommodation space of Cape Cod ,  
IF THEN ELSE ( Switch Segment Choice = 3, Initial accommodation space of St Mary Parish , 0 ) ) ) )  
Units: dmn1  
The accommodation space from the DIVA DB.  
Used by: (729)aspace if dike present -  
(730)aspace plus 0.25 -  
(748)ifthen sdikehght -

(666) Initial accommodation space of Cape Cod = 1.25  
Units: dmn1  
The classification value of the amount of accommodation space  
for Cape Cod. (DIVA)  
Used by: (665)Accommodation space of the segment -

(667) Initial accommodation space of Miami = 1.25  
Units: dmn1  
The classification value of the amount of accommodation space  
for Miami. (DIVA)  
Used by: (665)Accommodation space of the segment -

(668) Initial accommodation space of St Mary Parish = 1.25  
Units: dmn1  
The classification value of the amount of accommodation space  
for St. Mary Parish. (DIVA)  
Used by: (665)Accommodation space of the segment -

(669) Initial Forested Wetland Area = INITIAL( IF THEN ELSE ( Switch Segment Choice = 1, Initial forested wetland area for Miami / Initial Total Wetland Area Miami \* "Initial Undevelopable Area (Wetlands)" ,  
IF THEN ELSE ( Switch Segment Choice = 2, Initial forested wetland area for Cape Cod / Initial Total Wetland Area Cape Cod \* "Initial Undevelopable Area (Wetlands)" ,  
IF THEN ELSE ( Switch Segment Choice = 3, Initial forested wetland area for St Mary Parish / Initial Total Wetland Area St Mary Parish \* "Initial Undevelopable Area (Wetlands)" , 0 ) ) ) )  
Units: km\*km  
The initial amount of forested wetlands in the segment.  
Used by: (702)Forested Wetlands Area -  
(712)Initial total wetland area -

(670) Initial forested wetland area for Cape Cod = 41.5  
Units: km\*km  
The amount of the forested wetlands in Cape Cod. (DIVA data)  
Used by: (669)Initial Forested Wetland Area -  
(691)Initial Total Wetland Area Cape Cod -

(671) Initial forested wetland area for Miami = 0  
Units: km\*km  
The amount of the forested wetlands in Miami. (DIVA data)  
Used by: (669)Initial Forested Wetland Area -  
(692)Initial Total Wetland Area Miami -

(672) Initial forested wetland area for St Mary Parish = 0  
Units: km\*km  
The amount of the forested wetlands in St. Mary Parish. (DIVA data)  
Used by: (669)Initial Forested Wetland Area -  
(693)Initial Total Wetland Area St Mary Parish -

(673) Initial Freshmarsh Area = INITIAL( IF THEN ELSE ( Switch Segment Choice = 1, Initial freshmarsh area for Miami / Initial Total Wetland Area Miami \* "Initial Undevelopable Area (Wetlands)" ,  
IF THEN ELSE ( Switch Segment Choice = 2, Initial freshmarsh area for Cape Cod / Initial Total Wetland Area Cape Cod \* "Initial Undevelopable Area (Wetlands)" ,  
IF THEN ELSE ( Switch Segment Choice = 3, Initial freshmarsh area for St Mary Parish / Initial Total Wetland Area St Mary Parish \* "Initial Undevelopable Area (Wetlands)" , 0 ) ) ) )  
Units: km\*km  
The initial area of fresh water marshes and wetlands for the segment.  
Used by: (710)Freshmarsh Area -  
(712)Initial total wetland area -

(674) Initial freshmarsh area for Cape Cod = 0  
Units: km\*km  
The area of fresh water marsh in Cape Cod. (DIVA)  
Used by: (673)Initial Freshmarsh Area -  
(691)Initial Total Wetland Area Cape Cod -

(675) Initial freshmarsh area for Miami = 0  
Units: km\*km  
The area of fresh water marsh in Miami. (DIVA)  
Used by: (673)Initial Freshmarsh Area -  
(692)Initial Total Wetland Area Miami -

(676) Initial freshmarsh area for St Mary Parish = 0  
Units: km\*km  
The area of fresh water marsh in St. Mary Parish. (DIVA)  
Used by: (673)Initial Freshmarsh Area -  
(693)Initial Total Wetland Area St Mary Parish -

(677) Initial Mangrove Area = INITIAL( IF THEN ELSE ( Switch Segment Choice = 1, ( Initial mangrove area for Miami / Initial Total Wetland Area Miami ) \* "Initial Undevelopable Area (Wetlands)" ,  
IF THEN ELSE ( Switch Segment Choice = 2, ( Initial mangrove area for Cape Cod / Initial Total Wetland Area Cape Cod ) \* "Initial Undevelopable Area (Wetlands)" ,  
IF THEN ELSE ( Switch Segment Choice = 3, ( Initial mangrove area for St Mary Parish / Initial Total Wetland Area St Mary Parish ) \* "Initial Undevelopable Area (Wetlands)" , 0 ) ) ) )  
Units: km\*km  
The initial area of the mangrove biome in the segment.  
Used by: (713)Mangrove Area -  
(712)Initial total wetland area -

(678) Initial mangrove area for Cape Cod = 0  
Units: km\*km  
The area of mangrove forest in Cape Cod. (DIVA)  
Used by: (677)Initial Mangrove Area -  
(691)Initial Total Wetland Area Cape Cod -

(679) Initial mangrove area for Miami = 24  
Units: km\*km  
The area of mangrove forest in Miami. (DIVA)  
Used by: (677)Initial Mangrove Area -  
(692)Initial Total Wetland Area Miami -

(680) Initial mangrove area for St Mary Parish = 0  
Units: km\*km  
The area of mangrove forest in St. Mary Parish. (DIVA)  
Used by: (677)Initial Mangrove Area -  
(693)Initial Total Wetland Area St Mary Parish -

(681) Initial Saltmarsh Area = INITIAL( IF THEN ELSE ( Switch Segment Choice = 1, Initial saltmarsh area for Miami / Initial Total Wetland Area Miami \* "Initial Undevelopable Area (Wetlands)" ,  
IF THEN ELSE ( Switch Segment Choice = 2, Initial saltmarsh area for Cape Cod / Initial Total Wetland Area Cape Cod \* "Initial Undevelopable Area (Wetlands)" ,  
IF THEN ELSE ( Switch Segment Choice = 3, Initial saltmarsh area for St Mary Parish / Initial Total Wetland Area St Mary Parish \* "Initial Undevelopable Area (Wetlands)" , 0 ) ) ) )  
Units: km\*km  
The initial area of salt-water marshes in the segment.  
Used by: (720)Saltmarsh Area -  
(712)Initial total wetland area -

(682) Initial saltmarsh area for Cape Cod = 61  
Units: km\*km  
The area of salt marsh in Cape Cod. (DIVA)  
Used by: (681)Initial Saltmarsh Area -  
(691)Initial Total Wetland Area Cape Cod -

(683) Initial saltmarsh area for Miami = 0  
Units: km\*km  
The area of salt marsh in Miami. (DIVA)  
Used by: (681)Initial Saltmarsh Area -  
(692)Initial Total Wetland Area Miami -

(684) Initial saltmarsh area for St Mary Parish = 1560  
Units: km\*km  
The area of salt marsh in St. Mary Parish. (DIVA)  
Used by: (681)Initial Saltmarsh Area -  
(693)Initial Total Wetland Area St Mary Parish -

(685) Initial sediment supply for Cape Cod = 4.40707  
Units: dmn1  
The sediment supply providing nutrients to the wetlands. (DIVA;  
based segment length on weighted average)  
Used by: (699)Sediment supply of the segment -

(686) Initial sediment supply for Miami = 3.62  
Units: dmn1  
The sediment supply providing nutrients to the wetlands. (DIVA)  
Used by: (699)Sediment supply of the segment -

(687) Initial sediment supply for St Mary Parish = 4.08

Units: dmn1  
The sediment supply providing nutrients to the wetlands. (DIVA)  
Used by: (699)Sediment supply of the segment -

(688) Initial tidal range for Cape Cod = 2  
Units: dmn1  
The tidal range classification for the Cape Cod coast. (DIVA;  
value is "<2", so I chose one to make sure it was classified  
correctly in the next step.)  
Used by: (700)Tidal range of segment -

(689) Initial tidal range for Miami = 2  
Units: dmn1  
The tidal range classification for the Miami coast. (DIVA;  
value is "<2", so I chose one to make sure it was classified  
correctly in the next step.)  
Used by: (700)Tidal range of segment -

(690) Initial tidal range for St Mary Parish = 2  
Units: dmn1  
The tidal range classification for the St. Mary Parish coast.  
(DIVA; value is "<2", so I chose one to make sure it was  
classified correctly in the next step.)  
Used by: (700)Tidal range of segment -

(691) Initial Total Wetland Area Cape Cod = INITIAL( Initial forested wetland area for Cape Cod + Initial  
freshmarsh area for Cape Cod + Initial mangrove area for Cape Cod + Initial saltmarsh area for Cape Cod +  
Initial unvegetated area for Cape Cod )  
Units: km\*km  
The total wetland area in Cape Cod according to DIVA.  
Used by: (669)Initial Forested Wetland Area -  
(673)Initial Freshmarsh Area -  
(677)Initial Mangrove Area -  
(681)Initial Saltmarsh Area -  
(695)Initial Unvegetated Area -

(692) Initial Total Wetland Area Miami = INITIAL( Initial forested wetland area for Miami + Initial  
freshmarsh area for Miami + Initial mangrove area for Miami + Initial saltmarsh area for Miami + Initial  
unvegetated area for Miami )  
Units: km\*km  
The total wetland area for Miami according to DIVA.  
Used by: (669)Initial Forested Wetland Area -  
(673)Initial Freshmarsh Area -  
(677)Initial Mangrove Area -  
(681)Initial Saltmarsh Area -  
(695)Initial Unvegetated Area -

(693) Initial Total Wetland Area St Mary Parish = INITIAL( Initial forested wetland area for St Mary Parish +  
Initial freshmarsh area for St Mary Parish + Initial mangrove area for St Mary Parish + Initial saltmarsh area  
for St Mary Parish + Initial unvegetated area for St Mary Parish )  
Units: km\*km  
The total initial wetland area for St. Mary Parish according to  
DIVA. Segment is too big.  
Used by: (669)Initial Forested Wetland Area -  
(673)Initial Freshmarsh Area -  
(677)Initial Mangrove Area -  
(681)Initial Saltmarsh Area -  
(695)Initial Unvegetated Area -

(694) "Initial Undevelopable Area (Wetlands)" = ( 1 - Fraction of Community Area Developable ) \* Community  
Area

Units: km\*km  
 The initial area of land in the community that can never be developed. It is assumed to be wetlands.  
 Used by: (669)Initial Forested Wetland Area -  
 (673)Initial Freshmarsh Area -  
 (677)Initial Mangrove Area -  
 (681)Initial Saltmarsh Area -  
 (695)Initial Unvegetated Area -

(695) Initial Unvegetated Area = INITIAL( IF THEN ELSE ( Switch Segment Choice = 1, Initial unvegetated area for Miami / Initial Total Wetland Area Miami \* "Initial Undevelopable Area (Wetlands)" ,  
 IF THEN ELSE ( Switch Segment Choice = 2, Initial unvegetated area for Cape Cod / Initial Total Wetland Area Cape Cod \* "Initial Undevelopable Area (Wetlands)" ,  
 IF THEN ELSE ( Switch Segment Choice = 3, Initial unvegetated area for St Mary Parish / Initial Total Wetland Area St Mary Parish \* "Initial Undevelopable Area (Wetlands)" , 0 ) ) ) )  
 Units: km\*km  
 The initial area of unvegetated wetlands in the segment.  
 Used by: (724)Unvegetated Area -  
 (712)Initial total wetland area -

(696) Initial unvegetated area for Cape Cod = 287  
 Units: km\*km  
 The area of unvegetated wetland area in Cape Cod. (DIVA; the sum of high and low unvegetated areas)  
 Used by: (691)Initial Total Wetland Area Cape Cod -  
 (695)Initial Unvegetated Area -

(697) Initial unvegetated area for Miami = 0  
 Units: km\*km  
 The area of unvegetated wetland area in Miami. (DIVA; the sum of high and low unvegetated areas)  
 Used by: (692)Initial Total Wetland Area Miami -  
 (695)Initial Unvegetated Area -

(698) Initial unvegetated area for St Mary Parish = 26  
 Units: km\*km  
 The area of unvegetated wetland area in St. Mary Parish. (DIVA; the sum of high and low unvegetated areas)  
 Used by: (693)Initial Total Wetland Area St Mary Parish -  
 (695)Initial Unvegetated Area -

(699) Sediment supply of the segment = INITIAL( IF THEN ELSE ( Switch Segment Choice = 1, Initial sediment supply for Miami ,  
 IF THEN ELSE ( Switch Segment Choice = 2, Initial sediment supply for Cape Cod ,  
 IF THEN ELSE ( Switch Segment Choice = 3, Initial sediment supply for St Mary Parish , 0 ) ) ) )  
 Units: dmn1  
 The sediment supply variable for the segment. (DIVA DB - sedsup)  
 Used by: (731)CSVS -

(700) Tidal range of segment = INITIAL( IF THEN ELSE ( Switch Segment Choice = 1, Initial tidal range for Miami ,  
 IF THEN ELSE ( Switch Segment Choice = 2, Initial tidal range for Cape Cod ,  
 IF THEN ELSE ( Switch Segment Choice = 3, Initial tidal range for St Mary Parish , 0 ) ) ) )  
 Units: dmn1  
 The tidal range classification of the segment, based on the DIVA database. (DIVA-tidalrng)  
 Used by: (747)hTidal wm -

\*\*\*\*\*  
 .Wetlands  
 \*\*\*\*\*

(701) Forested to Open = ( 1 ) \* Forested Wetlands Area \* Forested PctChange  
Units: km\*km/Year  
The area of forested wetlands changed to open water in a year.  
Used by: (702)Forested Wetlands Area -  
(717)Open Water Area -

(702) Forested Wetlands Area = INTEG( - Forested to Open , Initial Forested Wetland Area )  
Units: km\*km  
The area of forested wetlands in the segment.  
Used by: (701)Forested to Open -  
(723)Total wetland area -

(703) Fraction Mangrove to Unvegetated = 0.5  
Units: dmn1  
The fraction of vulnerable mangrove that transitions to  
unvegetated wetlands.  
Used by: (714)Mangrove to Open -  
(715)Mangrove to Unvegetated -

(704) Fraction of Fresh to Salt = 0.3333  
Units: dmn1  
The fraction of vulnerable Freshmarsh that migrates to Saltmarsh.  
Used by: (707)Fresh to Open -  
(708)Fresh to Salt -

(705) Fraction of Fresh to Unvegetated = 0.3333  
Units: dmn1  
The fraction of vulnerable freshmarsh that transitions to  
unvegetated wetlands.  
Used by: (707)Fresh to Open -  
(709)Fresh to Unvegetated -

(706) Fraction of Salt to Unvegetated = 0.5  
Units: dmn1  
The fraction of vulnerable saltmarsh that transitions to  
unvegetated wetlands.  
Used by: (718)Salt to Open -  
(719)Salt to Unvegetated -

(707) Fresh to Open = ( 1 - Fraction of Fresh to Salt - Fraction of Fresh to Unvegetated ) \* Freshmarsh Area  
\* Freshmarsh PctChange  
Units: km\*km/Year  
The area of fresh-water wetlands that change to open water in a  
year.  
Used by: (710)Freshmarsh Area -  
(717)Open Water Area -

(708) Fresh to Salt = Fraction of Fresh to Salt \* Freshmarsh Area \* Freshmarsh PctChange  
Units: km\*km/Year  
The area of fresh-water marshes that change to salt-water  
marshes in a year.  
Used by: (710)Freshmarsh Area -  
(720)Saltmarsh Area -

(709) Fresh to Unvegetated = Fraction of Fresh to Unvegetated \* Freshmarsh Area \* Freshmarsh PctChange  
Units: km\*km/Year  
The area of fresh-water wetlands that change into unvegetated  
wetlands in a year.  
Used by: (710)Freshmarsh Area -

(724)Unvegetated Area -

(710) Freshmarsh Area = INTEG( New Freshmarsh from Migration - Fresh to Open - Fresh to Salt - Fresh to Unvegetated , Initial Freshmarsh Area )  
Units: km\*km  
The area of fresh-water marshes in the segment.  
Used by: (707)Fresh to Open -  
(708)Fresh to Salt -  
(709)Fresh to Unvegetated -  
(723)Total wetland area -

(711) Initial Open Water Area = 0  
Units: km\*km  
The initial area of open water in the segment.  
Used by: (717)Open Water Area -

(712) Initial total wetland area = INITIAL( Initial Forested Wetland Area + Initial Freshmarsh Area + Initial Mangrove Area + Initial Saltmarsh Area + Initial Unvegetated Area )  
Units: km\*km  
The initial area of wetland for the segment.  
Used by: (723)Total wetland area -

(713) Mangrove Area = INTEG( - Mangrove to Open - Mangrove to Unvegetated , Initial Mangrove Area )  
Units: km\*km  
The area of the mangrove biome in the segment.  
Used by: (714)Mangrove to Open -  
(715)Mangrove to Unvegetated -  
(723)Total wetland area -

(714) Mangrove to Open = ( 1 - Fraction Mangrove to Unvegetated ) \* Mangrove Area \* Mangrove PctChange  
Units: km\*km/Year  
The area of mangroves that change to open water in a year.  
Used by: (713)Mangrove Area -  
(717)Open Water Area -

(715) Mangrove to Unvegetated = ( Fraction Mangrove to Unvegetated \* Mangrove Area \* Mangrove PctChange )  
Units: km\*km/Year  
The area of mangroves that change to unvegetated wetlands in a year.  
Used by: (713)Mangrove Area -  
(724)Unvegetated Area -

(716) New Freshmarsh from Migration = Switch Wetland migration \* Max Annual Wetland Gain  
Units: km\*km/Year  
The area of new wetlands gained per year from inland migration.  
Used by: (710)Freshmarsh Area -

(717) Open Water Area = INTEG( Forested to Open + Fresh to Open + Mangrove to Open + Salt to Open + Unvegetated to Open , Initial Open Water Area )  
Units: km\*km  
The area of open water in the segment.

(718) Salt to Open = ( 1 - Fraction of Salt to Unvegetated ) \* Saltmarsh Area \* Saltmarsh PctChange  
Units: km\*km/Year  
The area of salt-water marshes that change to open water in a year.  
Used by: (717)Open Water Area -  
(720)Saltmarsh Area -

(719) Salt to Unvegetated = Fraction of Salt to Unvegetated \* Saltmarsh Area \* Saltmarsh PctChange



Units: km\*km/Year  
The area of salt-water marshes that change to unvegetated wetlands in a year.  
Used by: (720)Saltmarsh Area -  
(724)Unvegetated Area -

(720) Saltmarsh Area = INTEG( Fresh to Salt - Salt to Open - Salt to Unvegetated , Initial Saltmarsh Area )  
Units: km\*km  
The area of salt-water marshes in the segment.  
Used by: (718)Salt to Open -  
(719)Salt to Unvegetated -  
(723)Total wetland area -

(721) Switch Wetland area = 1  
Units: dmn1  
0 = Initial area (no loss) ,1 = DIVA model  
Used by: (723)Total wetland area -

(722) Switch Wetland migration = 0  
Units: dmn1  
Switch to turn the wetland gain/migration one. 0=off, 1=on.  
Used by: (716)New Freshmarsh from Migration -

(723) Total wetland area = Switch Wetland area \* ( Forested Wetlands Area + Freshmarsh Area + Mangrove Area + Saltmarsh Area + Unvegetated Area ) + ( 1 - Switch Wetland area ) \* Initial total wetland area  
Units: km\*km  
The total area of the segment covered by any type of wetland.  
Used by: (727)Annual value of wetlands -  
(769)Wetland Length along Coast -

(724) Unvegetated Area = INTEG( Fresh to Unvegetated + Mangrove to Unvegetated + Salt to Unvegetated - Unvegetated to Open , Initial Unvegetated Area )  
Units: km\*km  
The area of unvegetated wetlands in the segment.  
Used by: (723)Total wetland area -  
(725)Unvegetated to Open -

(725) Unvegetated to Open = ( 1 ) \* Unvegetated Area \* Unvegetated PctChange  
Units: km\*km/Year  
The area of unvegetated wetlands that change to open water in a year.  
Used by: (717)Open Water Area -  
(724)Unvegetated Area -

\*\*\*\*\*  
.Wetlands Support  
\*\*\*\*\*

(726) Annual unit value of wetland = 5e+006  
Units: dollars/(Year\*km\*km)  
The stream of wetland value of a square kilometer of wetland.  
(Fankhauser,1995)  
Used by: (727)Annual value of wetlands -

(727) Annual value of wetlands = Annual unit value of wetland \* Total wetland area  
Units: dollars/Year  
The total value of wetlands for the segment.  
Used by: (734)Discounted Value of Wetlands -

(728) aspace cnst 5 = 5  
Units: dmnl  
A constant for accommodation space classification.  
Used by: (729)aspace if dike present -

(729) aspace if dike present = IF THEN ELSE ( Accommodation space of the segment > 4.75, aspace cnst 5 ,  
"aspace plus 0.25" )  
Units: dmnl  
Classifying the accommodation space.  
Used by: (748)ifthen sdikehght -

(730) "aspace plus 0.25" = Accommodation space of the segment + 0.25  
Units: dmnl  
This is what they do.  
Used by: (729)aspace if dike present -

(731) CSVS = ( RSLR tidal score \* sltrwgt ) + ( RSLR tidal score / 5 ) \* ( Sediment supply of the segment \*  
sedwgt ) + ( modified aspace \* slopewgt )  
Units: dmnl  
The Coastal Segment Vulnerability Score from DIVA. The overall  
vulnerability given the tidal classification and the amount of  
accommodation space.  
// Combining horizontal and vertical forcing, the CSVS (coastal segment  
vulnerability score) value is based on three parameters that  
drive wetland response  
// (SLR/tidal forcing, sediment supply and accommodation space).  
Accommodation space (aspace) replaces the migratory potential  
rating and reflects both physical (slope) and  
// human (seawall) constraints on wetland migration. Sediment  
supply is weighted as a factor of sea-level rise.  
Used by: (732)CSVS Last -  
(736)ESS Forested -  
(737)ESS Freshmarsh -  
(738)ESS Mangrove -  
(739)ESS Saltmarsh -  
(740)ESS Unvegetated -

(732) CSVS Last = DELAY FIXED ( CSVS ,1, Initial CSVS db )  
Units: dmnl  
The previous CSVS value.  
Used by: (736)ESS Forested -  
(737)ESS Freshmarsh -  
(738)ESS Mangrove -  
(739)ESS Saltmarsh -  
(740)ESS Unvegetated -

(733) deltaSLR = Switch Wetlands Exog SLR \* Annual Relative SLR + ( 1 - Switch Wetlands Exog SLR ) \*  
Exogenous wetland SLR  
Units: meters/Year  
The rate of SLR for the wetlands module.  
Used by: (758)RSLR tidal raw score -  
(759)RSLR tidal score -

(734) Discounted Value of Wetlands = Annual value of wetlands / Discount Rate  
Units: \$  
The discounted value of the wetlands for the region.  
Used by: (134)Coastal Managers Recommended Height of Protection -

(735) DIVATIMESTEP = 5  
Units: years  
The time step of the DIVA model.

Used by: (758)RSLR tidal raw score -

(736) ESS Forested = Forested Current Weight \* CSVS + ( 1 - Forested Current Weight ) \* CSVS Last  
Units: dmn1  
The Ecological Sensitivity Score score for Forested.  
Used by: (744)Forested PctChange -

(737) ESS Freshmarsh = CSVS \* Fresh Current Weight + ( 1 - Fresh Current Weight ) \* CSVS Last  
Units: dmn1  
The Ecological Sensitivity Score score for Freshmarsh.  
Used by: (746)Freshmarsh PctChange -

(738) ESS Mangrove = Mangrove Current Weight \* CSVS + ( 1 - Mangrove Current Weight ) \* CSVS Last  
Units: dmn1  
The Ecological Sensitivity Score score for Mangrove.  
Used by: (751)Mangrove PctChange -

(739) ESS Saltmarsh = Saltmarsh Current Weight \* CSVS + ( 1 - Saltmarsh Current Weight ) \* CSVS Last  
Units: dmn1  
The Ecological Sensitivity Score score for Saltmarsh.  
Used by: (761)Saltmarsh PctChange -

(740) ESS Unvegetated = Unvegetated Current Weight \* CSVS + ( 1 - Unvegetated Current Weight ) \* CSVS Last  
Units: dmn1  
The Ecological Sensitivity Score score for Unvegetated.  
Used by: (767)Unvegetated PctChange -

(741) Exogenous wetland SLR = 0.002  
Units: meters/Year  
Exogenous rate of SLR, mainly for testing the wetlands module.  
Used by: (733)deltaSLR -

(742) F95 Max migration constant = 0.0005  
Units: km/Year  
The constant that Fankhauser used for maximum inland migration of wetlands.  
Used by: (753)Max inland migration distance -

(743) Forested Current Weight = 0.7  
Units: dmn1  
The weight on the current CSVS score for Forested.  
Used by: (736)ESS Forested -

(744) Forested PctChange =  $1 - (0.07 + 1) * ( (1 - \text{ESS Forested} / 5) ^{0.07} ) + 0.07 * ( (1 - \text{ESS Forested} / 5) ^{-(0.07 + 1)} )$   
Units: 1/Year  
The percentage of the Forested biome that is vulnerable to succession.  
Used by: (701)Forested to Open -

(745) Fresh Current Weight = 0.9  
Units: dmn1  
The weight on the current CSVS score for Freshmarsh.  
Used by: (737)ESS Freshmarsh -

(746) Freshmarsh PctChange =  $1 - (0.16 + 1) * ( (1 - \text{ESS Freshmarsh} / 5) ^{0.16} ) + 0.16 * ( (1 - \text{ESS Freshmarsh} / 5) ^{-(0.16 + 1)} )$

Units: 1/Year  
The percentage of the Freshmarsh biome that is vulnerable to succession.  
Used by: (707)Fresh to Open -  
(708)Fresh to Salt -  
(709)Fresh to Unvegetated -

(747) hTidal wm = IF THEN ELSE ( Tidal range of segment < 2, 0.25,  
IF THEN ELSE ( Tidal range of segment = 2, 1.25,  
IF THEN ELSE ( Tidal range of segment = 3, 3,  
IF THEN ELSE ( Tidal range of segment = 4, 6,  
IF THEN ELSE ( Tidal range of segment = 5, 9, -1e+006 ) ) ) ) )  
Units: dmn1  
Assigning a forcing score to tidal range: Basic tidal range data  
derived from LOICZ: consistent with htidal values within  
Indirect Erosion Module\!\!\!  
Used by: (758)RSLR tidal raw score -

(748) ifthen sdikeyght = IF THEN ELSE ( ( Completed Levee Protection > 0.5 ) , aspace if dike present ,  
Accommodation space of the segment )  
Units: dmn1  
The change of accomodation space if protection is present.  
Used by: (754)modified aspace -

(749) Initial CSVS db = 5  
Units: dmn1  
The initial CSVS score of the segment, as record in the DIVA DB.  
Used by: (732)CSVs Last -

(750) Mangrove Current Weight = 0.8  
Units: dmn1  
The weight on the current CSVS score for Mangrove.  
Used by: (738)ESS Mangrove -

(751) Mangrove PctChange =  $1 - (0.07 + 1) * ((1 - \text{ESS Mangrove} / 5) ^ 0.07) + 0.07 * ((1 - \text{ESS Mangrove} / 5) ^ (0.07 + 1))$   
Units: 1/Year  
The percentage of the Mangrove biome that is vulnerable to succession.  
Used by: (714)Mangrove to Open -  
(715)Mangrove to Unvegetated -

(752) Max Annual Wetland Gain = Max inland migration distance \* Wetland Length along Coast  
Units: km\*km/Year  
The maximum area of new wetlands that can be gained from inland migration.  
Used by: (716)New Freshmarsh from Migration -

(753) Max inland migration distance = F95 Max migration constant  
Units: km/Year  
The maximum distance inland that wetlands could have migrated.  
Used by: (752)Max Annual Wetland Gain -

(754) modified aspace = ifthen sdikeyght  
Units: dmn1  
The modified value for the accommodation space.  
Used by: (731)CSVs -

(755) Reference Protection Height = 0

Units: meters  
 The reference height of protection for a 50% chance of breaching. This parameter allows for a shifting of the fragility curve.  
 Used by: (073)Probability of Breach -

(756) Reference Sea Level Rise = 1  
 Units: meters  
 The reference sea level rise per time step in the DIVA model.  
 Does help with unit conversion.  
 Used by: (758)RSLR tidal raw score -

(757) RSLR tidal classification = IF THEN ELSE ( RSLR tidal raw score >= 0.0095 , 5,  
 IF THEN ELSE ( RSLR tidal raw score >= 0.0035, 4,  
 IF THEN ELSE ( RSLR tidal raw score >= 0.001, 3,  
 IF THEN ELSE ( RSLR tidal raw score >= 0.0001, 2,  
 IF THEN ELSE ( RSLR tidal raw score > 0, 1, 0 ) ) ) ) )  
 Units: dmnl  
 An if then else in the DIVA wetlands module for tidal zone classification.  
 Used by: (759)RSLR tidal score -

(758) RSLR tidal raw score = ( ( ( deltaSLR \* DIVATIMESTEP ) / Reference Sea Level Rise ) ^ 1.4 ) / ( hTidal  
 wm )  
 Units: dmnl  
 From the DIVA wetlands module. Was called 'rslr tidal equation'.  
 Original equation: ((Math.pow((cls.rslr - cls.rslr\_last),1.4)/dt / htidal)  
 Used by: (757)RSLR tidal classification -

(759) RSLR tidal score = IF THEN ELSE ( deltaSLR > 0, RSLR tidal classification , 0 )  
 Units: dmnl  
 The tidal range classification (DIVA) based on relative SLR.  
 Variable was named 'rslr tidal'.  
 Used by: (731)CSVS -

(760) Saltmarsh Current Weight = 0.9  
 Units: dmnl  
 The weight on the current CSVS score for Saltmarsh.  
 Used by: (739)ESS Saltmarsh -

(761) Saltmarsh PctChange = 1 - ( 0.11 + 1 ) \* ( ( 1 - ESS Saltmarsh / 5 ) ^ 0.11 ) + 0.11 \* ( ( 1 - ESS  
 Saltmarsh / 5 ) ^ ( 0.11 + 1 ) )  
 Units: 1/Year  
 The percentage of the Saltmarsh biome that is vulnerable to succession.  
 Used by: (718)Salt to Open -  
 (719)Salt to Unvegetated -

(762) sedwgt = 0.3  
 Units: dmnl  
 The weight on the sediment supply variable for the CSVS.  
 Used by: (731)CSVS -

(763) slopegwt = 0.2  
 Units: dmnl  
 The weight on the slope variable for the CSVS.  
 Used by: (731)CSVS -

(764) sltrwgt = 0.5  
Units: dmnl  
The weight on tidal range variable for the CSVS.  
Used by: (731)CSVS -

(765) Switch Wetlands Exog SLR = 1  
Units: dmnl  
Switch to control the SLR forcing for wetlands. 0=Separate  
Exogenous, 1=Model forcing  
Used by: (733)deltaSLR -

(766) Unvegetated Current Weight = 1  
Units: dmnl  
The weight on the current CSVS score for Unvegetated.  
Used by: (740)ESS Unvegetated -

(767) Unvegetated PctChange =  $1 - (0.2 + 1) * ((1 - \text{ESS Unvegetated} / 5)^{0.2}) + 0.2 * ((1 - \text{ESS Unvegetated} / 5)^{(0.2 + 1)})$   
Units: 1/Year  
The percentage of the Unvegetated biome that is vulnerable to  
succession.  
Used by: (725)Unvegetated to Open -

(768) Wetland distribution depth = 1  
Units: km  
The depth along that coast that wetlands extend inland.  
Used by: (769)Wetland Length along Coast -

(769) Wetland Length along Coast =  $\text{MIN}(\text{Total wetland area} / \text{Wetland distribution depth}, \text{Segment Length})$   
Units: km  
The length the segment's coastline that is covered with  
wetlands. This is determined by the distribution of wetlands in  
the segment.  
Used by: (752)Max Annual Wetland Gain -