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Does Tropical Cyclone Modification Make Sense?

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in

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The mind is its own place, and in itself, can make a Heaven of Hell, a Hell of Heaven.

~ John Milton

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Abstract

Recent dramatic increases in damages caused by tropical cyclones (TCs) and improved understanding of TC physics have led the Department of Homeland Security to fund research on intentional hurricane modification. Here I present a decision analytic assessment of whether hurricane modification is potentially cost effective in South Florida.

First, for a single storm I compare hardening buildings to lowering the wind speed of a TC by reducing sea surface temperatures with wind-wave pumps. I find that if it were feasible and properly implemented, modification could reduce net wind losses from an intense storm more than hardening structures. However, hardening provides "fail safe" protection for average storms that might not be achieved if the only option were modification. The effect of natural variability is larger than that of either strategy.

Second, for multiple storms over a given return period, I investigate TC wind and storm surge damage reduction by hardening buildings and by wind-wave pumps. The coastal areas examined experience more surge damages for short return periods, and more wind damages for long periods. Surge damages are best reduced through a surge barrier. Wind damages are best reduced by a portfolio of techniques including wind-wave pumps, assuming they work and are correctly deployed. Damages in areas outside of the floodplain will likely be dominated by wind damages, and hence a similar portfolio will likely be best in these areas.

Since hurricane modification might become a feasible strategy for reducing hurricane damages, to facilitate an informed and constructive discourse on implementation, policy makers need to understand how people perceive hurricane modification. Therefore using the mental models approach, I identified Florida residents' perceptions of hurricane modification techniques. First, hurricane modification was perceived as a relatively ineffective strategy for

damage reduction. Second, hurricane modification was expected to lead to changes in path, but not necessarily strength. Third, reported anger at hurricane modification was weaker when path was unaltered and the damages equal to or less than projected. Fourth, individuals who recognized the uncertainty inherent in hurricane prediction reported more anger at scientists across modification scenarios.

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Abbreviations

BFE	Base Flood Elevation
CCN	Cloud Condensation Nuclei
DHS	Department of Homeland Security
GIS	Geographic Information Systems
HAZUS	Not an abbreviation; name of software
FEMA	Federal Emergency Management Division
IPCC	Intergovernmental Panel on Climate Change
MANOVA	Multivariate Analysis of Variance
MIT	Massachusetts Institute of Technology
NHC	National Hurricane Center
SFBC	South Florida Building Code, 1994
SST	Sea Surface Temperature
TC	Tropical Cyclone

Symbols & Statistical Test Definitions

H_S	Significant wave height sustainable by buoy (m)
h	Mixed layer depth (m)
L	Distance between pipes (m)
P_N	Nominal pumping speed (m^3/s)
R	Diameter of the pipe (m)
ΔSST	Change in sea surface temperature, ranging from -0.5°C to -2.0°C (°C)
T_P	Wave period (sec)
t	Time spent in the altered SST area, ranging from 1.5-22 hours (sec)
•T	Temperature difference between the surface buoy and the valve (°C)
V	Volume of water being cooled by the pumps (m^3)
V_{MAX}	Maximum 1 minute sustained wind speed at 10m height (m/s)
ε	Efficiency of pipe

Multivariate Analysis of Variance (MANOVA)

Used when there is more than one dependent variable, such as ratings of effectiveness for multiple damage reduction strategies. It examines the effect of one or more independent variables on the means of the dependent variables, as well as interaction effects between the levels of the independent and the dependent variables. Like univariate Analysis of Variance (ANOVA) t, it uses the *F*-test to examine these effects.

Stevens, J. P. Applied multivariate statistics for the social sciences. Mahwah, N.J.: Lawrence Erblaum, 2002.

Cronbach's alpha

Mathematically equivalent to the average value of all possible split-half correlations. Indeed, a split-half correlation is the correlation between mean two mean ratings computed from two halves of the same set of items. Hence, it is an indicator of internal consistency reliability across items.

Cronbach, L.J. Coefficient alpha and the internal structure of tests. *Psychometrika*, 1951; 16, pp.297-334.

DeVellis, R.F. Scale development. Theory and applications. Second edition. Thousand Oaks, CA: Sage Publications, 2003.

McNemar change tests

Designed for use with 2 x 2 contingency tables of nominal data obtained in a repeated-measures design, for example to compare whether expected change (yes vs. no) is more likely with different types of hurricanes (modified vs. unmodified).

McNemar, Quinn. Note on the sampling error of the difference between correlated proportions or percentages. *Psychometrika*, 1947; 12, pp. 153–157.

Note to the Reader

Portions of this work have been accepted to or are in review at peer-reviewed journals. Papers include:

Klima, K.; Morgan, M.G.; Grossmann, I.; Emanuel, K. Does It Make Sense To Modify Tropical Cyclones? A Decision-Analytic Assessment. *Engineering Science and Technology*. 2011. 45:10 pp 4242–4248.

Klima, K.; Bruine de Bruin, W.; Morgan, G.; Grossman, I. Public Perceptions of Hurricane Modification. Accepted 2011 at Risk Analysis.

Klima, K.; Lin, N.; Emanuel, K.; Morgan, G.; Grossman, I. Hurricane modification and adaptation in Miami-Dade County, Florida. In review at ES&T.

Chapter 1. Introduction

1.1. What are Tropical Cyclones?

According to the American Meteorological Society Glossary of Meteorology, a tropical cyclone (TC) is a "general term for a cyclone that originates over the tropical oceans" (*1*). Tropical cyclone formation and intensification depend critically on several thermodynamic and dynamic conditions (*2*). Genesis occurs with an initial disturbance, such as an African easterly wave or a monsoon trough. Given an appropriate variety of thermal conditions (e.g. warm tropical oceans, atmospheric instability, mid-tropospheric moisture) and dynamic factors (vorticity, coriolis force, lack of vertical wind shear) these disturbances will intensify into a tropical cyclone (*3*, *4*, *5*, *6*). After formation, potential intensity theory indicates that the structure is maintained through a Carnot cycle (*7*); in other words, the tropical cyclone is maintained by the extraction of latent heat from the ocean at high temperature and heat export at low temperatures of the tropical upper troposphere. The efficiency of the Carnot cycle can be described using the temperature difference between the surface and the tropical upper troposphere, and the total rate of heat input to a hurricane is the integral o9ver the surface area covered by the storm of the surface enthalpy flux and dissipative heating (*8*). Figure 1.1 indicates the theoretical maximum wind speeds as a function of sea surface temperature and outflow temperature based on potential intensity theory (*7*). Although higher gusts have been recorded (*9*), the highest recorded 1-minute sustained wind speed as of 2011, 190mph, occurred in the eyewall of a Typhoon Tip, 1979 (*10*).

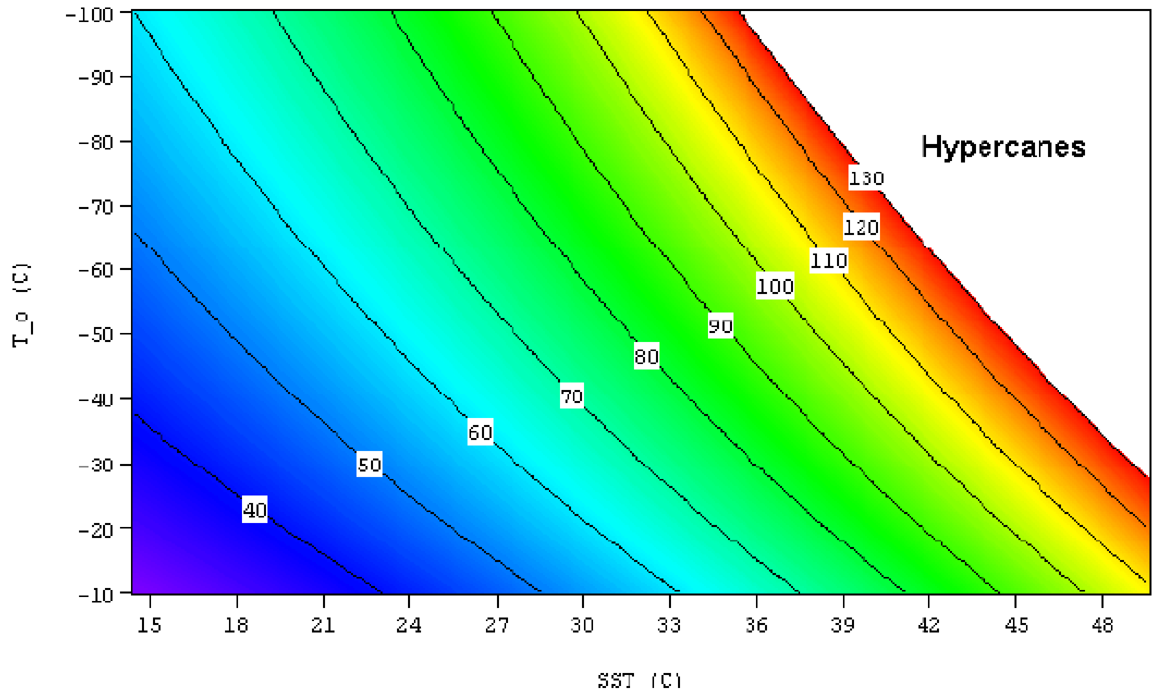


Figure 1.1. Contour plot of maximum wind speed (m/s, recall 1m/s=2.23mph) for sea surface temperature (SST) and storm top temperature (T_o). Enthalpy H =0.75, C_K/C_D=1.2. Figure courtesy of Emanuel, (*7*).

Tropical cyclones can be recognized by their wind patterns (*2, 11*). Mature tropical cyclones are nearly circularly symmetric, and can range in diameter over several hundred kilometers. The prevailing winds in the tropics generally cause storm to move westward, but as they mature they are often entrained into mid-latitude westerlies and recurve poleward and eastward. Viewed in a stationary frame, a tropical cyclone's surface winds spiral inward cyclonically, becoming roughly tangent at the eyewall (*12*). The winds rise along the eyewall, and spiral outward at the tropopause (*13*). Spiral bands appear in the outer regions of the hurricane (*14*). The most intense rain/winds occur in the eyewall, and the lowest pressure occurs in the eye (*14*). Observations indicate that the eyewall can break down and/or reform unpredictably, resulting in concentric eyewalls and eyewall replacement cycles (*15*, *16*).

Table 1.1. Saffir-Simpson Hurricane Scale (*18*) and additional classifications (*17*)

Rank	Wind Speed mph	kt	km/hr
Tropical Depression	0-38	0-34	0-62
Tropical Storm	39-73	35-63	63-118
Severe Tropical Cyclone: Category 1	74-95	64-82	119-153
Severe Tropical Cyclone: Category 2	96-110	83-95	154-177
Severe Tropical Cyclone: Category 3	111-130	96-113	178-209
Severe Tropical Cyclone: Category 4	131-155	114-135	210-249
Severe Tropical Cyclone: Category 5	>155	>135	>249

Each tropical cyclone is internationally classified as a tropical depression, tropical storm, or a severe tropical cyclone (*17*) as shown in Table 1.1. Severe tropical cyclones are called hurricanes in the Atlantic and typhoons in the West Pacific, and are further broken down into category by the Saffir-Simpson Hurricane Scale (*18*), also shown in Table 1.1. The U.S. uses 1-min average wind speeds at anemometer level (10m). The annual number of Atlantic tropical cyclones reaching at least tropical storm strength usually varies between 2 and 15 (*19*), but there is no upper bound; the 2005 season saw 28 named storms (*20*). Note the Saffir-Simpson Scale does not account for size of storm (storm radius), storm-surge, rain-induced floods, or tornadoes (*18*).

1.2. Tropical Cyclones Damages and Damage Reduction Strategies

When they make landfall, TCs can cause great devastation. Hurricane Katrina (2005) is estimated to have caused losses of over $80-billion, and Hurricane Andrew (1992) losses of just under $60-billion normalized to 2006 United States dollars (USD) using inflation, per capita wealth, and population change adjustments (*21*). Additionally, over 1200 deaths are attributable to Katrina (*22*). Researchers have also identified many environmental impacts of hurricanes (*23, 24*). Annual normalized total losses in the United States are now estimated to average about

$10-billion/year (*25*). Given increasing coastal populations and increasing wealth at the coast, studies suggesting an upward shift of the average intensity of TCs with global warming (*26*, *27*), and given work linking observed hurricane intensities to observed global warming (*28*), future damage rates from TCs are expected to increase.

Several methods exist to reduce TC damages. Hardening structures includes applying storm shutters, reinforcing roofs, and using stronger building materials. Currently, several hardening strategies have been adopted in various locations along the U.S. Atlantic coast (*29*).

A second method, hurricane modification, attempts to intentionally change a storm. Serious research on this strategy began in 1961, when the United States government undertook experiments to change hurricanes by seeding clouds from aircraft. Project Stormfury was consequently formed in 1962, but discontinued in 1983 due to lack of statistically significant results and because the technique was not viable (*30*). Given newer scientific understanding, there is a possibility that small amounts of energy, input in the right way, may be able to modify a TC (*31*). The U.S. Department of Homeland Security (DHS) and the American Meteorological Society have recently devoted renewed attention to TC modification (*32, 33*) and DHS has funded an effort to identify and evaluate hurricane modification strategies through Project HURRMIT (*34*). Despite continued study, there are many extremely serious concerns with the implementation and effectiveness of any modification technique.

1.3. Overview of Thesis

Before undertaking a new multi-million dollar effort on a range of possible hurricane modification techniques, three questions should be addressed. First for a *single storm*, how much of a change might hurricane modification produce, and if these changes played out exactly as anticipated, how much might they reduce damages and net social costs compared to adaptation techniques? Second, for *seasonal damages over multiple years*, how much of a change in damages might hurricane modification produce, and if these changes played out exactly as anticipated, how much might they reduce damages and net social costs compared to adaptation techniques? Third, how does the public perceive the possibility of hurricane modification?

This thesis presents a decision analytic assessment of the hurricane modification technique of wind-wave pumps as compared with hardening techniques such as putting shutters on all windows and doors. Unlike previous work (*35*), this study examines specific storms, hardening methods, and TC modification techniques to calculate damages, costs, and net benefits. Additionally, this work is the first of its kind to examine public perceptions of hurricane modification techniques.

This thesis is divided into eight chapters. First, this chapter provides a brief background on tropical cyclones and damages. Chapter 2 provides a description, costs, and limitations of hardening methods which can reduce damages from TCs. Chapter 3 describes hurricane modification, including the costs and limitations associated with the specific technique considered in the remainder of the thesis, wind-wave pumps. Chapter 4 describes the functionality and limitations of FEMA's publically available HAZUS-MH MR3 used to calculate total direct economic losses.

Chapter 5 hypothesizes that a large Andrew-like storm will make landfall near Miami, Florida. Here I examine possible wind damages from 27 Andrew-like storms in the Miami, Florida area for control, adaptation, and hurricane modification scenarios.

Chapter 6 hypothesizes that the policy maker is more concerned with expected damages from different return periods. Here I examine wind and surge storm damages in five coastal groups of census blocks for return periods ranging from 10-1000 years.

Although research on modification is being done, no one has looked into how the public perceives this possibility and what kind of emotions might be involved if the government were to decide, to do some experimental modification on an approaching hurricane. Chapter 7 discusses public perceptions of hurricane modification techniques obtained from an interview and a survey of 157 Miami-Dade County residents.

Finally, Chapter 8 briefly describes plans for future work and concludes this thesis.

Chapter 2. Adaptation

Portions of the discussion in this Chapter are based on Klima, K.; Morgan, M.G.; Grossmann, I.; Emanuel, K. Does It Make Sense To Modify Tropical Cyclones? A Decision-Analytic Assessment. *Engineering Science and Technology*. 2011. 45:10 pp 4242–4248. AND Klima, K.; Lin, N.; Emanuel, K.; Morgan, G.; Grossman, I. Hurricane modification and adaptation in Miami-Dade County, Florida. In review at ES&T.

Various techniques are available to reduce damages from natural hazards such as TCs, tsunamis, floods, and earthquakes (*36, 37*, *38*). The insurance industry calls these techniques "hardening" or "mitigation", while the Intergovernmental Panel on Climate Change (IPCC) would call hardening "adaptation".

This chapter describes adaptation. First I discuss the background of adaptation. Second I describe the method, cost, and limitation to several types of adaptation. Chapters 5-6 apply these cost estimates to particular problems.

2.1. Background

Adaptation is "tried-and-true"; several hardening strategies have been adopted in various locations along the U.S. Atlantic coast (*39, 29*). Techniques can be applied as a function of the owner's risk tolerance, and will yield added protection for all hurricanes regardless of the forecasted track uncertainty. Research indicates perhaps due to its current level of usage, adaptation is widely known by Florida residents (*40*).

Some techniques protect buildings against wind and wind-blown debris, such as installing storm shutters, strengthening roofs, and assuring that structures have a negative load path to ground (*37*). Other techniques help protect buildings from water damage, such as elevating structures on pilings to avoid flood damage and building dams or dikes (*41, 42, 43, 44, 45*). Once implemented, hardening techniques can remain in place for 30 years or more to provide protection against wind, storm surge, and rain damages from hurricanes of various sizes. However, these techniques are often insufficient to protect against very intense hurricanes.

Non-structural adaptation techniques may also be used to reduce damages (*46, 47*) and, in particular, prevent loss of life. Some techniques include improved awareness ("Being prepared"), evacuation ("Evacuating everyone but emergency personnel"), and adaptive behavior ("Putting the car in the garage", "Bringing in loose lawn items"). Additionally, better forecasts and their improved communication to residents can help reduce damages (*48*). While these non-structural techniques help to reduce damages from hurricanes, it is unclear exactly how much perception and awareness decrease damages. Due to cost and efficacy uncertainty, I do not examine these techniques in benefit-cost analyses (Chapter 5 or Chapter 6), but only include them in the interview/survey (Chapter 7).

2.2. Proposed Techniques

Extensive work has been done to identify damage reduction techniques and observe their effects (*36, 37, 41, 46, 47*). Here I list describe techniques examined in this thesis.

2.2.1. Storm shutters

Miami-Dade County Office of Emergency Management reports that improving shutters is the most cost-effective hardening technique. The Office has implemented a shutter regulation for new buildings in the South Florida Building Code (SFBC) in 1994 (*39*), demanding that shutters withstand impact by debris having an energy equal to or greater than 350 ft-lb. (i.e., a 9 lb. wood

2×4 with a speed of 34mph). Although the actual compliance rate is unknown, FEMA estimates from census data indicate that no more than 30%, 15%, 5%, and 8% of residential buildings meet SFBC code in southeast, south, central, and north Florida, respectively (*49*). FEMA work indicates unshuttered windows with a lifetime of 15-50 years may last hundreds of years if shutters are correctly employed (*49, 50*), although it is possible that this work does not include damages due to gusts. The percentage of total buildings that are protected in this way will continue to increase as new structures are built and as old are eliminated, replaced, or retrofitted. Changes in the wind damage resistance function are calculated automatically in HAZUS when shuttering is enabled *(49)*.

One hardening option assumes that corrugated aluminum shutters are added to all Florida and Georgia residential buildings lacking shutters in the default census values of HAZUS (2002). The cheapest shutters that meet SFBC are corrugated aluminum panels costing $\$8/ft^2$. Assuming from damage curves that these shutters last at most 30 years *(49)*, annualizing at a 5% discount rate yields annual costs of \$1.4-1.8B for Florida and \$0.7-0.9B for Georgia. Adding shutters to all non-shuttered commercial buildings will cost \$4-5 million per year in Florida and \$15-17 million in Georgia. These are upper bound cost estimates given incentives to install shutters such as zoning laws, insurance breaks, and tax free matching grants such as the "My Safe Florida Home" program (*29*).

2.2.2. Strengthening the Roof and Improved Roof Wall Connections

This group of techniques strengthens the connection between roof beams and walls. In common configurations, the roof is only lightly nailed to the bearing walls. Strong horizontal wind causes the roof to "fly up" or lift off from the walls. In new homes, improved architectural design including avoiding gabled roofs, using a negative load-path to ground, fastening the shingles w/ adhesive or nails, using additional truss bracing, nailing gable end trusses to the wall, improving truss sheathing, bracing gable ends, and installing hurricane straps (*37*) increases the uplift resistance. For existing houses, roof-wall and roof-truss connections can be strengthened with 0.125" straps and 8D nails (*39*) or in some cases, 16D nails (*51*). Newer regulations in southeast Florida mandate that up to 15% of the roof cost is used to reinforce roof-wall connections. Costs can greatly increase for "full strapping" of the roof to the walls by firmly connecting the roof, top plate, studs, and foundation; often the entire roof needs to be replaced (*29*).

I assume that a roof replacement costs $10/ft^2 of lot size, and that the roof-wall connections cost 15% of the roof cost. Annualizing over 30 years at a 5% discount rate yields annual costs of $1-1.5B for all residential and commercial buildings in Florida and $0.5-0.7B in Georgia. "Full strapping" might necessitate an entire roof replacement, or roughly $6.5-10B for all residential and commercial buildings in Florida and $3-0.4.5B in Georgia.

2.2.3. Other Hardening During Roof Replacement

When the roof is replaced, several hardening techniques can be applied, including strengthening the roof-deck connection and adding a secondary water barrier. Since roofs can last 30 years or more, these techniques cannot be swiftly applied. However, if the roof is being redone, the extra cost for superior roof deck attachment and secondary water resistance is only about half the cost of adding shutters.

2.2.4. Tie downs

Tie downs, used in manufactured houses, are inexpensive and cost effective. However, due to the low cost of manufactured housing, they make only a minor contribution to the total economic damage reduction. This highlights equity issues and the importance of metrics other than total direct economic losses.

2.2.5. Elevating buildings above the Base Flood Elevation

FEMA maintains extension information on ways one can protect property from floods and storm surges (*45*, *41, 42, 43*, *44*, *52*). One method is to elevate buildings above the expected flooding level, or base flood elevation (BFE). Florida regulations require that when buildings below BFE are damaged by floods must be elevated or in some other way protected from future water damages when repaired (*53*). The highest foundation height described in HAZUS is pile foundation height (*54*).

The cost of elevating a building varies with building characteristics. On the basis of consultation with a Florida construction company, I estimate a lower bound cost for elevating a standard single family home as \$40K plus \$10K per foot raised up to nine feet. The approximate square foot costs of elevating a home in FEMA's retrofitting guide are similar; it costs \$80, \$83, and \$88/sq-foot to elevate a frame home without basement and \$88, \$91, and \$96/sq-foot to elevate masonry homes without basements by 2, 4, or 8 feet respectively (*52*).

2.2.6. Dams, dikes, and levees

Another adaptation technique to reduce storm surge involves large-scale civil engineering of the coast through coastal reinforcement, the raising of quaysides, or the building of dikes, levees, and seawalls. Recently, countries have initiated more elaborative engineering projects, such as the MOSE Project in Venice, Italy (*55*). In this thesis I consider installing a traditional coastal dike similar to Florida's Herbert Hoover Dike in a line protecting each group of census blocks. Optimal dike design depends on the characteristics of local bathymetry (*56*). The U.S. Army Corps of Engineers suggests building to a height that would protect against a 100 year event. Costs of these structures are uncertain because of continual upkeep and maintenance. Recently, $14.45 billion USD2010 was allocated to build the Hurricane and Storm Damage Risk Reduction System, 560km of 6m high levees in New Orleans (*57*), suggesting a cost of $4,000 per square meter. Note this structure would cause heightened flooding at the edges of the dike if it were simply terminated at the ends of our study region, similar to the Galveston seawall which did not protect the entire city from Hurricane Ike. The "Ike Dike", if built, would more fully protect Galveston from both storm surges overtopping and flooding at the edges of the dike (*58*).

Chapter 3. Hurricane Modification

Portions of the discussion in this Chapter are based on Klima, K.; Morgan, M.G.; Grossmann, I.; Emanuel, K. Does It Make Sense To Modify Tropical Cyclones? A Decision-Analytic Assessment. *Engineering Science and Technology*. 2011. 45:10 pp 4242–4248.

This chapter describes hurricane modification, the ability to weaken storms or change their paths. First I discuss the background leading to Project HURRMIT. Second I review some proposed techniques, several of which are not viable. Third, I describe and discuss limitations of a technique close to implementation, wind-wave pumps, which is used in the remainder of this thesis.

Despite continued study, there are many extremely serious concerns with the implementation and effectiveness of any modification technique such as unintended side-effects, our limited capacity to forecast the hurricane's track, and ethical or liability concerns. While further study may be appropriate in some cases, clearly it is premature at this stage to call for the full-scale development of an operational program of any technique.

3.1. Background

Hurricane modification, the ability to weaken storms or change their paths, has been seriously considered since the 1960s. The last of three large scale testing efforts, "Project Stormfury", began in 1962 (*30*). Although several modification ideas were discussed, field studies focused on silver iodide cloud seeding of the periphery of the eyewall. It was theorized that the latent heat release of droplet formation would cause outward migration of the eyewall, reducing the amount of inflowing mass and thus decreasing the intensity of the tropical cyclone. However, in the seeding experiments, natural eyewall replacement cycles and changes in tropical cyclone intensity were indistinguishable from the hypothesized hurricane changes. Due to lack of statistically significant results and because the technique was not viable, Project Stormfury was deemed unsuccessful and discontinued in 1983 (*30*).

Since then, understanding of physics and track prediction has improved. For instance, scientists now have improved insight about how sea surface temperature relates to TC intensity as in Figure 1.1 (*59*). Given this theory, satellite data, and other improved scientific understanding, some feel modification may be more plausible (*31*). In 2008, the U.S. Department of Homeland Security (DHS) and the American Meteorological Society held conferences on TC modification (*32, 33*), and in 2009 DHS funded an effort to identify and evaluate hurricane modification strategies through Project HURRMIT (*34*). Specifically, in response to the DHS Science and Technology Directorate, the jointly sponsored DHS and NOAA "Hurricane Modification Workshop" sought to:

- Identify viable hurricane modification hypothesis that warrant further study
- Understand hurricane physical processes including their initial development, mechanics, life cycle, instabilities and responses to outside dynamics and forces
- Understand DHS specific concerns regarding hurricane threats to life and property caused by wind, rain and storm surge
- Define potential DHS specific hurricane modification factors, requirements and risks (i.e. pre-development modification, track changes, intensity change)
- Address projected effort/cost/viability/time-lines for hurricane modification implementation
- Recommend a path forward

Even if DHS loses interest in this topic, other countries such as Japan and China may express interest in hurricane modification techniques if and when there is intensification in the strength of or increase in the frequency of tropical cyclones due to climate change, or changing demographics leads to an increase in coastal population.

3.2. Proposed Techniques

As understanding of hurricanes increased, dozens of new hurricane modification techniques have been proposed. Many suggested techniques (*60*, *61*, *62, 63*, *64*, *65*), including the Project Stormfury attempt at cloud seeding (*30*, *66, 67, 68*), will simply not work.

A minority of proposed techniques may be plausible after further testing. Project HURRMIT mainly focuses on cloud seeding techniques, including injection of black carbon aerosol (*69*, *70, 71*), using cloud condensation nuclei to alter rainfall (*72*, *73, 74*, *75*), and increasing dust during genesis (*76*, *77*, *78*, *79*, *80*). Project HURRMIT also examines reducing heat transfer from the ocean through wind-wave pumps, described in detail below and used in the remainder of this thesis. Outside of Project HURRMIT, other techniques may exist. There has been some experimental work in surfactants, liquids that when placed over the ocean surface would prevent evaporation from occurring (*81*). Also, tropical cyclones are highly sensitive to initial conditions, and by altering one of these conditions very early on in the storm's life, the tropical cyclone might be prevented before it begins (*82*). Finally, dynamical steering of hurricanes (*83*, *84*) may also be plausible.

I stress that even these ideas may not, after further testing, be actually plausible. Additionally, whether successful or not, any attempt to modify hurricanes introduces a variety of issues of liability that do not arise in the absence of human intervention (*35*). No longer could hurricanes be considered solely a force of Nature; these techniques allow some choice in who is affected, and someone could be liable for those damages. This liability could extend beyond immediate hurricane induced destruction to unforeseen consequences. Indeed, hurricanes transport a tremendous amount of heat, moisture, and energy (*85*, *86*), and any disruption to this process could prove problematic. It is possible that in years with fewer hurricanes passing over Florida, droughts would be more prevalent. Other unforeseen consequences could arise in the event of hurricane modification. This study will not address such possible side effects beyond any immediate changes in hurricane induced damages.

3.3. Wind-wave Pumps

Although much more study is needed before implementation, wind-wave pumps appear to be the closest to implementation. Accordingly I discuss this technology at greater length. The devices have been constructed (*87*), and tested in the open ocean (*88*). Here I investigate the likely effect of cooling the Atlantic Ocean in a box protecting Miami on TC intensity, which will be applied in a decision analysis framework in Chapter 5-6.

3.3.1. Description

Theory indicates that a TC is sustained through a "Carnot-like cycle", in which the storm draws heat from the ocean surface (*7*). The effect of a local change in sea surface temperature (SST), i.e. under the eyewall, is much larger than that of a global change (*59*, *89*). As hurricanes move into region of cooler SST on a large scale, the atmosphere around them is likewise cooler. Thus the change in potential intensity with large-scale SST gradients is far less than the change in potential intensity with a strictly local cooling of the SST that does not affect the large-scale atmospheric environment of the storm.

Wave-driven pumps have been demonstrated to be capable of bringing deep, cooler ocean water to the surface (*88*), which will cause a local decrease in SST. Each pump has a long tube connecting a surface buoy to a valve located in the colder water below the mixed layer. The valve opens in a wave trough and closes at the next wave peak, impelling cold water to the surface. The technique pumps more when waves are bigger until buoyancy limits are reached. Observations show the cold water mixes with the surface water, creating a SST decrease (*88*) of the same magnitude as natural TC induced upwelling (*90*); since pumps draw water from a different depth, the cooling should be additive to the cooling affected by the TC itself.

Pumps could be deployed for different durations and over different suitable regions. While difficulties in pump implementation exist, the purpose of this thesis is not to resolve the engineering and logistical problems, but rather to assume that the pumps can be made to work as hypothesize and estimate the associated benefits and costs.

3.3.2. Pump Quantity Needed to Affect SST Change

Following work by Philip Kithil and Isaac Ginis (*87*), I can characterize the number of pumps necessary to employ this technique. Pumping rate is limited by amount of buoyancy; regardless of wave height, the device can only lift the amount the buoy supports. The nominal pumping rate (P_N m^3/s) is given by

$$P_N = \frac{\pi R^2 H_S}{T_P}$$

where H_S is the significant wave height sustainable by the buoy (typically 3m), T_P is the wave period (10sec), and R is the diameter of the pipe (here assumed as 3m). If wave height exceeds 8m the buoy will submerge but continue to pump at this rate.

Given pumping rate, average cooling can be calculated as a function of the water volume being cooled and the pumping rate. Salinity stratification (such as in the Gulf of Mexico and mid-

Atlantic) prevents thermals from mixing down below 10m. However, hurricane winds efficiently mix the upper layers of the ocean, assumed to be the same as the mixed layer depth. Hence, recalling P_N is given by the equation above, the SST degree change per day is given as

$$\frac{\theta}{t} = \frac{\varepsilon P_N \Delta T}{V} = \frac{\varepsilon P_N \Delta T}{hL^2}$$

where *V* is the volume of water being cooled (m^3), •*T* is the temperature difference between the surface buoy and the valve (a function of pipe length, •K), and   is the efficiency (also a function of pipe length). Here I assume the volume of water to be cooled has a horizontal measure of *L*, the distance between pipes (assumed 333m), and a depth of *h,* the mixed layer depth (30m, ranging from 20m-40m to the east of Florida). Using actual temperature profiles for a location east of Florida (*91,* MITGCM 2^0 spinup run, *92*) and Kithil's test information on pipe inefficiency as a function of pipe length (*87*), I can calculate •SST/day. On the basis of their internal work, I take the optimal pump tube to be 3m in diameter and 300m long (*87*).

Average cooling can be calculated as a function of the water volume being cooled and the pumping rate. In the waters southeast of Florida, a pipe of length 300m reaches below the mixed layer to water approximately 10^oC cooler than the surface (*92*). Published test results indicate that for the a pipe of diameter 1m and length of 300m, after cold water is brought from the base of the pipe to the surface in approximately 3 hours (roughly 0.5 m^3/s) (*87*). After exiting the pipe at the surface, the water forms a cold plume that sinks to the bottom of the mixed layer (30m) in 6-10 minutes, where the temperature has greatly decreased due to entrained water. Thermals (discrete water volumes) mix more efficiently than plumes. Background current velocity (u) and gravity waves mix the water horizontally (timescale of 30-60 minutes for 100m, much faster than turbulent mixing). Theoretical results indicate that 100-200min are needed for the water to move 333m by gravity waves. I assume that hurricane-speed winds perform vertical mixing with the result that the colder water is fully mixed throughout the mixed layer in approximately 4.5 hours.

Assume that pumps are placed in a fixed grid with 333m spacing. Given the assumption of uniform mixing throughout the mixed layer in about 4.5 hours (*87*), this pump configuration would result in a swift 0.5^{0}C reduction in SST per day in the east Atlantic, but the cooling would level out at 1.0-1.5^{0}C (*88*). Thus if pumps were deployed in front of a storm, they might achieve a 0.5-1.0^{0}C reduction in SST, while if pumps were deployed seasonally, they might cause a 1.0-1.5^{0}C reduction in SST. Pumps would be much less effective in the comparatively warmer Gulf of Mexico. Note, the leading part of a TC's circulation induces about this much cooling in advance of the center of a hurricane, much of which also occurs through an upwelling and mixing process of the cooler subsurface waters (*90*). However, the processes are drawing cooler water from different depths; TCs have been shown to deepen the mixed layer to ~150m via surface wind/waves (*2*), whereas the pump technique uses even colder water from a depth of 300m. Thus while natural upwelling will decrease surface temperature, the pumps access even colder water and will further decrease surface temperature. Furthermore, the model used is a coupled model and fully accounts for the natural cooling effect of hurricanes (as well as the pre-storm imposed cooling).

3.3.3. Pump Cost

I assume that pumps would be deployed by a combination of barges and tugboats. Estimates indicate a single wind-wave pump costs $2000-3500 to create and deploy (via a system of barges and tugs) with a 25% maintenance cost per year (*87*). Given this cost estimate, as well as estimates of track uncertainty from the National Hurricane Center (NHC), I can estimate costs to deploy appropriate lattices as discussed in subsequent chapters.

3.3.4. Effect on TCs

To investigate the effect of the pumps on hurricane characteristic and return periods, I considered how storm characteristics and return periods are a function of SST reductions described in Section 3.3.2. For this study, I provided conditions (area of coverage, SST reductions, etc) to Kerry Emanuel and Ning Lin (Massachusetts Institute of Technology, MIT), who then provided the data from the downscaling experiment.

Function of Storm Characteristics: I derived theoretical functions of wind speed change as a function SST. This derivation used data from a hurricane downscaling technique driven by NCEP/NCAR reanalysis data from 1980-2005 provided by Kerry Emanuel (*93, 94*). Emanuel generated a set of 500 control events that had been selected from a much larger sample to pass through a predefined box (25-27^{o}N, 78-80^{o}W). This box was chosen box for the purpose of this study. Kerry did this analysis because he wanted to explore how cooler SSTs would affect TCs, and how this would affect damages. He then assumed a uniform SST decrease in that box, so as to "protect Miami". In the downscaling technique, this SST decrease only affects storm intensities, not tracks. Figure 3.2 shows that when a sample hurricane with a large wind speed in the control run is subjected to a uniform 1^{o}C SST decrease, it experiences a decrease in wind speed of almost 20% from the control run. Figure 3.2 gives the average maximum 1 minute sustained wind speed at 10m height (over a 500 trial event set) as a function of return period and uniform SST decrease for all points passing through the box (25-27^{o}N, 78-80^{o}W), both for the control and the modified SST experiments. I found that a change in SST decrease only affects wind speed (and thus radius to maximum winds), not translational speed or eye bearing.

Using model data, I regressed the fractional wind speed reduction against the change in SST (ΔSST, ranging from -0.5^{o}C to -2.0^{o}C), maximum 1 minute sustained wind speed at 10m height

(V_{MAX}), and time spent in the altered SST area (t, ranging from 1.5-22 hours), yielding (with R^2 of 0.89)

$$
\begin{aligned}
\Delta V_{FRACTIONAL} = & -7.02 + 0.052\Delta SST - 0.0031t + 0.00022t^2 + 0.033V_{MAX} \\
& - 0.000041V_{MAX}^2 + 4.3\ln(V_{MAX}) - 0.74(\ln(V_{MAX}))^2 \\
& - (0.014t + 0.00093V_{MAX})\Delta SST
\end{aligned}
$$

The equation was fit to nonzero ΔSST and nonzero t. I find that for a Category 3 TC in an area of 1ºC SST reduction for t=1.5 hours, wind speed will decrease by 6.7-7.3%. For a longer time, such as t=2 hours, wind speed would decrease by 14.7-15.4%. For a slowly translating TC where t=7 hours or more, wind speeds could be decreased enough to result in the collapse of the storm. Note the alacrity of TC response would suggest that if the TC passed through the cooled area and then reentered the normal SST area, the TC could strengthen before making landfall. Hence, pumps must be applied near the coast in areas with steep coastal bathymetry (e.g. the east coast of Florida).

This equation was applied at each time step to the family of unmodified hurricanes to create a family of wind-wave pump modified hurricanes.

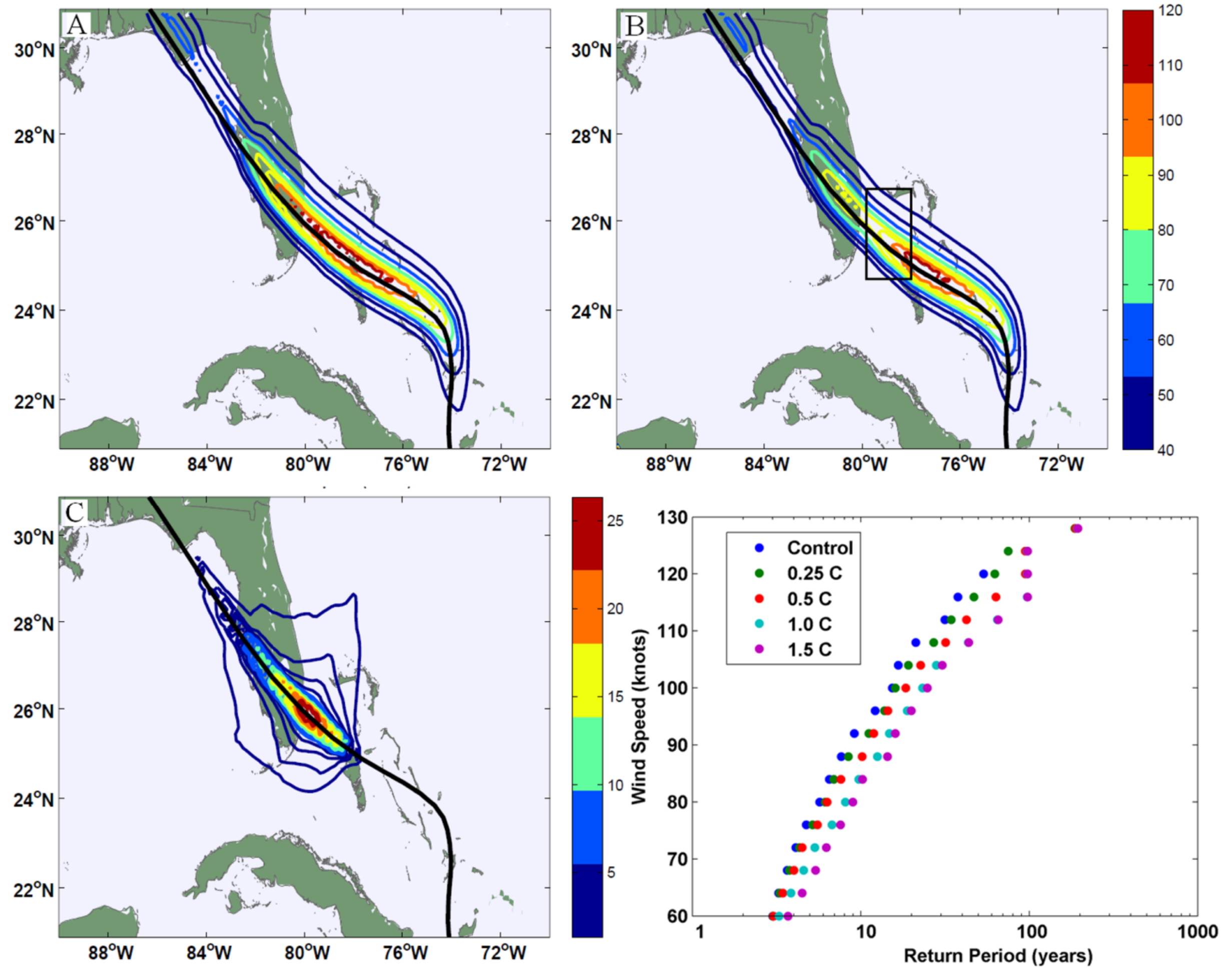


Figure 3.2. Results for the 500 hurricane track event set through the area east of Florida. Figure A is the maximum wind speed (knots) of a sample 100-year hurricane (contour bar to far right). Figure B is the maximum wind speed (knots) of a sample 100-year hurricane with a uniform SST decrease of 1°C in the box (25-27°N, 78-80°W). Figure C is the difference between Figure A and Figure B. Figure D is the maximum 1 minute sustained wind speed at 10m height as a function of return period and uniform SST decrease in the box (25-27°N, 78-80°W). Figures constructed by Kerry Emanuel.

Function of Return Period: To characterize the effect of SST changes on return period, I needed more storms. Kerry Emanuel and Ning Lin (MIT) adapted a risk assessment method previously applied to study storm surge risk for New York City (*93*, *95*, *96*). They simulated large numbers of synthetic TCs for the study area under different SST conditions, and conducted storm surge simulations using the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model (*97*) with a grid for Miami basin for each storm. Return level curves (or, equivalently, exceedance probability curves) could then be estimated for the wind and surge as functions of return period and SST reduction for local regions of interest.

3.3.5. Uncertainties, optimal configurations, deployment techniques, and other issues

I recognize that difficulties in pump implementation exist. Here I include a brief discussion on some issues that will affect the cost and effectiveness of sea surface temperature reduction via wind-wave pumps.

First, although the price of the pump apparatus itself will likely vary little, deployment costs may vary greatly. If redundancy in deployment is required (e.g. multiple boats are deployed in case one breaks down), the price will increase. Because it is not yet possible to anticipate which hurricanes will intensify to the threshold at which modification would be most cost-effective, the system would need to be implemented more often than would be desirable in a world with perfect foresight. Similarly, it is not yet possible to forecast accurately which strong hurricanes will naturally weaken to below the intensity threshold of interest. Both cases, however, would lead to employing the modification technique and incurring the associated costs beyond what is implied in the historical landfall records. If forecasting ability improved in the future, the deployment area would decrease and therefore the deployment price would decrease.

Second, in addition to deployment costs, the engineering problem of sustaining pump location must be solved. Along the east coast of Florida is the Gulf Stream, which will carry free floating pumps northward. I have not investigated the feasibility of using anchors. Also, if pumps are placed in front of a storm (as opposed to be placed seasonally and widely over the entire Florida coast), the Gulf stream will rather quickly replenish the initial target area with warm water it carries into the area from the south; over the course of 24 hours, the cooled waters will have moved beyond the target grid and will have been replaced with waters of about the original SST. This might be accounted for by deploying the pumps upstream. Finally, although a 300m pipe will reach to sufficiently cold water in most areas, if the pumps are deployed in the Gulf current itself, the temperature differential between the surface and 300m depth may be lower, perhaps only 8^{o}C (*91*).

Third, assume that the correct number of pumps is deployed in the correct places. For deployment before an individual storm, the speed of deployment (perhaps decreased due to harsher pre-hurricane conditions one day previous to the storm) and spin-up time for the pumps contribute uncertainty to the reduction of sea surface temperature achieved when the storm arrives. To some extent these factors will offset each other; with high waves, implementation speed would be expected to increase but spinup time would be expected to decrease. However, if the seas are very bad, or if multiple hurricanes come in succession, the wind-wave pumps would be less effective.

Fourth, the proposed network of pumps would pose significant navigational hazards and would be subject to damage from encounters with vessels, raising the overall cost. For the seasonal scenario, the pumps would have a negative impact on marine commerce as vessels are either rerouted or not employed in an effort to avoid the obstacles. For the per event scenario, the fact that the pumps would be operating during the time when many vessels are likely to be transiting the area, either to find safe harbor or passage exacerbates the problem. Rescue or other emergency response missions could also be compromised.

Fifth, the pumps could have adverse environmental impacts if left in place for a long time. For example, coral reefs are highly sensitive to water temperature and might be adversely affected by the colder water. Additionally, if in the long term pumps could decrease hurricane activity, this might decrease rainfall in the protected area and/or reduce pole-ward heat transport (*85, 86*).

Sixth, public perceptions can also influence pump effectiveness. If the public learns that there is a way to reduce hurricanes, they may demand it even though it will not be cost effective. For instance, the Gulf of Mexico is relatively shallow, and even though the mixed layer is somewhat thinner and the lapse rate of temperature is greater, the pumps cannot access deep cold water and pumps would work less effectively there. However, it is at least possible that Gulf of Mexico coastal residents might demand that pumps be deployed if they have been successfully deployed elsewhere and another Katrina-like disaster appeared imminent.

Seventh, political /budgetary constraints exist. Let us suppose a 100 year hurricane event is predicted to make landfall on the Florida coast. The massive outlay of money may be enough to prevent policy makers from buying the "insurance" provided by the wind-wave pumps, or the current political climate may prevent implementation. Additionally, the target area not only spans international waters, but also sovereign land and adjacent waters of the Bahamas. It may not be possible to obtain all permissions necessary.

Clearly if policy makers seek to implement a wind-wave pump technique, these and other difficulties must be addressed. However, the purpose of this thesis is not to solve the remaining engineering/ implementation/ political problems. Rather I assume that wind-wave pumps work as hypothesize and calculate the technique's benefits and costs.

Chapter 4. Hazards U.S. Multi-Hazard, Version 1.3

Portions of the discussion in this Chapter are based on Klima, K.; Morgan, M.G.; Grossmann, I.; Emanuel, K. Does It Make Sense To Modify Tropical Cyclones? A Decision-Analytic Assessment. *Engineering Science and Technology*. 2011. 45:10 pp 4242–4248.

To estimate direct economic losses from TCs, I used FEMA's publically available Hazards U.S. Multi-Hazard, Version 1.3 (HAZUS-MH MR3) model with their default input data (*98*). HAZUS uses general building stock data from the 2000 U.S. Census Bureau, commercial data by Dun and Bradstreet (2006) *(99)*, and RSMeans Residential Cost Data (2006) for calculations at census tract level (*100*).

Below I describe the HAZUS sub-models used in Chapter 5 and Chapter 6. In Section 4.1, I describe the wind damage sub-models. In Section 4.2, I describe the storm surge damage sub-models. In Section 4.3, I discuss limitations of HAZUS.

4.1. Wind Model

In Chapter 5 I use the HAZUS hurricane model to calculate wind damages. The HAZUS hurricane model uses NHC data as its input. The program modifies NHC data by decreasing wind values to roughly 90% of the given values. This is done because the winds in HURDAT are the maximum surface wind speed (peak 1-minute wind at the standard meteorological observation height of 10 m over unobstructed exposure) associated with the TC every six hours. These peak 1-minute winds in hurricanes diminish about 10-15% within a short distance, roughly a kilometer of the coastline, because of the increased frictional roughness length (*101*).

Chapter 6 used the H-Wind feature in HAZUS-MH MR3 Hurricane Model (*49*) to aggregate losses from wind damage, including total loss, building loss, contents loss, inventory loss, relocation costs, income loss, rental income loss, wage loss, and direct output employment loss.

Although HAZUS has been independently verified against insurance values (*98*), I performed my own validation of predicted wind damage versus historical damage information for Hurricane Wilma. According to the NHC, Hurricane Wilma had a historical recorded damage of $20.6 billion USD2005, and 23 direct fatalities (*22*). Figure 4.3 gives the house-by-house damages reported by policemen and firemen to the Miami-Dade County Office of Emergency Management. Additionally, data exist (from NHC, H*Wind, ARA) that describe Wilma's evolution of position, wind speeds, and central pressures. Note that although Wilma moved from southwest to northeast across South Florida, inducing little or no storm surge and modest rainfall in Miami-Dade and Broward Counties, several buildings in Figure 4.3 are reported to have sustained water damage.

Figure 4.4 shows the HAZUS total building loss (all types, USD2002) for the Historical Wilma scenario. Although not strictly comparable to the building damages reported by firemen and policemen of Figure 4.3, HAZUS reports higher building damage in areas similar to those officially reported. Differences are likely due to storm surge/flood damages (data not reported in a HAZUS wind analysis), and the difference in reporting methods.

Damage values were summed over the study area. I find that in the historical Wilma scenario total direct economic loss ($18.902 billion USD2002) are less than the actual recorded total damages ($29.1 billion USD2005). This occurs because my study lacks both storm surge and flood damages and indirect economic losses. No historical recorded data were available to compare to the HAZUS predicted values of the number of buildings damaged (460,000), the

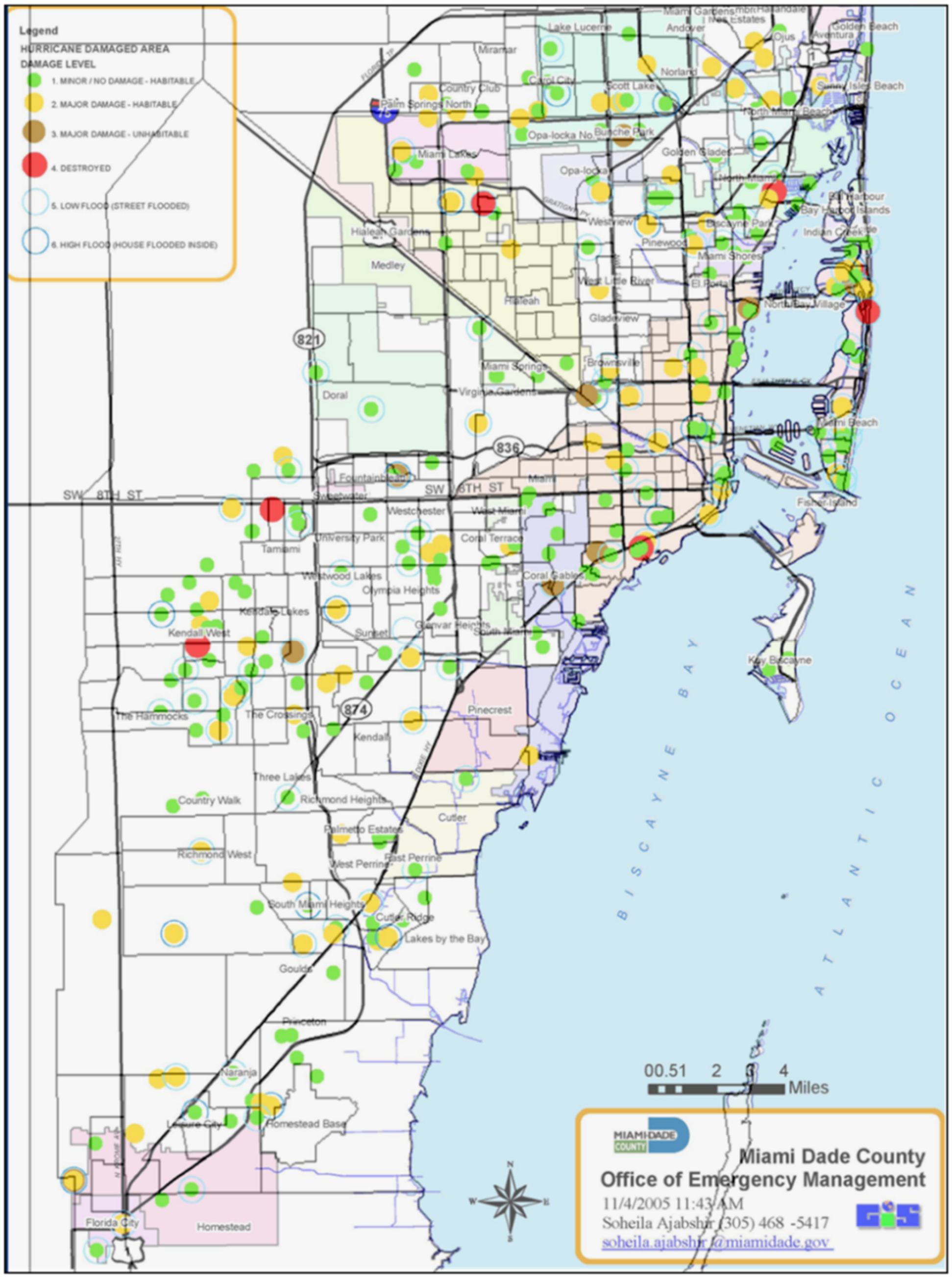


Figure 4.3. Damaged area after Hurricane Wilma (2005), courtesy of the Miami-Dade County Office of Emergency Management. Damage values are reported by policemen or firemen. Green dots indicate minor damage, yellow dots indicate major damage, red dots indicate destruction, light blue circle indicates minor water damage, dark blue circle indicates major water damage. Census blocks are overlaid.

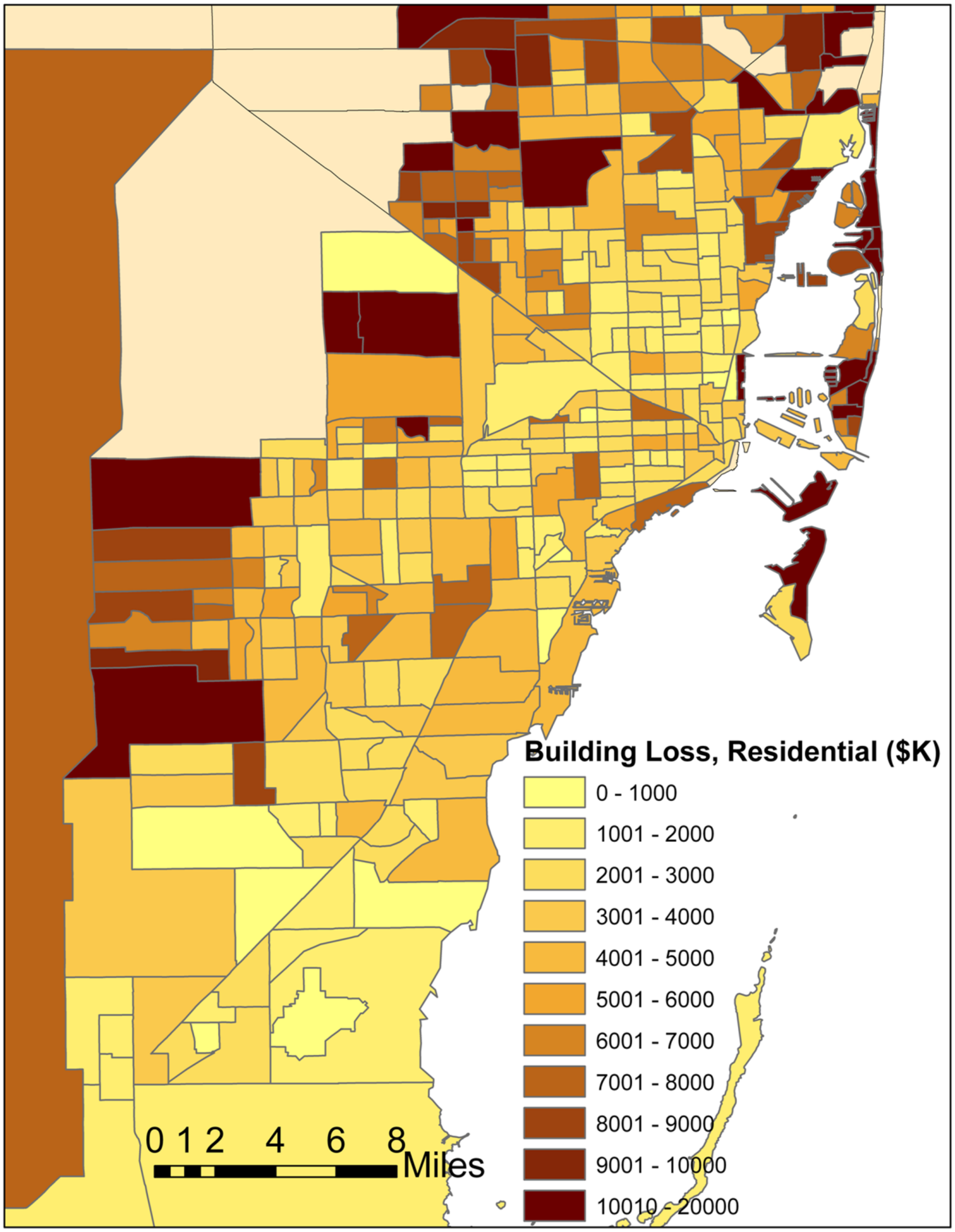


Figure 4.4. HAZUS Building Loss of all types (wood, concrete, steel, etc) from Hurricane Wilma ($K). This is partially comparable to Figure 4.3.

number of displaced households (45,000), and the number of short-term shelters needed (12,000). Although specific houses damaged were not accurately predicted by HAZUS, the model performed well at predicting average damages in each census tract.

4.2. Storm Surge Model

The analysis reported in Chapter 5 did not use a storm surge model. In Chapter 6 I used FEMA's Coastal Standard Operating Procedure (*102*) to subtract the appropriate digital elevation model (DEM) in the North American Datum of 1983 (NAD83) (*103*) and convert these data to a user defined flood grid. I then used the HAZUS-MH MR3 flood model (*54*) to aggregate total losses for storm surge damages for each return period for all scenarios.

Table 4.2. Raster download information for Miami-Dade County area (*104*). Note, values are given with the correct number of significant figures.

Item	Value
Number of columns	2747
Number of rows	3101
Resolution in x direction	0.00028 Degree = 1 arc-second ~ 30m/pixel
Resolution in y direction	0.00028 Degree = 1 arc-second ~ 30m/pixel
Coordinate system ID Native, WGS84	4269
Top edge Native, WGS84	26.0 Degree
Bottom edge Native, WGS84	25.1 Degree
Left edge Native, WGS84	-80.9 Degree

Initial calculations indicated that storm surge damages values do not monotonically increase with storm surge height. This did not appear logical since the damage functions were monotonically increasing with storm surge height and the total building counts were the same in each scenario. Thus I investigated the source of the nonlinearity within HAZUS.

First, I examined the number of buildings damaged for different storm surge values (2.0 m, 2.1m) in two census blocks (120860041012008, 120860041012012), see Figure 4.5. I found that the number of buildings damaged is not monotonically increasing with the surge level. Specifically, I see that in the 120860041012008 case, compared to the 2.1-m storm surge level, the 2.0-m storm surge level has the same or more residential buildings in each cumulative Percent Damage Bin. Census block 120860041012012 shows an equal amount damaged in each Percent Damage Bin except the 0 bin. Note the 0 bin should add up to the total number of residential buildings in each census block. Only the case of 2.0-m surge in 120860041012008 actually does this.

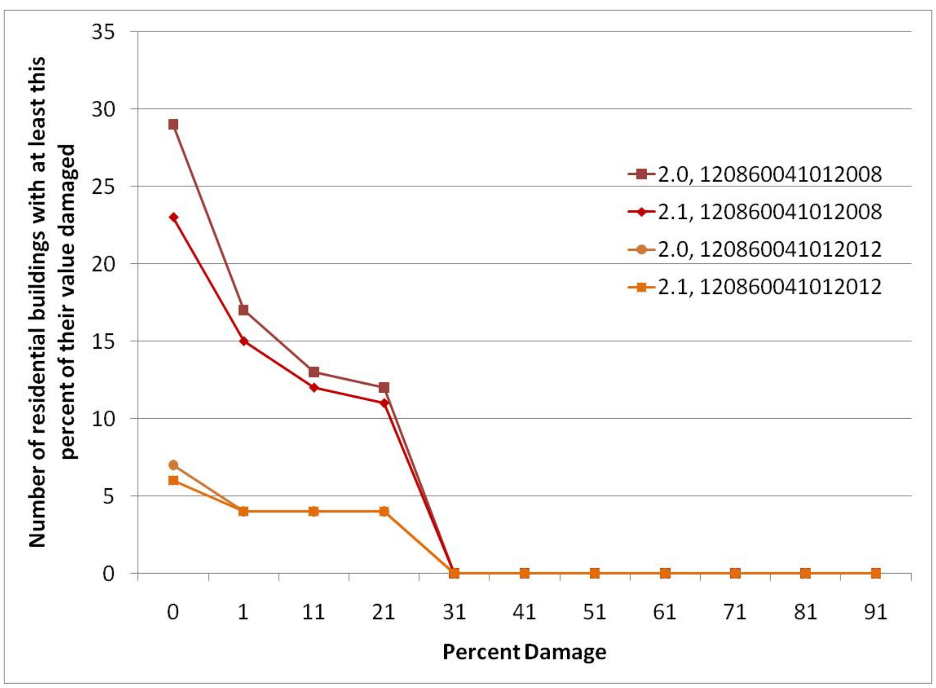


Figure 4.5. Number of residential buildings with at least the percent of their value damaged for different storm surge values (2.0 m, 2.1m) in two census blocks (-2008, -2012).

Second, I hypothesized that FEMA's Coastal Standard Operating Procedure (*102*) creates storm surge values incorrectly, such that the 2.1m storm surge case actually has lower storm surges heights than the 2.0m height. I examined the five regions, shown in Figure 4.6 and Figure 4.7. Census blocks with higher damage values in the 2.0-m surge rather than the 2.1-m surge are highlighted in blue. In some cases the 2.1m case has nonzero storm surge height, while the 2.0-m case has 0-m height.

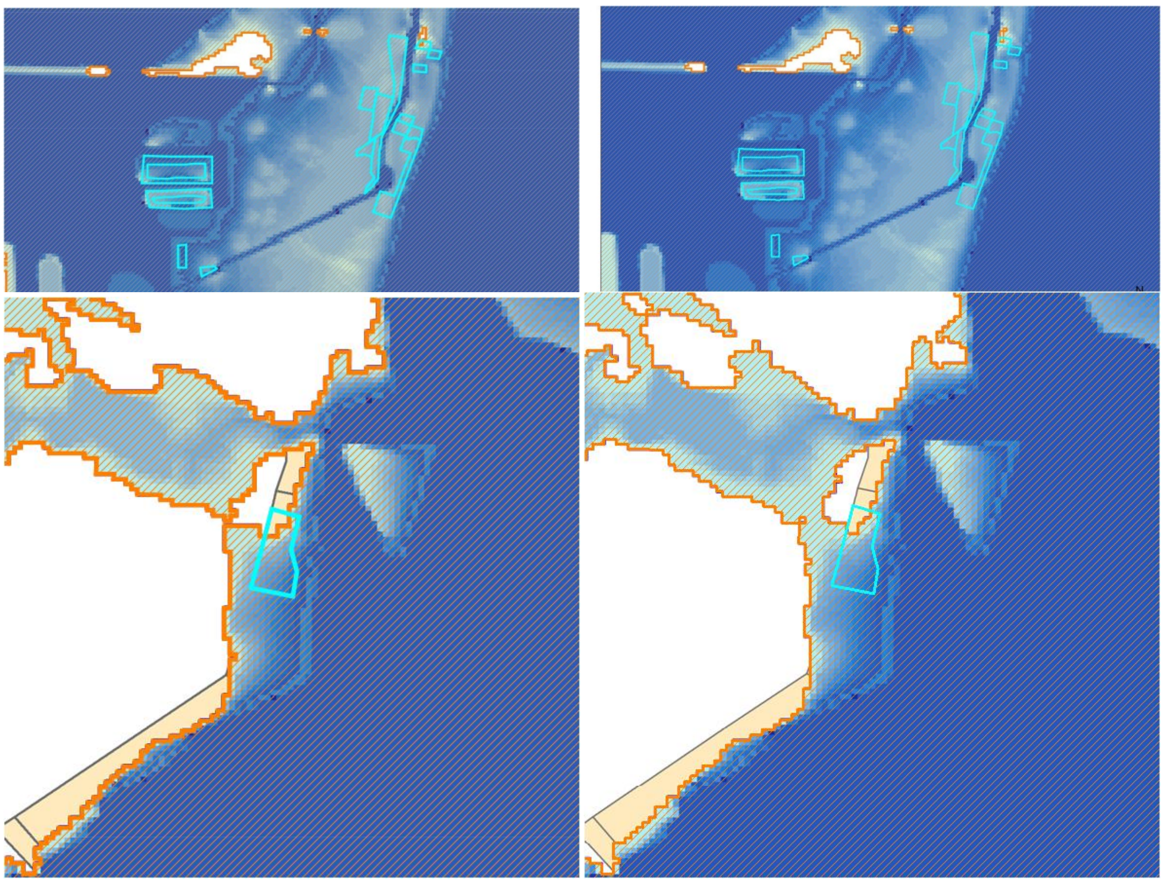


Figure 4.6. Storm surge grids for a Group 1 (top) and Group 2 (bottom). The left side is the storm surge grid for the 2.0-m depth (depth scale = 9.22858 to 2.1509 E-005), the right side for the 2.1-m depth (depth scale = 9.55666 to 3.44174 E-005). Census blocks with the 2.0m run damages higher than the 2.1m run damages are highlighted in blue.

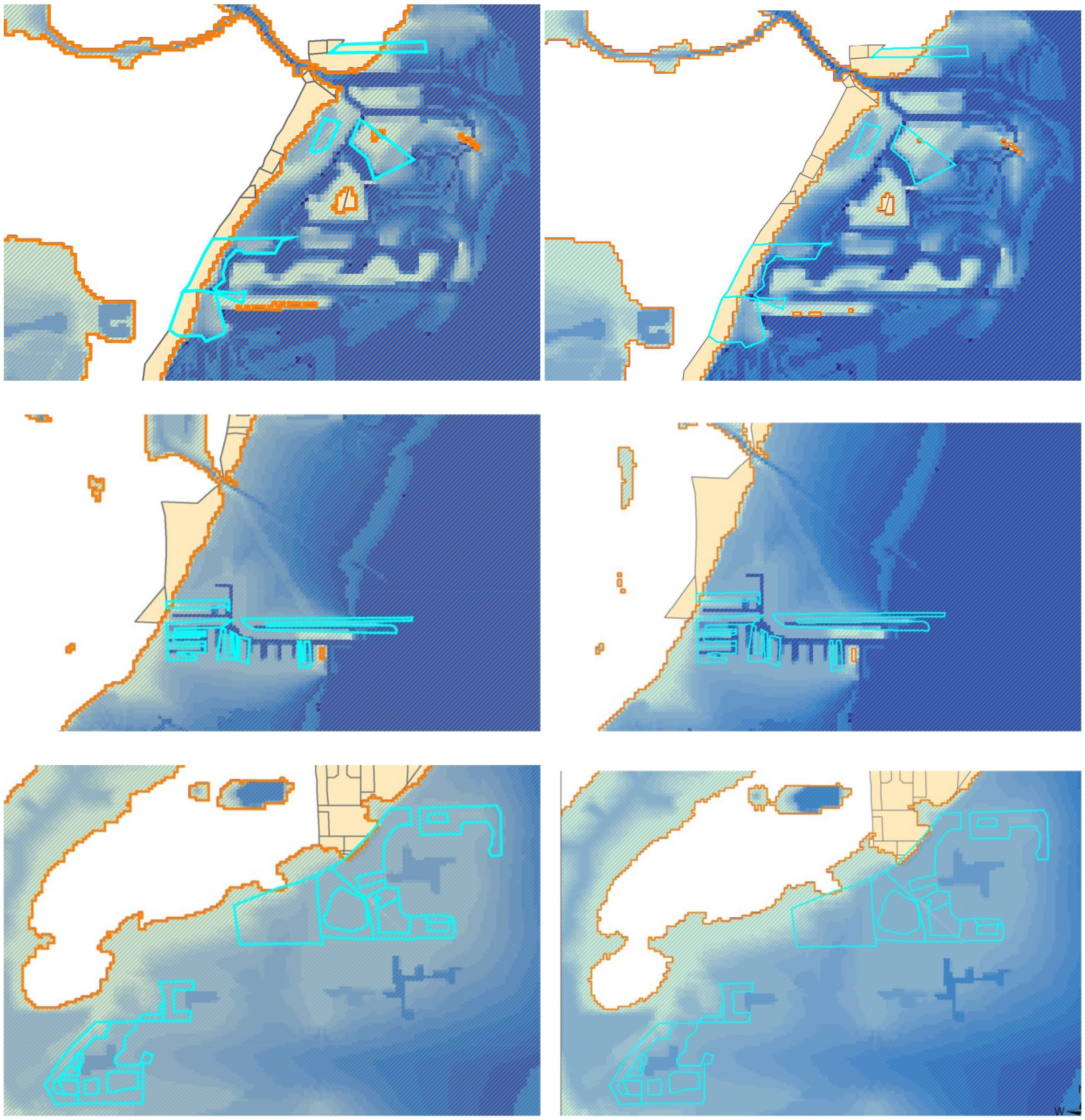
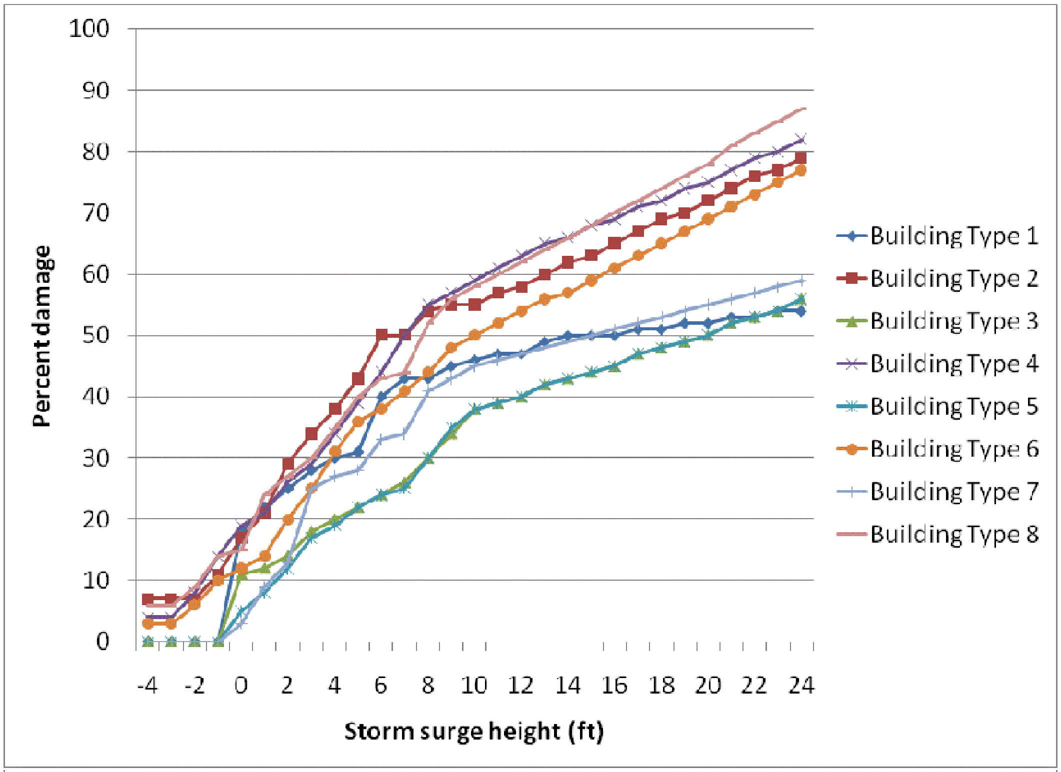


Figure 4.7. Storm surge grids for Group 3 (top), Group 4 (middle), and Group 5 (bottom). The left side is the storm surge grid for the 2.0-m depth (depth scale = 9.22858 to 2.1509 E-005), the right side for the 2.1-m depth (depth scale = 9.55666 to 3.44174 E-005). Census blocks with the 2.0m run damages higher than the 2.1-m run damages are highlighted in blue.

Third, I hypothesized that boundary problems might cause the problem. When running a user defined flood map, HAZUS defines some areas as "Coastal A" and some as "Coastal V". Both areas are prone to flooding, but Coastal A areas are more landward than Coastal V areas (*105*). Figure 4.8 gives the percent damage as a function of flood height for Coastal A Zone and Coastal V zone. There is not a smooth correlation between these values (i.e. Coastal A is not always larger than Coastal V or vice versa), so when switching between different area definitions, the damages may not be monotonically increasing with storm surge height. This only matters when a larger extent of land is covered by flood, since the Coastal A and Coastal V areas become defined differently. For a storm surge height of 2 m over the entire census block, this meshing problem can account for a 3-4% error in the residential damage values calculated. The uncertainty percentage increases nonlinearly with increasing storm surge. Values presented in this thesis are smoothed deal partially address this nonlinearity problem.



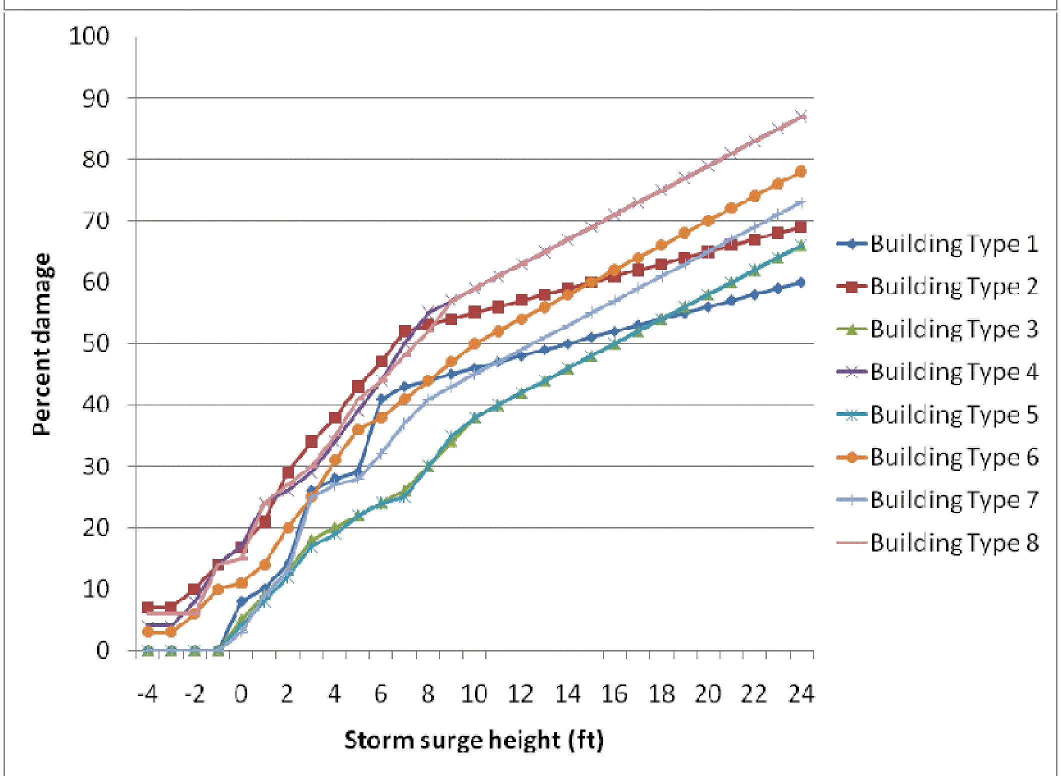


Figure 4.8. Percent damage as a function of storm surge height for 10 building types for Coastal A Zone (top) and Coastal V Zone (bottom).

4.3. Limitations

HAZUS has several limitations in addition to the computational problem listed above.

First, HAZUS does not use time series data. Logic dictates that while a single short burst of wind or high water may harm a structure, sustained force can wear it down. The HAZUS damage functions are not clear as to the length of exposure to forcing, and certainly do not have damages as a function of time.

Second, while the HAZUS hurricane model takes into account translational velocity of the storm, the flood model is only capable of determining damages for standing water. Storm surges have a significant added force due to the water moving landward then seaward; do to the lack of time series data, this extra forcing is not accounted for and thus storm surge estimates may be considered underestimates.

Third, work here is necessarily cautious since I examine wind and storm surge damages separately. The combination of wind and storm surge damage is nonlinear and poorly understood (*36*). In some cases, the damages are less than the sum of the parts; for instance the same window might be broken from either wind or storm surge debris. At other times the total damage is larger than the sum of the parts; a foundation weakened by storm surge might fail when the wind blows on the walls, or the surge may be able to penetrate a house once it has some structural damage from wind. Additionally, since storm surge damages dominate for coastal locations, an attempt to solely protect against wind damages may be overwhelmed by the large storm surge losses. These issues are discussed at greater length in Chapter 6.

Chapter 5. Decision Analysis of 27 Andrew-like hurricanes

Portions of the discussion in this Chapter are based on Klima, K.; Morgan, M.G.; Grossmann, I.; Emanuel, K. Does It Make Sense To Modify Tropical Cyclones? A Decision-Analytic Assessment. *Engineering Science and Technology*. 2011. 45:10 pp 4242–4248.

Suppose that a hurricane modification strategy could be found that, within some bounds of uncertainty, is likely to yield a reduction in the strength or a change in the path of a TC. How sure would one need to be about the intended and unintended consequences and distributional effects before it would make sense to proceed? In 1972, Howard et al. explored this question (*35*) by considering a range of average property damages with a 5% upper bound of approximately $250-million 1969 USD. Damage values were a function of control characteristics and different probabilities of seeding the eyewall to reduce peak winds. Howard et al. concluded that hurricane seeding would impose a "great responsibility" on policy makers, and would be a "complex decision" with "uncertain consequences"; while land-falling TCs are random natural events, modified hurricanes raise issues of responsibility and liability.

In this chapter, I compare the damages and benefits from hardening structures and from hurricane modification for a hypothetical strong storm that makes landfall in Miami-Dade County, Florida. Unlike previous work (*35*), I use census data and a damage model to consider a specific technique. First, I define a control scenario using census data on property value at risk and prior distributions on changing storm behavior calculated from historical data. Second, I estimate changes resulting from the HURRMIT-reviewed hurricane modification technique of "wind-wave pumps" and from standard hardening techniques including shuttering windows and doors. In this analysis I do not assess the actual performance of arrays of wind-wave pumps. Rather, I examine the more fundamental question: if they could be made to work as advertised, could they become the basis for a cost effective modification strategy? Then I calculate the net benefits as a function of wind damages and technique costs. Finally, I calculate break-even costs given the possibility that modification might be unreliably deployed.

5.1. Method

I assume that a hypothetical storm similar to Hurricane Andrew (1992) is forecasted to make landfall in Miami-Dade County in 48 hours. Given perfect knowledge of the storm up to that moment, I first characterize future evolution of the storm using discretized probability distributions for TC characteristics. For most of the Andrew-like storms examined in this chapter, storm surge is a small component of the total damages. This occurs due to coastal bathymetry features such as the narrow continental shelf and because most of the populated area of southeast Florida lies at an elevation above that affected by storm surges (topography given in Figure 5.9). While for the low probability scenarios, those making landfall just south of Miami, FL, the storm surge damages rise to 80% of wind damages, the total contribution to expected damage across the full set of storms is very small. Thus here I focus on wind damages only.

Given the set of ways the hurricane could evolve, I calculate a range of possible wind damages with a three-step model. First I calculate a wind field at census block level for each of the possible hurricane tracks with FEMA's HAZUS-MH MR3 (*98*, *106*) hurricane model. Next, I use the wind field and HAZUS empirical wind damage functions to calculate wind damages for each building type. I then use wind damages and HAZUS census data to aggregate damages (capital loss, business interruption, and similar metrics) in the areas of interest. To calculate the effects of hardening structures, I alter empirical wind damage functions. To calculate the effects of hurricane modification, I alter hurricane tracks as described below. While I have focused on a particular hurricane modification technique, my methodology could be applied to a range of impact categories and hardening options.

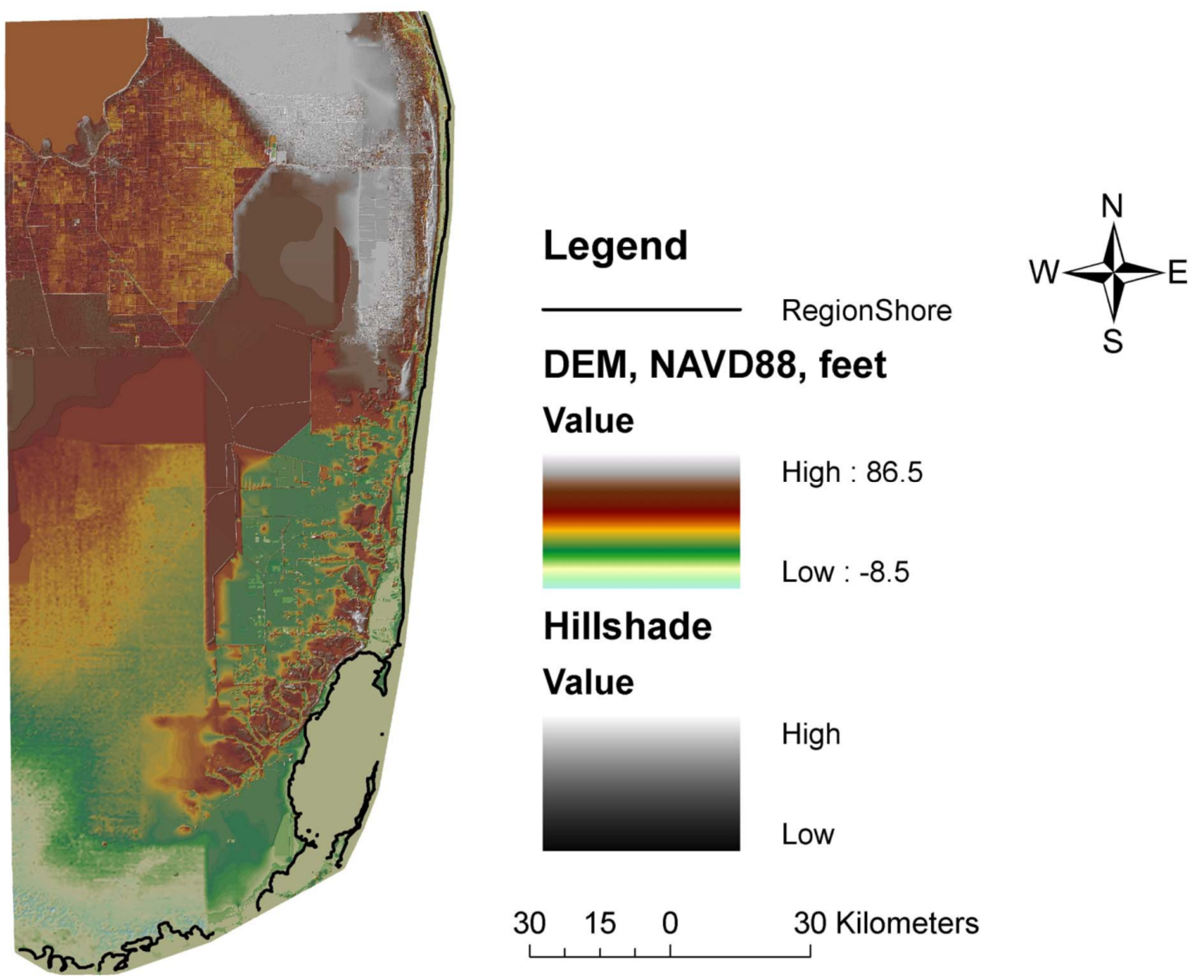


Figure 5.9. The Digital Elevation Model (DEM) of Miami-Dade, Broward, and Palm Beach County constructed from HAZUS and National Flood maps. Note that the land rises relatively steeply from the shore. This area contains 1.7 million buildings worth $376 USD 2006. Residential buildings compose 70.9% of total exposure value.

5.1.1. Creation of the family of unmodified TCs

I characterized TC variability by developing discretized (three-element) probability distributions for changes in wind speed, eye translational speed, and eye bearing of a TC approaching the east coast of Florida using Atlantic TC Geographic Information Systems (GIS) data from the HURDAT database of the NOAA Coastal Services Center for the period 1953-2004, when aircraft reconnaissance was regular (*107*, *108*). I calculated separate values for TCs moving over water, making landfall, and moving across land. I identified all hurricanes that crossed the line connecting (30ºN,70ºW) to (25ºN,75ºW) and made landfall on the U.S. mainland. I removed storms that were likely affected by island interaction. Probabilistic changes in eye bearing (degrees) and eye translational speed (fractional) were then calculated over a 12-hour period. Given large differences in fractional wind speed changes north and south of roughly 27ºN, I separately examined TCs south of 27ºN (43 data points over 15 TCs) and in the latitude belt 27º-29ºN (111 data points over 21 TCs). Values are given in Table 5.3. Next, I characterized TC evolution at landfall (34 TCs) assuming wind speed, eye bearing, and eye translational speed change linearly between the data available before and after landfall. Values are given in Table 5.4. Finally, I characterized TC evolution over the first 12 hours on land (20 TCs). Values are given in Table 5.5.

Table 5.3. TC priors over water computed over a period of 12 hours. All values are calculated in an area east of Florida. Most metrics sample from 21 TCs for a total of 111 data points. The metric "Wind Speed Change South of 27N" samples from 15 TCs for a total of 43 data points.

Metric	Event (in 12 hours)	P(event)	Average Change	Standard Deviation
Eye Bearing Change (Deg)	Decreases by 5º or more	0.22	-14.32	12.40
	Changes by 5º or less	0.24	0.72	2.62
	Increases by 5º or more	0.54	21.40	14.18
Eye Translational Speed Change (Fractional)	Decreases by 5% or more	0.39	-0.31	0.18
	Changes by 5% or less	0.22	0.00	0.02
	Increases by 5% or more	0.39	0.30	0.25
Wind Speed Change south of 27ºN (Fractional)	Decreases by 5% or more	0.27	-0.10	0.02
	Changes by 5% or less	0.40	0.01	0.02
	Increases by 5% or more	0.33	0.10	0.05
Wind Speed Change 27ºN-29ºN (Fractional)	Decreases by 5% or more	0.22	-0.10	0.06
	Changes by 5% or less	0.42	0.00	0.03
	Increases by 5% or more	0.36	0.12	0.05

Table 5.4. TC priors over land calculated using two points before and after landfall (over 12 hours). All metrics sample from 34 TCs for a total of 34 data points.

Metric	Event (in 12 hours)	P(event)	Average Change	Standard Deviation
Eye Bearing Change (Deg)	Decreases by 5º or more	0.18	-19.32	7.07
	Changes by 5º or less	0.21	-1.46	3.03
	Increases by 5º or more	0.62	15.75	7.95
Eye Translational Speed Change (Fractional)	Decreases by 5% or more	0.29	-0.24	0.12
	Changes by 5% or less	0.18	0.00	0.02
	Increases by 5% or more	0.53	0.32	0.31
Wind Speed Change (Fractional)	Decreases by 5% or more	0.56	-0.19	0.09
	Changes by 5% or less	0.38	0.00	0.03
	Increases by 5% or more	0.06	0.08	0.02

Table 5.5. Tropical Cyclone land priors. First 12 hours across land. All metrics sample from 20 tropical cyclones for a total of 20 data points.

Metric	Event (in 12 hours)	P(event)	Average Change	Standard Deviation
Eye Bearing Change (Deg)	Decreases by 5º or more	0.20	-15.20	8.48
	Changes by 5º or less	0.25	-0.03	3.06
	Increases by 5º or more	0.55	21.43	18.05
Eye Translational Speed Change (Fractional)	Decreases by 5% or more	0.40	-0.25	0.09
	Changes by 5% or less	0.05	0.00	-
	Increases by 5% or more	0.55	0.71	0.54
Wind Speed Change (Fractional)	Decreases by 5% or more	0.85	-0.34	0.16
	Changes by 5% or less	0.15	0.01	0.01
	Increases by 5% or more	0.00	-	-

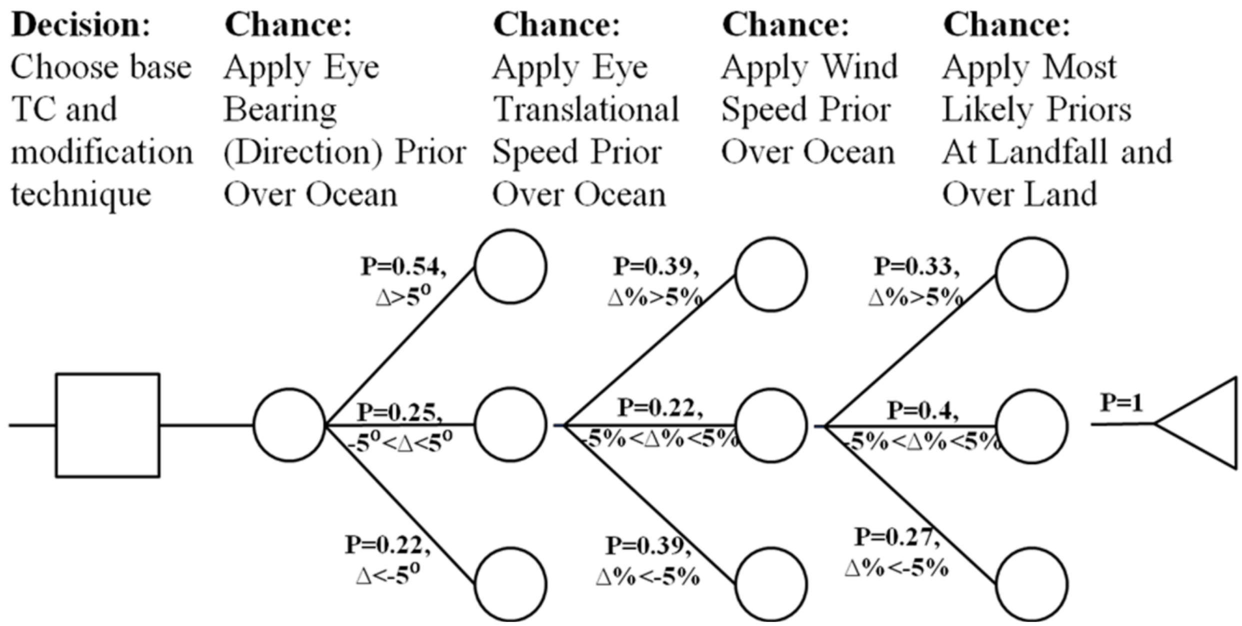


Figure 5.10. Schematic indicating how the discretized prior probabilities are applied. Data are from National Hurricane Center historical tracks (1953-2004). Circles indicate choice nodes, and branches indicate the available choices. Δ indicates an absolute or a percent change of characteristic over 12 hours.

To create a probabilistic range of control TCs, I chose a base TC and then applied the priors as in Figure 5.10. Because I was interested in strong hurricanes that may make landfall between Miami and Jacksonville, I used the 1992 track of Hurricane Andrew. To obtain tracks with a range of interesting landfalls, I rotated the eye bearing of this track by 11 degrees clockwise over the last 5 data points. I refer to the resulting hurricane tracks as “Andrew-like” TCs.

Next, I used these priors, the probabilistic ranges of wind speed, bearing, and translational speed, to create 27 tracks based on the parameters of Hurricane Andrew. Ocean priors were applied beginning at the third track point west of the line connecting (30ºN,70ºW) to (25ºN,75ºW). The prior distribution of eye bearing was applied, first resulting in 3 Andrew-like TCs. Applying the prior distribution of eye translational speed and wind speed resulted, respectively in 9 and then 27 Andrew-like TCs. Central pressure was calculated from the wind speed within the HAZUS model.

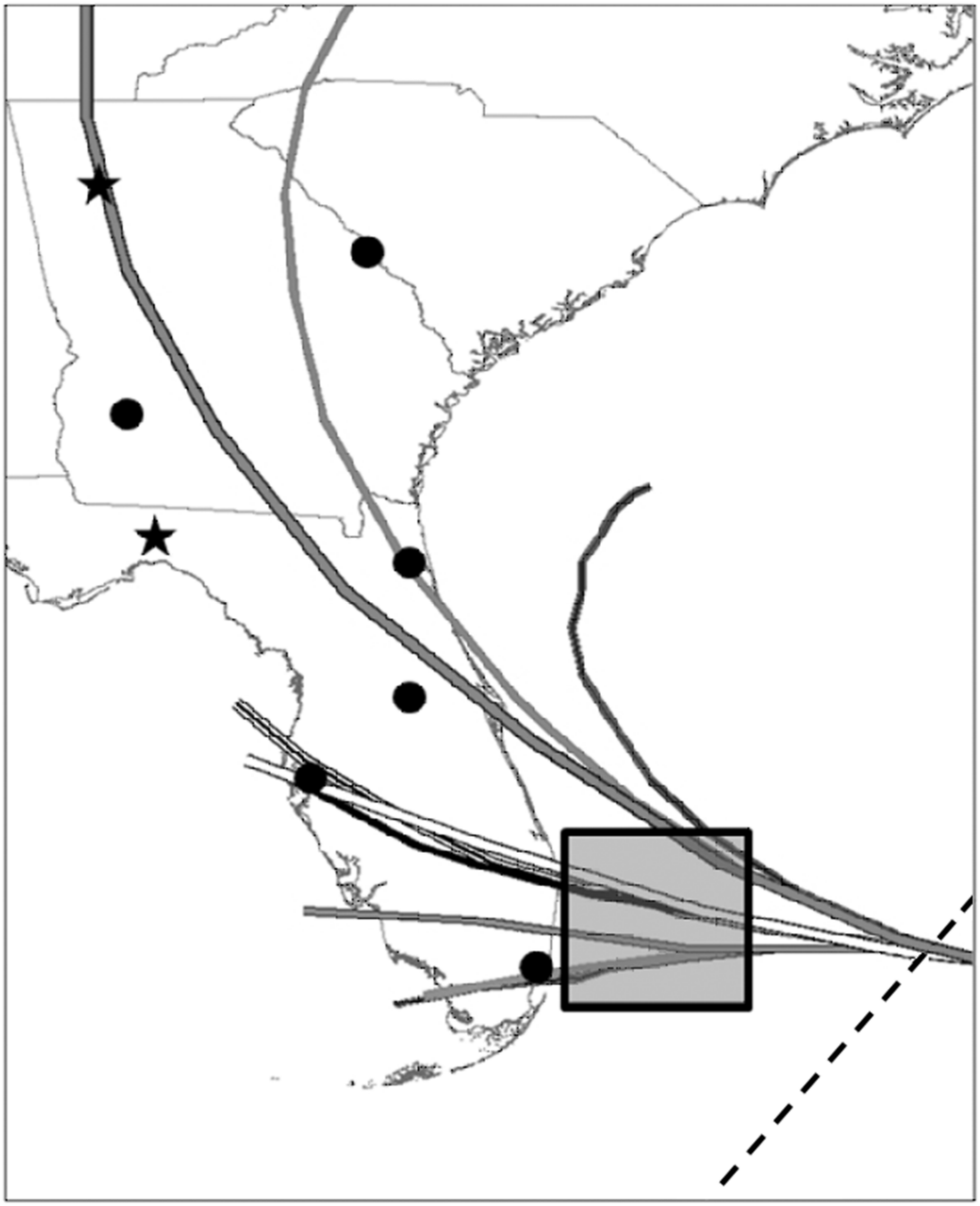


Figure 5.11. Visualization of the "Andrew-like" TCs examined in the study. Priors from Table 5.3-Table 5.5 are applied at the first point west of the dotted line. Nine different tracks are shown. Colors indicate eye bearing trajectory, (dark grey=clockwise change in eye bearing, white=no change in eye bearing, light grey=counter-clockwise change in eye bearing), and line types indicate eye translational speed (two black lines=high translational speed, solid color=medium translational speed, three black lines=low translational speed). Wind speed priors (not shown) are applied when the storm passes the dotted line, while wind-wave pump modifications are applied in the box.

If one of the resulting TCs remained in the ocean, its probabilistic track alteration was complete. However, if the TC made landfall, I applied the landfall and land priors as pertinent. A track was immediately ended if a TC reentered the ocean.

Figure 5.11 is a visualization of the tracks used in this study; note this shows changes in eye bearing and eye translational speed, but not wind speed.

5.1.2. Modifying hurricanes with wind-wave pumps

For this study, I consider SST reductions and costs from 300m long pumps spaced 333m apart as listed below.

Seasonally and regionally. Using the cost estimate of \$2,000-\$3,500 per pump with a 25% maintenance cost, I estimate that deploying the pumps in an array to protect Miami, FL (25-27ºN, 78-80ºW) would cost \$0.9-1.5B annually and should decrease the SST by 1-1.5ºC. This would take roughly 350,000 pumps.

In front of an approaching TC. If one had perfect knowledge of the TC track up until the area to be cooled and further assumed that the hurricane moved in conformity with my estimated priors, then pumps could deployed in a square 150km×150km area (eddies are much smaller). This would take 451×451, or over 200,000 pumps. I estimate that this would cost \$400-700 million per TC, and deployment time would be 12-24 hours. Assuming deployment begins 48 hours ahead of the storm, the SST should decrease by 0.5-1ºC.

5.2. Results

Following the method outlined above, 27 Andrew-like tracks were constructed and wind damages were estimated with HAZUS-MH MR3 for six cases:

1. Control,

2. Wind-wave pumps deployed 48 hours in advance of a TC (0.5-1.0ºC SST decrease),

3. Wind-wave pumps deployed seasonally (1.0-1.5ºC SST decrease),

4. Shutters on 100% of residential buildings in Florida and Georgia,

5. Shutters on 100% of residential and commercial buildings in Florida and Georgia,

6. All possible hardening techniques in Florida and Georgia.

Resultant values are given in Table 5.6.

Figure 5.12 compares the HAZUS-calculated wind fields for the most probable scenario in control, with a 1°C SST decrease, and with natural variability. In cases 2 and 3, the SST change only modifies wind speed, and therefore the effect of the SST decrease is superimposed on the control priors. Note that the prior probabilities indicate a larger change in winds due to natural variability than the decrease in wind speed due to wind-wave pumps. Thus, it is possible that a storm could naturally intensify despite modification. In cases 4, 5, and 6, hardening causes a change in the damage resistance functions, and therefore does not affect the TC tracks.

I find that the 27 Andrew-like TCs respond quickly to the decreased SST, resulting in an expected decrease of wind speeds through much of Florida and Georgia by one or more Saffir-Simpson categories (*18*). This suggests that an action taken to protect one city (a deployment area "protecting Miami") may have far reaching benefits.

Figure 5.13A-B show the total direct economic losses for the most likely control trial and the difference in damages for the same trial with a modification resulting in a 1°C SST decrease (note the log scale). The changes in wind speeds along the track are magnified in the change in damages throughout Florida and Georgia. When tracks remain in the cooled SST area for longer than this trial, the percent decrease in total direct economic losses is much higher.

Scenario			Probability	Total Direct Economic Loss (billions USD2002) Per Modification Technique						
Eye Bearing Change (deg)	Wind Speed Change (fractional)	Eye Translational Speed Change (fractional)		None	Wind-Wave Pump (-0.5 deg SST)	Wind-Wave Pump (-1 deg SST)	Wind-Wave Pump (-1.5 deg SST)	Shutters in 100% Florida & Georgia Residential Buildings	Shutters in 100% of Florida & Georgia Residential & Commercial Buildings	100% Hardening
Decreases by 5º or more	Decreases >=5%	Decreases >=5%	2.32%	19.4	9.6	4.9	2.7	14.1	9.4	4.7
		Changes <5%	1.31%	27.6	11.9	6.0	3.0	19.1	12.6	6.4
		Increases >=5%	2.32%	16.6	10.9	5.8	3.0	11.3	8.2	4.0
	Changes <5%	Decreases >=5%	3.43%	76.6	49.8	23.5	9.9	50.4	30.8	17.8
		Changes <5%	1.94%	52.8	45.2	19.8	8.5	35.4	21.7	16.5
		Increases >=5%	3.43%	29.9	21.3	13.0	6.5	19.6	13.8	6.8
	Increases >=5%	Decreases >=5%	2.83%	160.5	128.6	87.8	48.8	118.5	86.3	62.7
		Changes <5%	1.60%	134.3	99.0	63.9	29.7	91.6	60.3	38.6
		Increases >=5%	2.83%	50.9	37.4	24.1	14.2	33.2	23.2	12.2
Changes by 5º or less	Decreases >=5%	Decreases >=5%	2.06%	12.7	5.0	2.7	1.6	9.2	7.0	3.6
		Changes <5%	1.16%	13.0	5.4	2.6	1.6	9.2	6.6	3.4
		Increases >=5%	2.06%	9.2	5.6	3.2	1.7	6.9	5.4	2.6
	Changes <5%	Decreases >=5%	3.93%	51.8	22.5	7.4	2.9	33.2	23.0	12.2
		Changes <5%	2.22%	34.0	18.3	7.7	3.3	22.0	15.0	8.1
		Increases >=5%	3.93%	17.3	10.4	3.5	3.2	12.2	9.0	4.2
	Increases >=5%	Decreases >=5%	3.37%	133.9	80.9	35.3	10.8	90.4	65.7	38.6
		Changes <5%	1.90%	69.2	46.0	24.0	11.9	45.4	32.8	18.5
		Increases >=5%	3.37%	32.5	20.6	10.7	5.6	23.5	17.8	7.5
Increases by 5º or more	Decreases >=5%	Decreases >=5%	4.63%	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
		Changes <5%	2.61%	18.7 (1.2)	14.3 (0.9)	7.0 (0.6)	4.7 (0.5)	13.4 (1.2)	10.6 (0.9)	3.7 (0.9)
		Increases >=5%	4.63%	5.8 (7.8)	3.7 (5.6)	2.1 (3.7)	1.5 (2.0)	4.0 (6.7)	3.5 (5.8)	1.7 (3.1)
	Changes <5%	Decreases >=5%	8.85%	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
		Changes <5%	4.99%	60.8 (5.0)	52.8 (3.7)	37.9 (2.4)	22.4 (1.5)	43.2 (3.7)	32.0 (2.7)	13.1 (2.8)
		Increases >=5%	8.85%	21.4 (32.1)	18.1 (21.0)	9.6 (11.3)	4.5 (6.6)	14.7 (22.6)	11.4 (17.5)	5.6 (7.3)
	Increases >=5%	Decreases >=5%	7.58%	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)	0.0 (0.0)
		Changes <5%	4.28%	116.5 (13.5)	107.2 (11.5)	87.1 (8.3)	66.2 (5.5)	92.9 (9.2)	74.4 (7.3)	40.3 (7.5)
		Increases >=5%	7.58%	40.2 (95.0)	35.4 (74.5)	26.8 (44.8)	20.4 (25.8)	31.1 (61.4)	23.6 (46.6)	13.2 (17.7)

Table 5.6. Direct Economic Loss (billions of USD 2002) for Florida. Georgia values in parentheses.

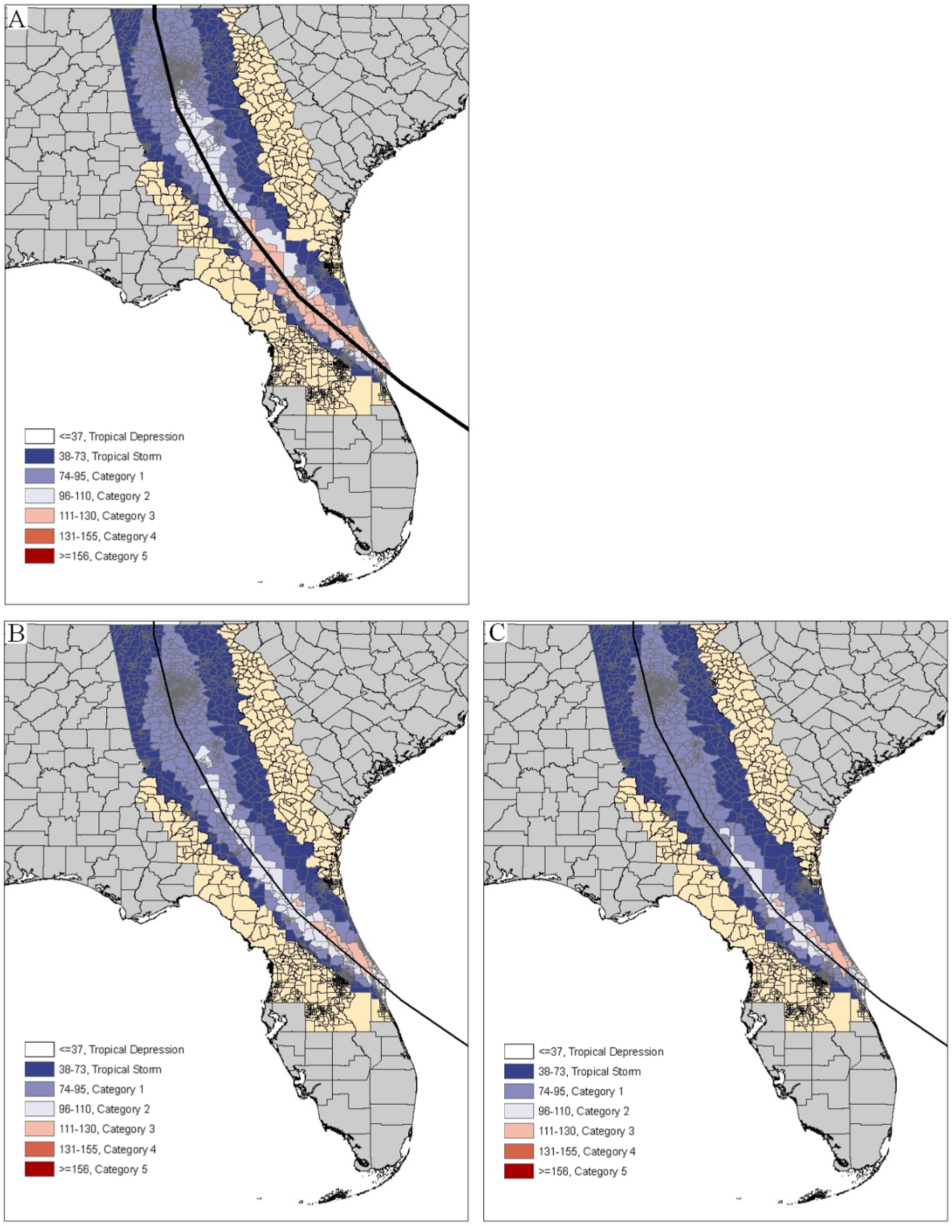


Figure 5.12. Maximum 1-minute sustained wind speed (knots) for the most likely scenario. Figure A is the most probable control scenario, with a wind speed change of 0%. Figure B is the control scenario with a wind-wave pump modification resulting in a 1°C decrease in SST. Figure C is the natural variability; the same eye translational speed and eye bearing, but decreased wind speed prior (~10%).

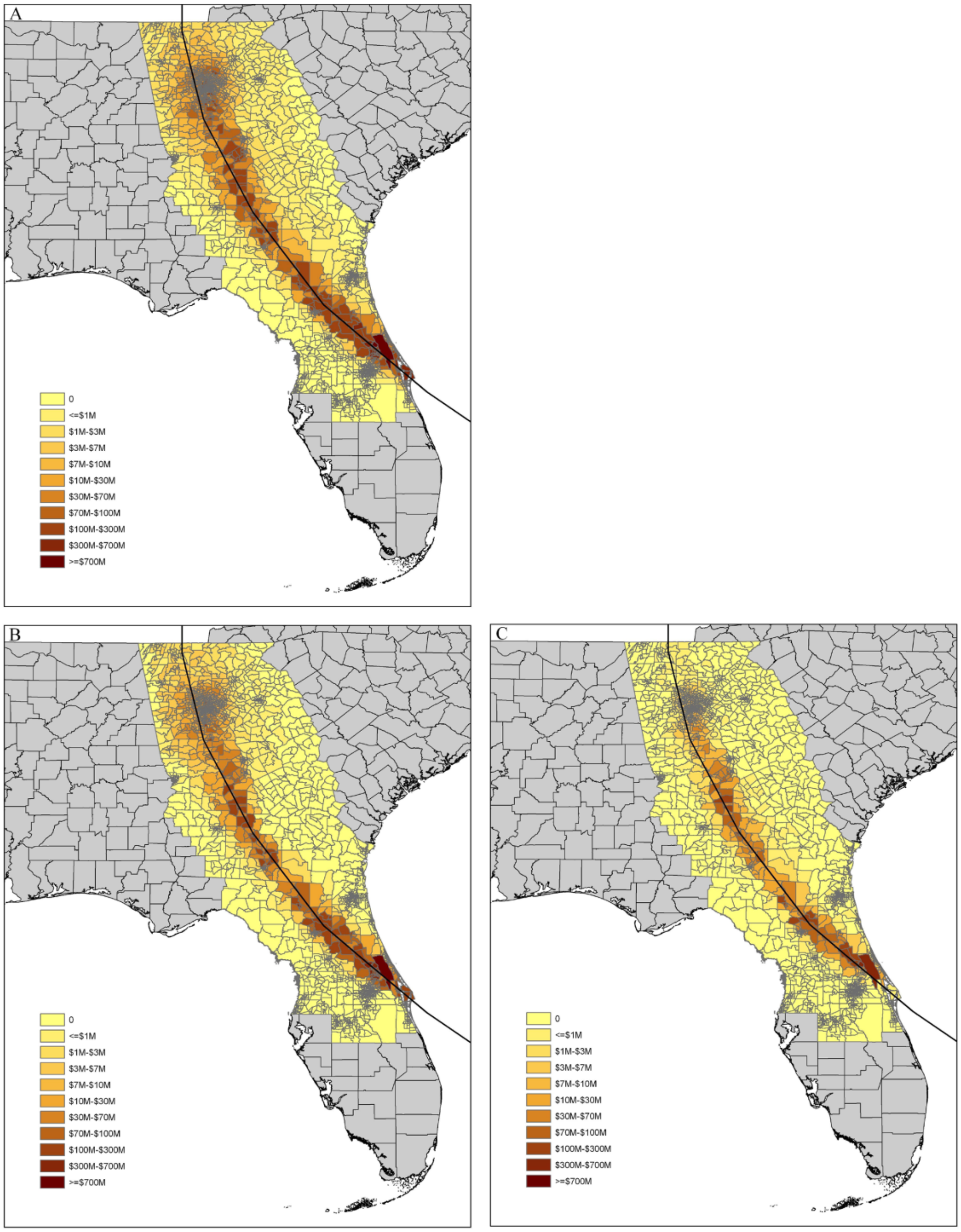


Figure 5.13. Total direct economic losses (log USD 2002) for the most likely technique. A: the most probable control trial (no wind speed change). B: Difference between control trial and the same trial with a 1°C SST decrease. C: Difference between control trial and the same trial with shuttering of all Florida and Georgia homes.

Figure 5.13C shows the difference in damages between the most likely control trial and the same trial in which 100% of Florida and Georgia residential buildings are shuttered. I find that shuttering homes yields slightly higher damage reductions than the wind-wave pump modification. However, damage reductions are limited to buildings with shutters. Additionally, shuttering would not protect against storm surge, which is expected to decrease under this particular program of hurricane modification. On the other hand, hardening protects against all storms, not just this particular one.

Probabilities and total direct economic losses for all scenarios are reported in Table 5.6. In all cases, both modification and hardening decrease total direct economic losses compared to the control trial.

In the modification trials, I find three results. First, time spent in the cooled SST area greatly affects wind speed and damage reduction. Second, seasonal deployment results in a larger damage reduction than deployment in front of a TC. Third, the greatest damage reduction occurs due to the reduction of the fastest winds along the middle of the hurricane track.

According to the HAZUS data, few hardening improvements are in use in northern Florida and Georgia (~5-10% have shutters employed correctly) compared to areas in south and southeast Florida (~25% have shutters employed correctly). Thus 100% hardening yields a larger percentage decrease in total direct economic losses in northern Florida and Georgia. However, for storms with very high wind speeds, hardening structures cannot protect against the fastest winds along the middle of the hurricane track. Comparing techniques, shuttering 100% of residential and commercial buildings is twice as effective in reducing total direct economic losses as all other hardening techniques combined (tie-downs, hardening in roof replacement, roof-wall connections). Technique effectiveness appears slightly improved when multiple techniques are used.

Figure 5.14 shows aggregated total direct economic losses. Figure 5.15 shows the aggregated net costs (losses and implementation) for each trial for Florida and Georgia. Uncertainties are highly correlated between trials (i.e., a storm that has high damages in one scenario will have high damages in other scenarios). Note that for this particular storm, there is a 21% chance that the modified TC will recurve into the Atlantic Ocean and not make landfall. For such a storm, a program of modification or hardening would cost more than doing nothing.

I find that for the case of an intense, swiftly translating "Andrew-like" TC, seasonal deployment of wind-wave pumps may be the lowest cost option in expected value decision analytic terms. However, employing all possible hardening techniques achieves nearly the same damage reduction. Additionally, hardening scenarios have a smaller range of uncertainty in net costs. Given that there could be a failure to deploy pumps before a major storm, a risk averse decision maker may be more likely to employ all possible hardening techniques in order to avoid the highest losses. However, note that modification and hardening work differently; the two techniques can be employed in parallel to achieve higher damage reductions than seen by either technique alone.

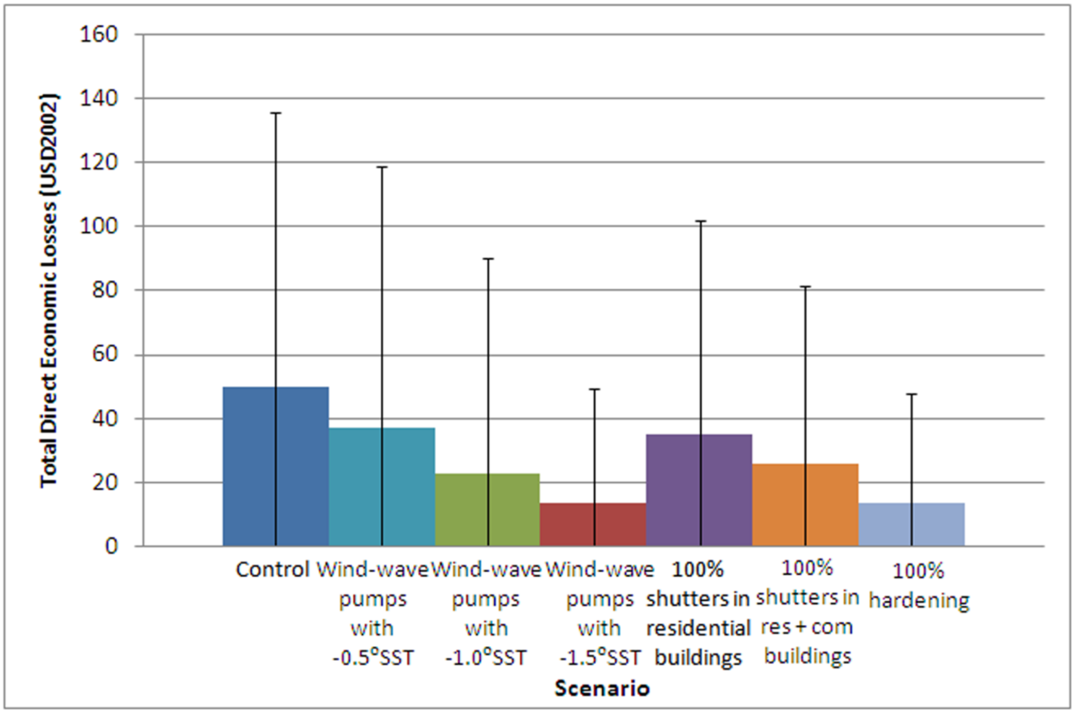


Figure 5.14. Aggregated total direct economic losses for each trial (billions USD 2002). Bars denote the average weighted value, whiskers the 5th and 95th percentiles.

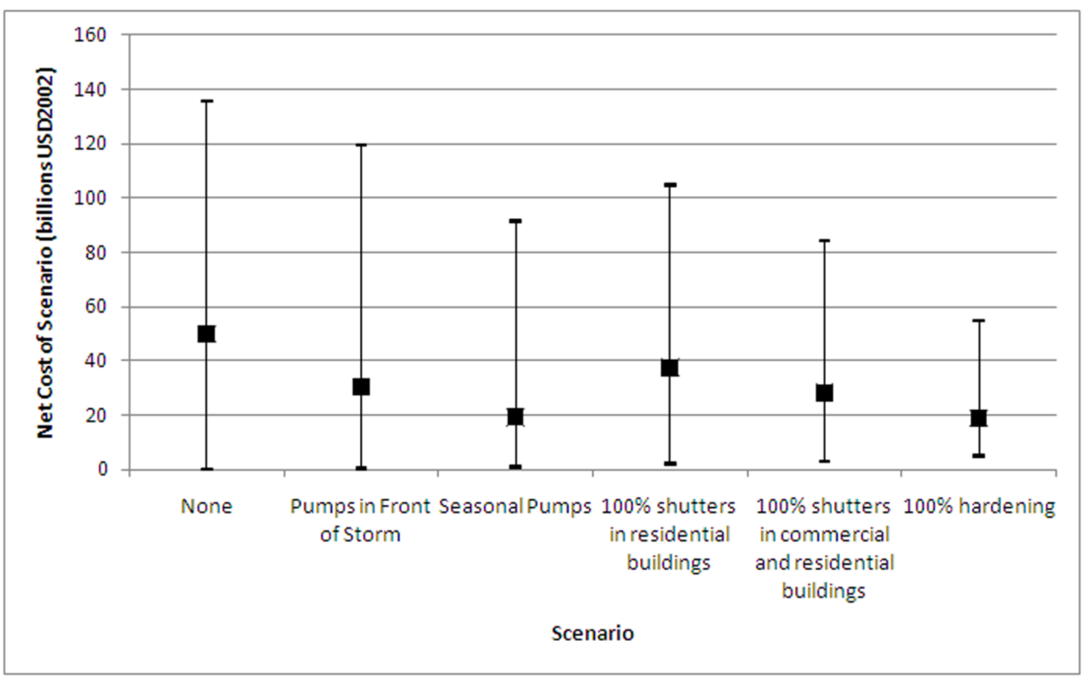


Figure 5.15. Aggregated net costs for each trial (billions USD 2002). Bars denote the average weighted value, whiskers the 5th and 95th percentiles.

5.2.1. Justification of neglecting storm surge

This chapter only considers wind damages. Another component of damages is storm surge. According to the NHC, "storm surge is often the greatest threat to life and property from a hurricane" (109), and thus some discussion on the effects of storm surge on my results is pertinent.

Storm surge is a function of coastal bathymetry and storm characteristics. For instance, Katrina (2005) was a very large storm approaching from the Gulf of Mexico to make landfall in a low-lying area. Therefore life and property losses from storm surge were very high.

This chapter examines Andrew-like hurricanes making landfall near Miami, FL. Unlike Katrina, Andrew-like storms are expected to have a relatively low storm surge impact. This can be demonstrated by considering both coastal bathymetry and storm characteristics. First consider coastal bathymetry. The Atlantic Ocean east of Florida has a relatively narrow continental shelf, and thus storm surges will be lower. Additionally, most of the southeast Florida coast rises relatively steeply from the shoreline (i.e. near Miami most land is at an altitude of 40ft or higher, see Figure 5.9), likely too high to be impacted by storm surges. The southwest Everglades, a low lying coastal area, might be expected to have high storm surges. However, the Everglades are protected through extensive natural barriers (e.g. roughness created by mangrove forests). Storm characteristics also affect storm surge. Andrew had a small storm radius, a well-formed eye, and a relatively high translational speed. All other factors being equal, this type of storm will produce a lower storm surge than a storm with a large radius, that is moving slowly, or experiencing an eye-replacement cycle (*110*). Therefore Andrew-like storms should have relatively low storm surge damages. The NHC notes that at the Florida landfall point, Andrew had a 17' surge, but the "vast majority of damage in Florida was due to the winds" (*111*).

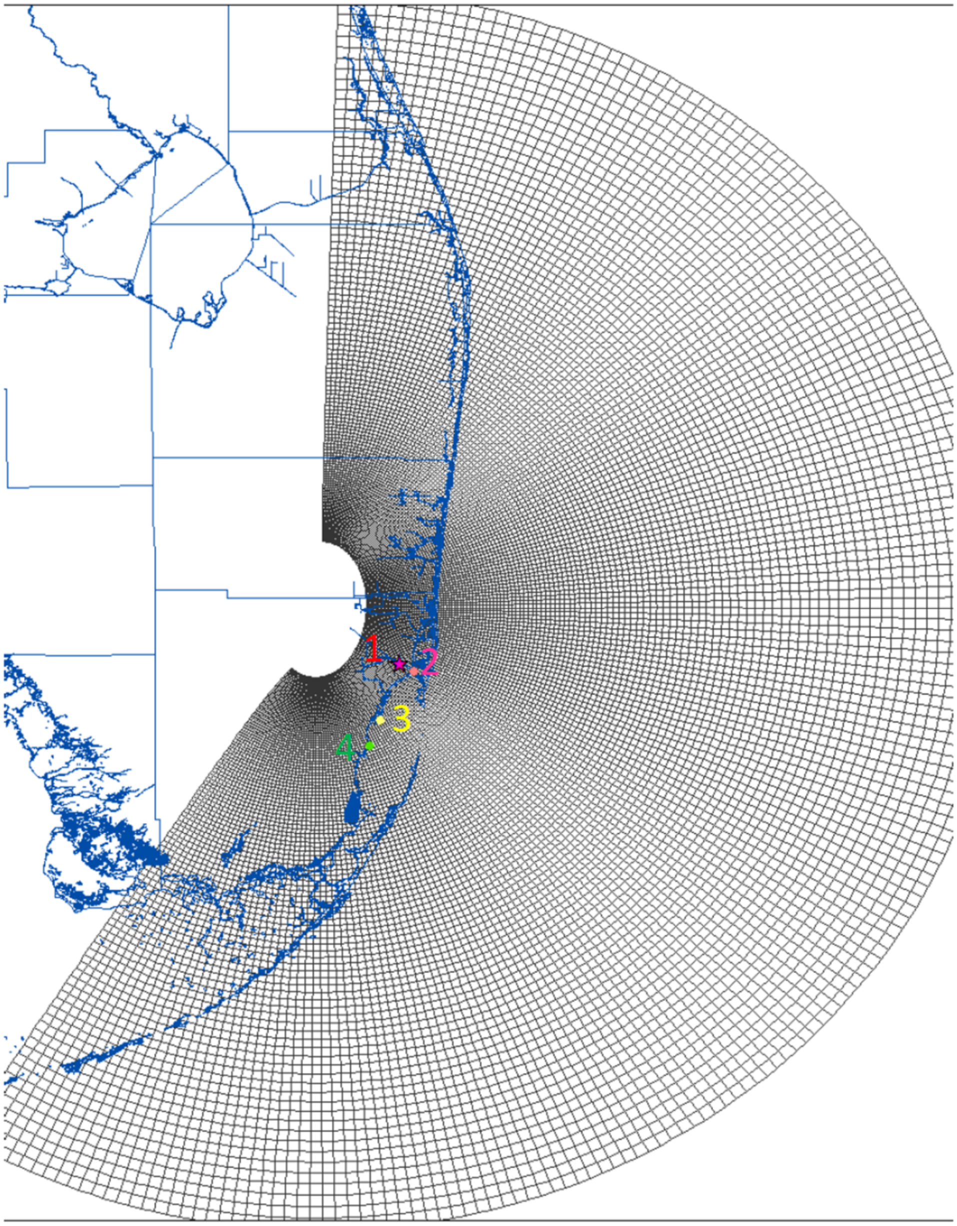


Figure 5.16. SLOSH hmi3 mesh and points of interest, courtesy of Ning Lin. Point 1 is Miami. Point 2 is a coastal point near to Miami. However, due to coastal bathymetry, both of these points are thought to have computationally intensive storm surge estimates, and thus storm surges here are less reliable. Point 3 and Point 4 are located in a less computationally intensive area, and are also chosen to be on the mesh grid (no interpolation between points). Point 3 is thought to have the best results.

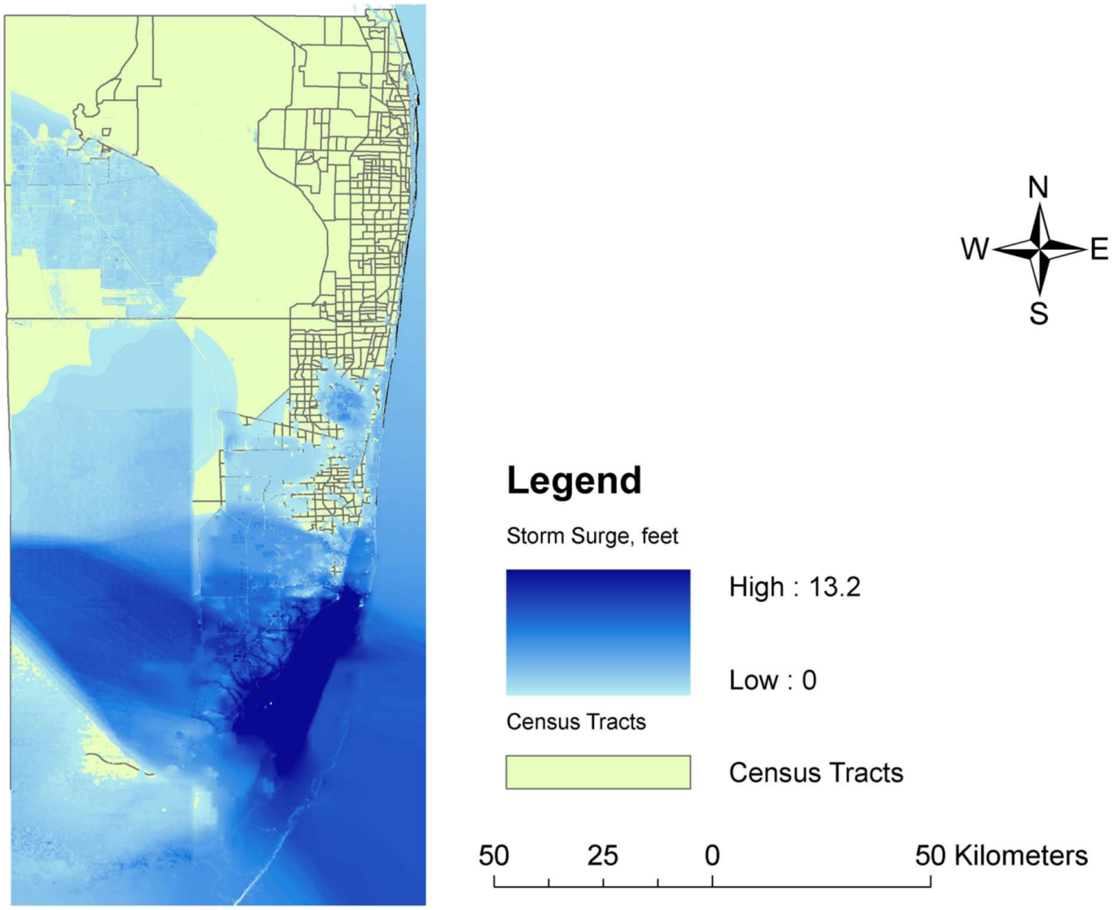


Figure 5.17. An example SLOSH .shp file output converted to HAZUS flood (30 m resolution) (this particular run is Florida Control run with highest storm surge at Miami, Run #262). Note values represent the amount of water on the surface (SLOSH output minus the elevation). Not all blue areas are connected.

To test this assertion, researchers at the NHC and (separately) at MIT ran the SLOSH model for two of the Andrew-like scenarios expected to have the highest storm surge damages. Figure 5.16 is the SLOSH grid used (*112*), and Figure 5.17 is a sample storm surge run. Since the elevation of east Florida rises quickly, given equivalent storm sizes/intensities I expect the largest storm surge damages to be where large populations are located within a mile or the coast. In this study, the TCs with a counter-clockwise change in eye bearing make landfall near Miami, FL, and thus are expected to have high storm surges.

Figure 5.18.A shows the most intense storm making landfall the closest to Miami. Here storm surge damages are negligible due to the steep bathymetry near the coast, the very narrow Biscayne Bay at this location, and the moderately high terrain overland. Specifically, Figure 5.19 and Table 5.7 show the wind and storm surge damages. Note direct economic loss includes capital stock losses (cost building damage, cost contents damage, inventory loss) and income losses (relocation loss, capital relate loss, wages loss, rental income loss). Therefore total losses can be larger than the value of building exposed. Wind damages were $132.6 billion USD, storm surge damages were $9.1 billion USD. If the maximum damage value is chosen in each census tract, the combined damages are $134.3 billion USD. If the damage values are summed, the combined damages are $141.7 billion USD (no census tract has a damage value higher than the total value at risk).

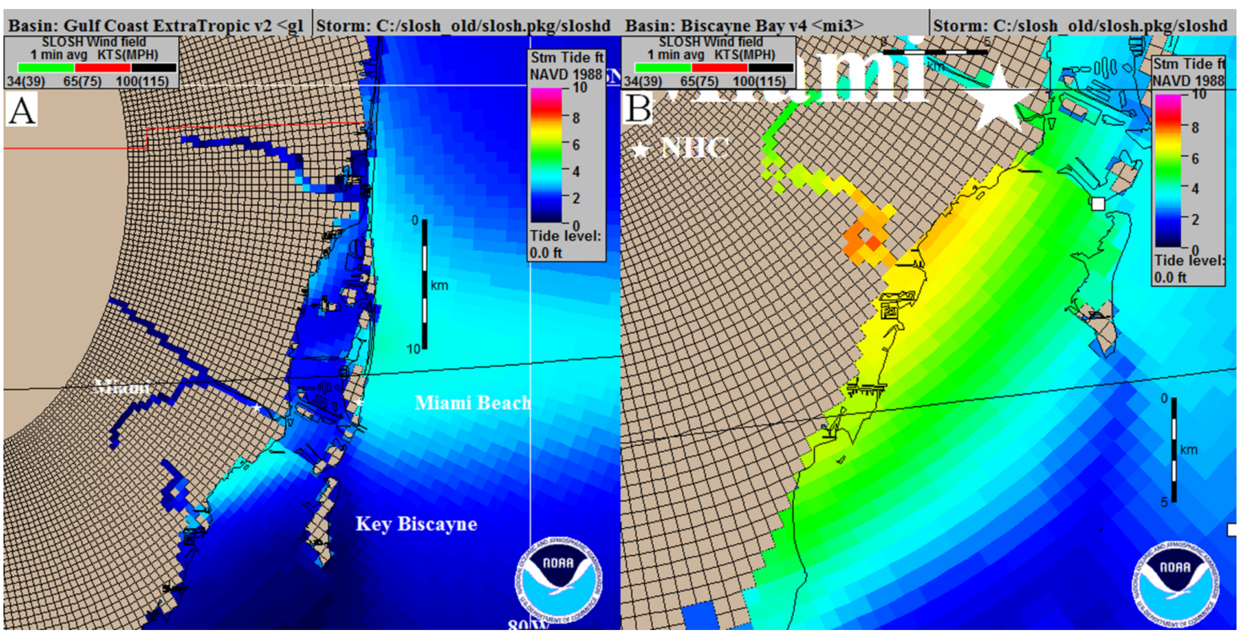


Figure 5.18. SLOSH output for two Andrew-like hurricanes with a direct hit on Miami. Figure A is the most intense storm making landfall closest to Miami (wind speeds increase by more than 5%, translational speed changes by less than 5%). Figure B is the most likely TC with a counter-clockwise change in eye bearing (wind speeds change less than 5%, translational speed decreases by more than 5%).

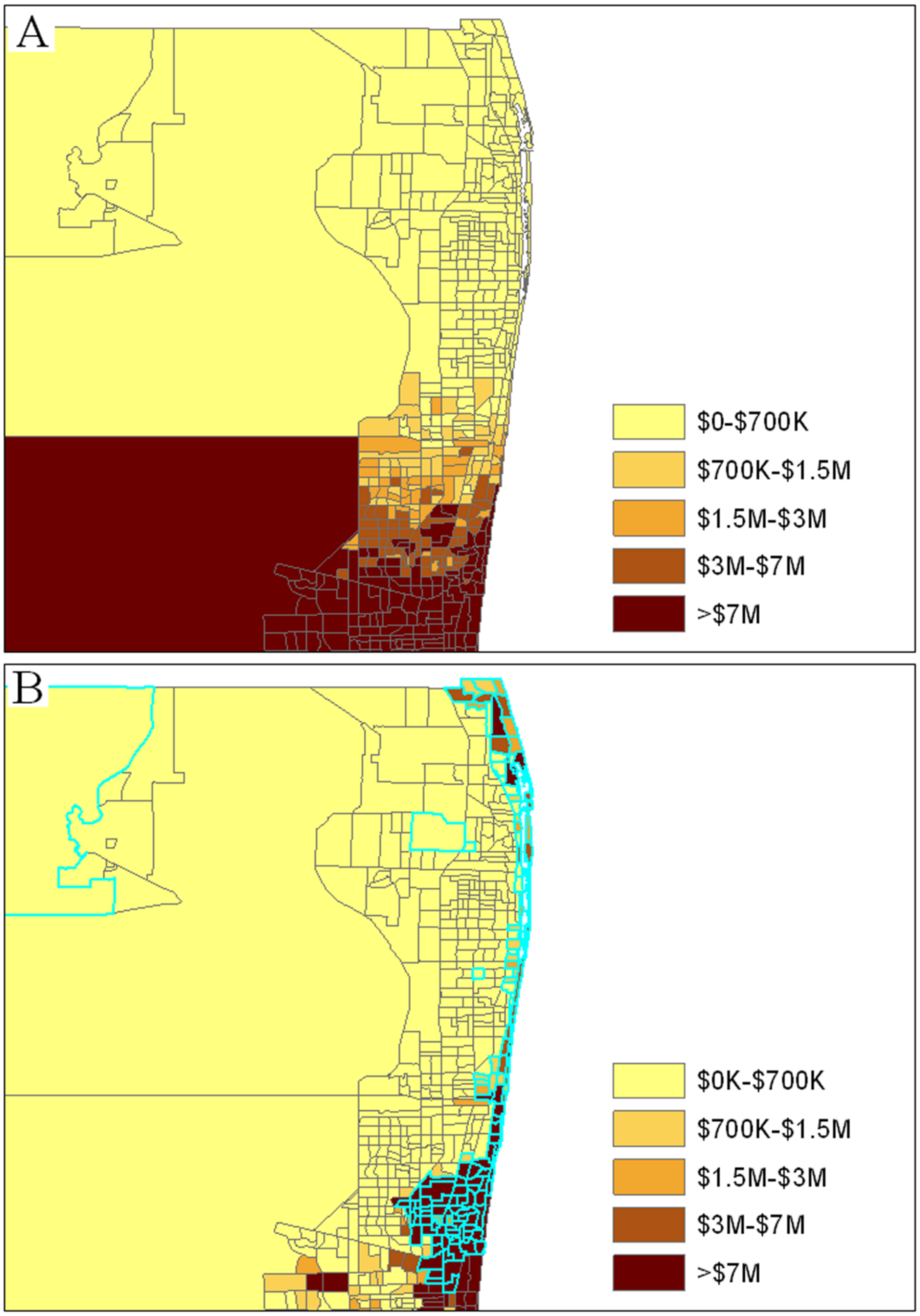


Figure 5.19. HAZUS calculated direct economic losses for buildings at the census tract level for the Andrew-like hurricane shown in Figure 5.18A (wind speeds increase by more than 5%, translational speed changes by less than 5%). Figure A is the total wind loss, Figure B is the total storm surge loss. Light blue outlines census tracts where the storm surge value is higher than wind value.

Table 5.7. Direct Economic Losses for Buildings on county level (billions of USD 2002) for Figure 5.18A (the most intense storm making landfall closest to Miami where wind speeds increase by more than 5%, translational speed changes by less than 5%). Total storm surge losses are much less than total wind losses. However, note that in Broward County, the damages from storm surge are higher than the damages from winds.

Value (billions of USD2002)		County and Source of Damage					
		Miami-Dade		Broward		Palm Beach	
		Wind	Storm Surge	Wind	Storm Surge	Wind	Storm Surge
Building Stock Exposure		150.6	150.6	125.7	125.7	99.9	99.9
Direct Economic Losses							
Capital Stock Losses	Cost Building Damage	84.6	2.3	1.7	1.6	0.004	0.1
	Cost Contents Damage	47.9	2.9	0.39	1.7	0	0.08
	Inventory Loss	1.0	0.04	0.009	0.04	0	0
Income Losses	Relocation Loss	9.9	0.015	0.21	0.015	0	0
	Capital Related Loss	4.2	0.028	0.035	0.024	0	0.001
	Wages Loss	4.9	0.07	0.039	0.06	0	0.002
	Rental Income Loss	5.8	0.01	0.12	0.009	0	0
	Total Loss	157.8	5.37	2.5	3.5	0.005	0.19

Figure 5.18.B shows one of the low probability storms with a counter-clockwise change in eye bearing which in this case results in a maximum storm surge of approximately 8 feet on the right hand side of the storm. Note that due to coastal bathymetry, the storm surge does not penetrate very far inland; additionally since land elevation has not been subtracted from these data, the depth of the inundation would be less than the storm surge values, except right at coastal regions at sea level. Using HAZUS, storm surge damages are 60.6 billion (compared to 76.6 billion in wind damages, Figure 5.20). Comparing county by county (see Table 5.8), I find that most of the storm surge and wind damages occur in the same three counties (Miami-Dade, Broward, and Palm Beach counties). However, at census tract and census block level, it is obvious that the wind losses are spread over a much larger area than the storm surge losses; wind causes a moderate amount of damage throughout a large area, while the storm surge destroys more but

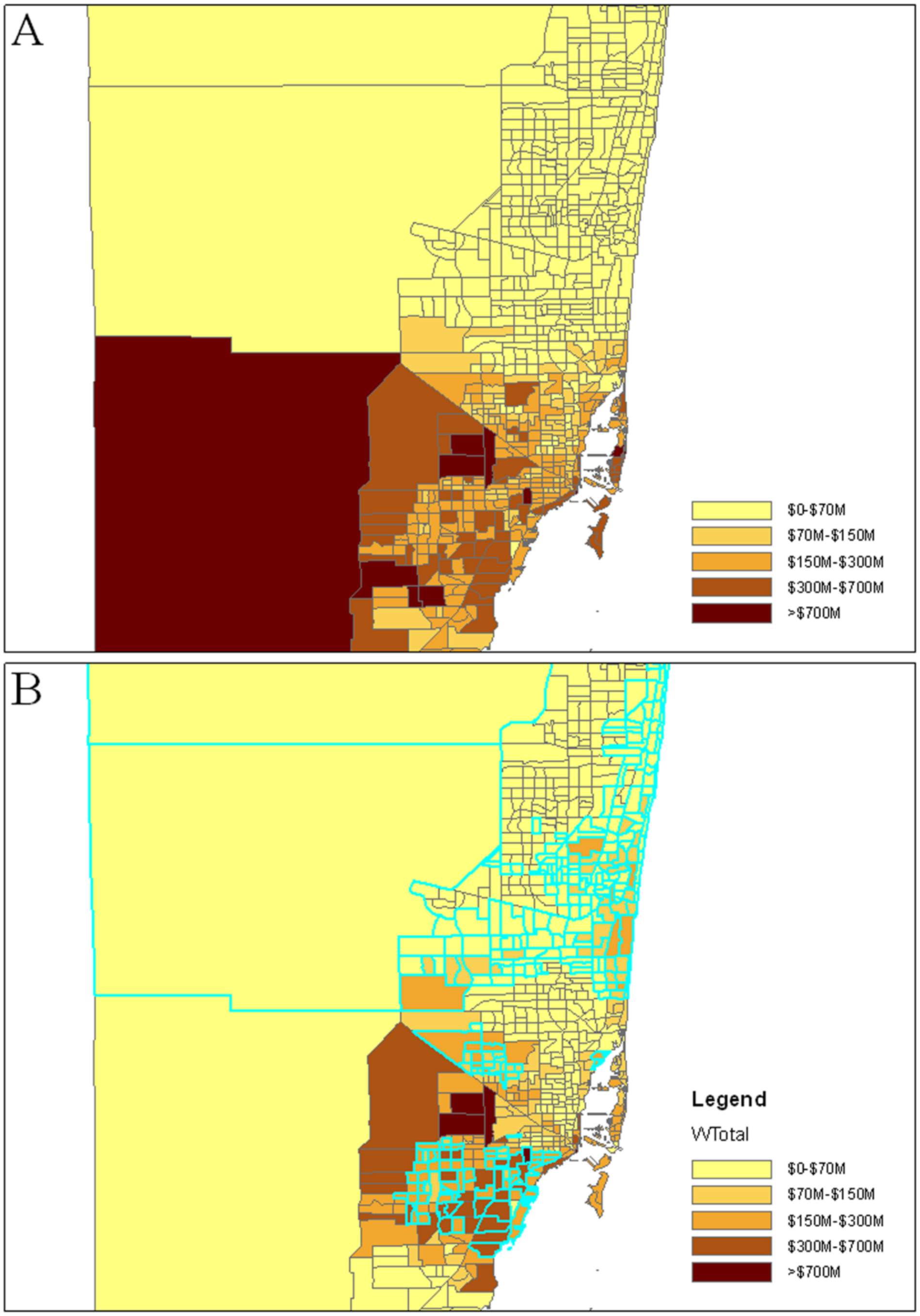


Figure 5.20. HAZUS calculated direct economic losses for buildings at the census tract level for the Andrew-like hurricane shown in Figure 5.18B (wind speeds change less than 5%, translational speed decreases by more than 5%). Figure A is the total wind loss, Figure B is the total storm surge loss at census tract level. Light blue outlines census tracts where the storm surge value is higher than wind value.

Table 5.8. Direct Economic Losses for Buildings on county level (billions of USD 2002) for Figure 5.18B (the most likely TC with a counter-clockwise change in eye bearing where wind speeds change less than 5%, translational speed decreases by more than 5%). Total storm surge losses are ~80% of total wind losses. However, note that in Broward County, the damages from storm surge are higher than the damages from winds.

Value (billions of USD2002)		County and Source of Damage					
		Miami-Dade		Broward		Palm Beach	
		Wind	Storm Surge	Wind	Storm Surge	Wind	Storm Surge
Building Stock Exposure		150.6	150.6	125.7	125.7	99.9	99.9
Direct Economic Losses							
Capital Stock Losses	Cost Building Damage	40.9	22.7	1.4	3.7	0.006	0.19
	Cost Contents Damage	19.8	28.1	0.26	4.1	0	0.16
	Inventory Loss	0.49	0.76	0.006	0.1	0	0.002
Income Losses	Relocation Loss	5.6	0.09	0.15	0.03	0	0.001
	Capital Related Loss	2.1	0.13	0.02	0.04	0	0.002
	Wages Loss	2.5	0.30	0.026	0.11	0	0.005
	Rental Income Loss	2.9	0.05	0.095	0.02	0	0.001
	Total Loss	74.44	52.1	2.0	8.2	0.006	0.36

only near the coast. However, most of the damages are in the same areas; if the maximum damage value is chosen in each census tract, the combined damages are $85.9 billion USD. If the damage values are summed, the combined damages are $137 billion USD (no census tract has a damage value higher than the total value at risk).

I conclude that for most of the Andrew-like storms examined in this chapter, storm surge is likely a small component of the total damages. However, for three of the scenarios (the storms with a counter-clockwise change in eye bearing storms where translational speed decreases by 5% or more), the hurricane hits a "sweet spot" where storm surge damages rise to approximately 80% of wind damages.

Initial work indicates that for the 100 year return period for a tropical cyclone making landfall at Miami, storm surges could be as high as 4-5meters (13-16.5 feet), but that storm surge decreases as intensity decreases; thus modification could only be more attractive than when considered in the wind only scenario. Chapter 6 discusses using the NHC storm surge model, SLOSH for a variety of different storm types.

5.3. Discussion

Results from the estimates of wind damage in this first-order assessment make a strong case for extensive hardening of structures. They also suggest that more serious analysis and field trials are warranted to assess strategies to reduce SST using wind-wave pumps, since such an intervention may be valuable as an added response to limit damage from infrequent but very intense storms. Hardening alone provides only limited protection against such intense storms.

Although some of the uncertainties associated with track forecast and hurricane modification can probably be reduced in the future, some uncertainty will remain irreducible. Thus, although modification using a small grid to protect a high value area such as Miami might prove viable in the future, it seems much less likely that modification using the method examined here will ever be a viable strategy for more general regional protection.

If TC modification based on wind-wave pumps is ever developed in an operational program, there is always the risk that when "the big one comes" deployment might not take place due to forecasting, political, budgetary or other factors. For example, after a few years of operation, a series of false positive deployments might raise the threshold for deployment, with the result that deployment does not occur to protect against a serious low-probability event. In contrast, most hardening techniques, once applied, remain effective and need little or no maintenance for 30 years or more. Given zero probability of failure, seasonal deployment of pumps is preferred. If seasonal pump deployment has a probability of failure larger than 30% or 60% while hardening has a zero probability of failure, then the expected value of benefit from the pumps changes such that the preferred actions become, respectively, 100% shutters on residential and commercial buildings and 100% shutters on residential buildings.

There are several TC damage mechanisms that have not been considered in this chapter. Storm surge and rainfall damage are a small portion of the total damages from Andrew-like storms of the type examined here. For TCs with larger radius, or that make landfall at more vulnerable location, local damage from storm surge may be comparable to, or larger than, wind damages. Similarly, for slower moving storms, flooding damage from rainfall may be significant. Neither of these additional damage mechanisms changes the conclusions I reach about physical damage from wind. Modeling these other damage mechanisms present significant technical challenges to be addressed in future work.

Chapter 6. Decision Analysis of Return Period Damages in Five Census Blocks

Portions of the discussion in this Chapter are based on Klima, K.; Lin, N.; Emanuel, K.; Morgan, G.; Grossman, I. Hurricane modification and adaptation in Miami-Dade County, Florida. In review at ES&T.

In Chapter 5 I found that, given reliable deployment, wind-wave pumps that reduce local SST and therefore TC intensity may offer a cost-effective method to limit wind-induced damages. However, the utility of such a strategy in limiting damage from storm surge is less clear and would likely be a strong function of location. U.S. coastal areas such as Miami-Dade County experience high TC wind speeds and contain geophysical features vulnerable to storm surges and flooding (*113*). Since the Miami-Dade County coastline contains a range of topography, bathymetry (*104*), and infrastructure (*99*, *100*) with different susceptibilities to TCs, optimal future policy choices regarding methods to reduce TC damages depend strongly on locale.

In this chapter, I use a risk assessment model to compare wind and storm surge damage reduction from wind-wave pumps and hardening strategies for five areas along the Miami-Dade County coastline (see Figure 6.21). In contrast to Chapter 5, this methodology yields wind and storm surge damages for a range of return periods. Additionally, damage reductions from adaptation and modification can be combined.

6.1. Method

Five regions along the Miami-Dade County coastline were chosen to reflect a range of topographies, bathymetries, and infrastructure, Figure 6.21. Regions 1, 2, and 5 are the full census tracts 12086004101, 12086006701, 12086010605 respectively, in which buildings values are \$1.4, \$2.2, and \$1.3 billion respectively. Regions 3 and 4 are respectively the northern and southern parts of census track 12086008000, containing buildings worth \$600 and \$160 million.

I created damage scenarios for each region in three steps. First I obtained data from Kerry Emanuel on wind speed and storm surge height as functions of TC return period and SST reductions by wind-wave pumps. Next I calculated implementation costs of several possible scenarios of adaptation and hurricane modification from Chapter 2 and 3. Then, I used FEMA's HAZUS-MH MR3 (Chapter 4) to calculate damages and aggregate total losses from wind and storm surge for each scenario.

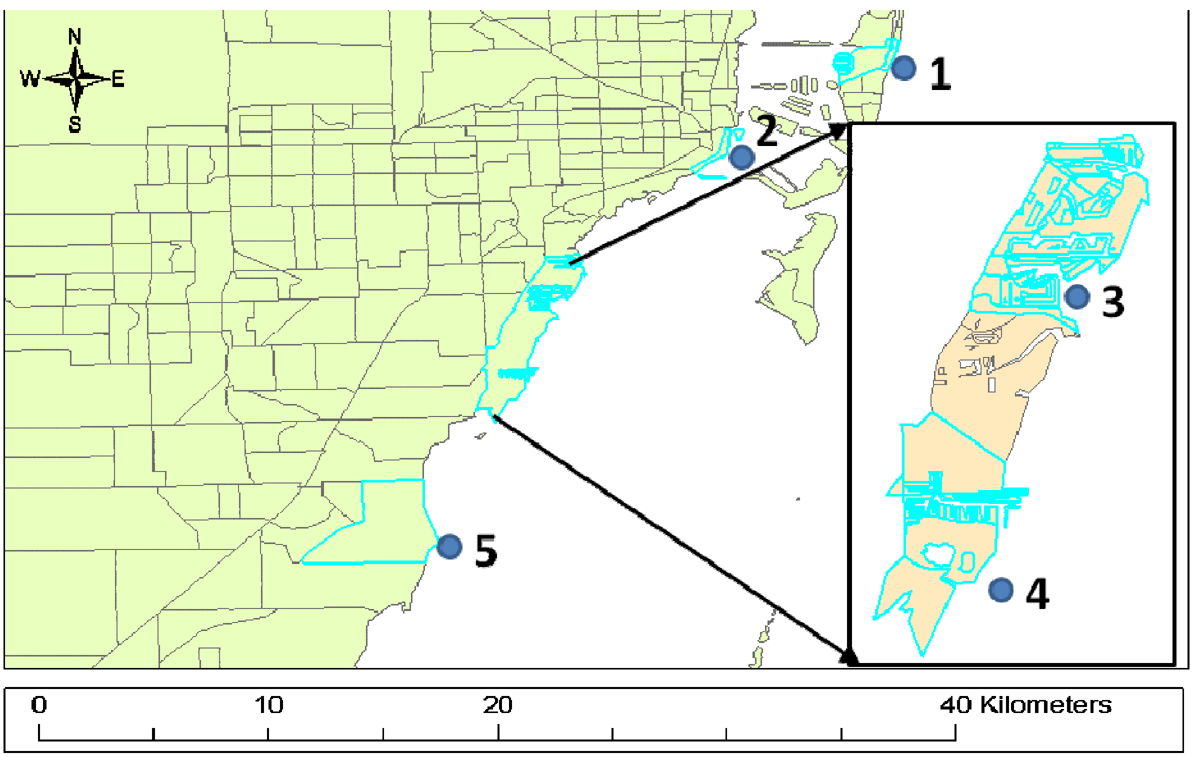


Figure 6.21. The five regions along the Miami-Dade County coastline with varying topographies, bathymetries, and housing types examined in this study. Regions 1, 2, and 5 include the full census tract (12086004101, 12086006701, 12086010605 respectively), while Regions 3 and 4 are respectively the northern and southern part of census track 12086008000.

6.1.1. *TC wind and surge risk assessment*

For a coastal point near each region, Ning Lin and Kerry Emanuel (MIT) provided estimates of storm surge height and wind speed as functions of TC return period and SST reductions by wind-wave pumps (see Figure 6.22 - Figure 6.26). I assumed that the storm surge and wind speed at the nearby coastal point represent the wind and surge values over the region. This assumption makes it convenient to compare risks among the regions and the modification conditions. It is also reasonable, as the area of the regions was selected to be small so that the simulated winds and surges do not change much over the area.

Wind return level curves are very similar for all regions, while the storm surge values of Region 1 are lower than those of other regions. It is noted that, although the wind and surge values decrease with SST reduction up to 1°C as expected, the wind and surge values are higher for SST reduction of 1.5°C than for SST reduction of 1°C. This indicates that SST reduction of 1°C is about the optimal for TC modification for this region. Further reduction of SST may have little impact on storm intensity.

6.1.2. *Cost analysis for hardening and hurricane modification scenarios*

I examine two hardening methods to reduce wind damages, three adaptation techniques to reduce storm surge damages, and one hurricane modification technique.

Hardening to reduce wind damages: Using data in Chapter 2, according to the building data in HAZUS, adding corrugated aluminum shutters to windows and doors of all non-shuttered residential buildings will, when annualized over 30 years at a 5% discount rate, cost \$530-760, \$220-450, \$250-\$340, \$50-70, and \$700-920 thousand per year respectively in Regions 1, 2, 3, 4, and 5. Employing all wind hardening techniques to reduce damages (shutters, improved roof-wall connections, improvement of roof during replacement, and tie-downs) will cost \$1.2-5.6, \$0.4-1.7, \$0.6-2.5, \$0.1-0.5, and \$1.6-6.6 million per year respectively.

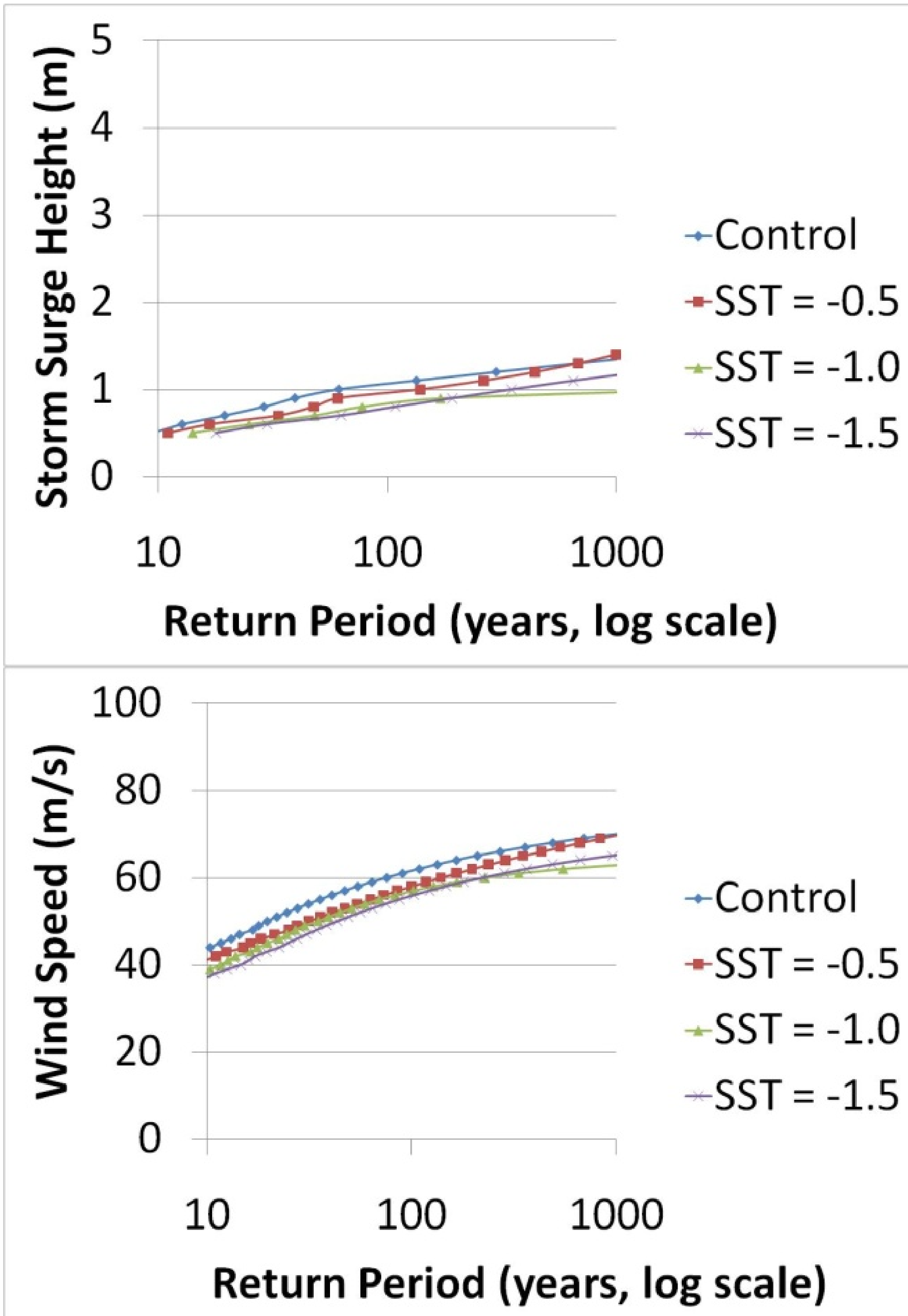


Figure 6.22. Storm surge (top) and wind (bottom) return level curves for Region 1.

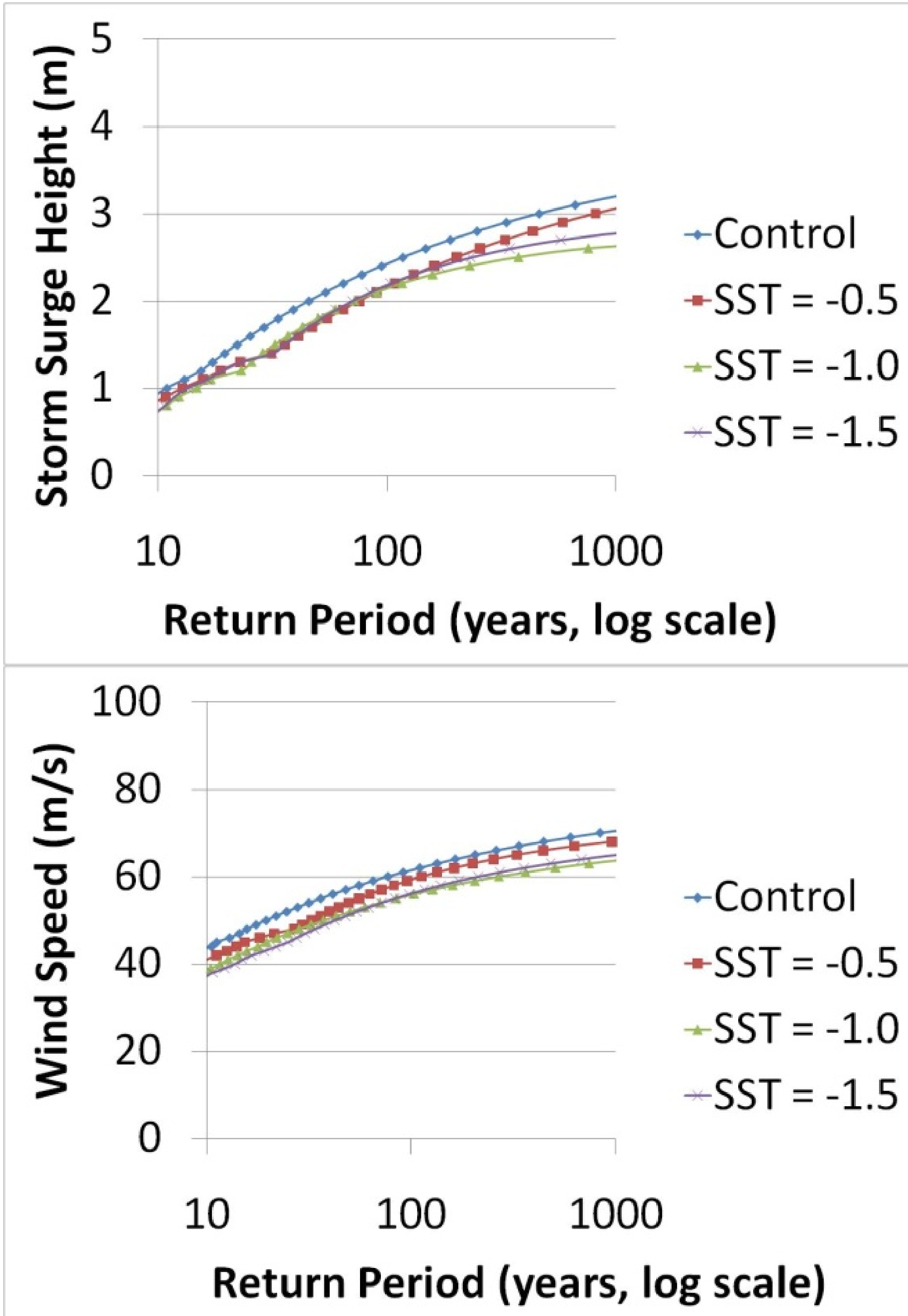


Figure 6.23. Storm surge (top) and wind (bottom) return level curves for Region 2.

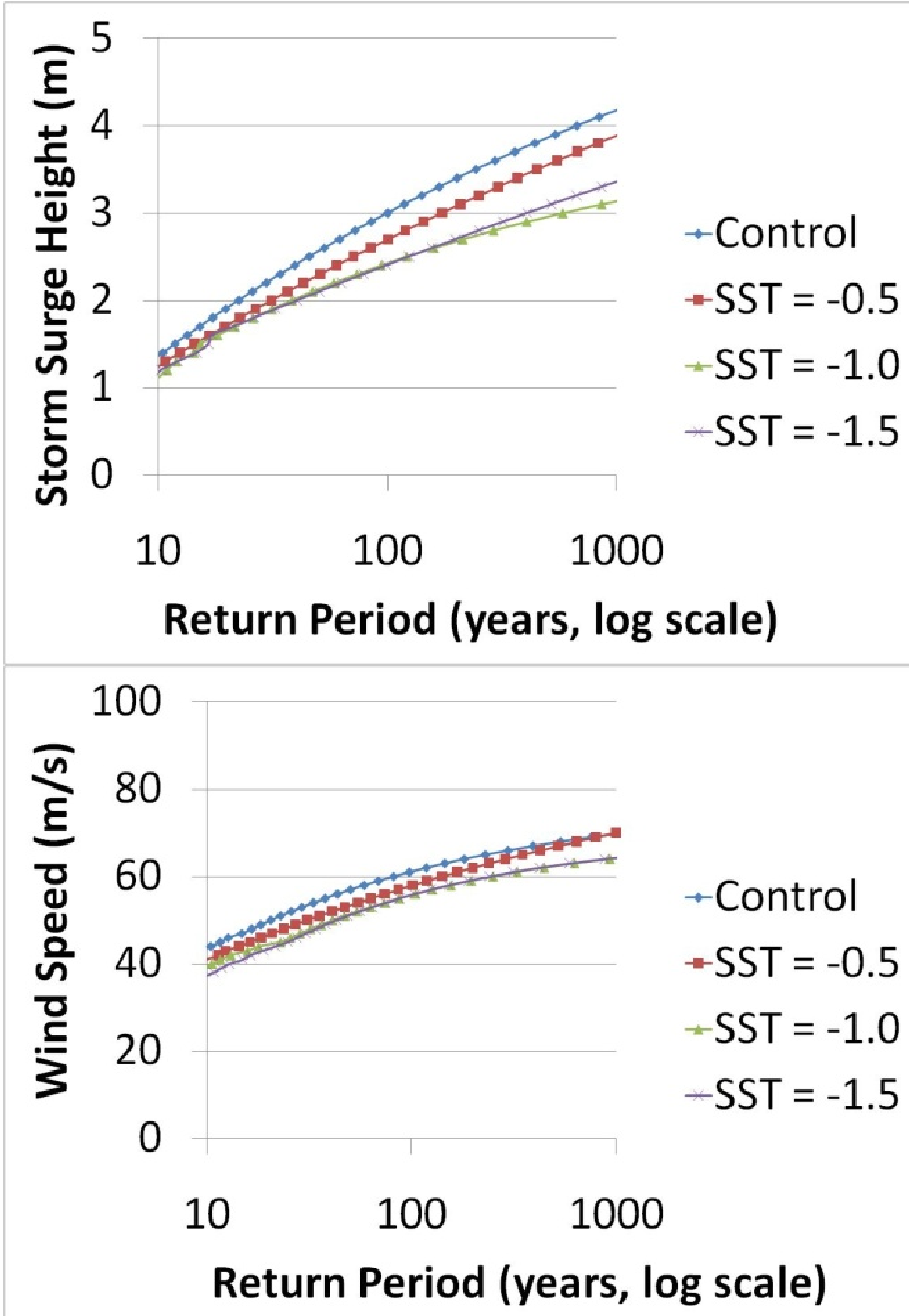


Figure 6.24. Storm surge (top) and wind (bottom) return level curves for Region 3.

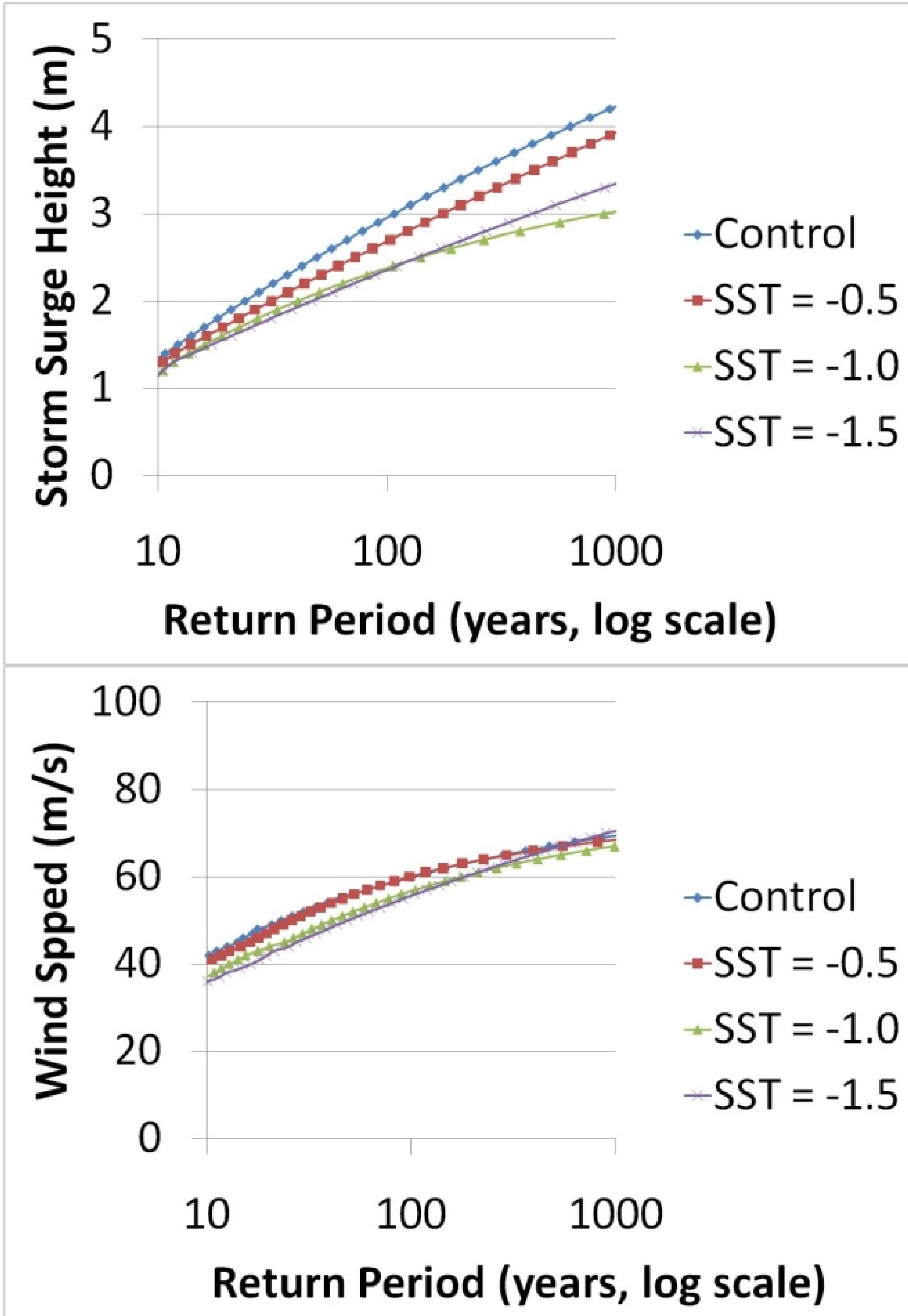


Figure 6.25. Storm surge (top) and wind (bottom) return level curves for Region 4.

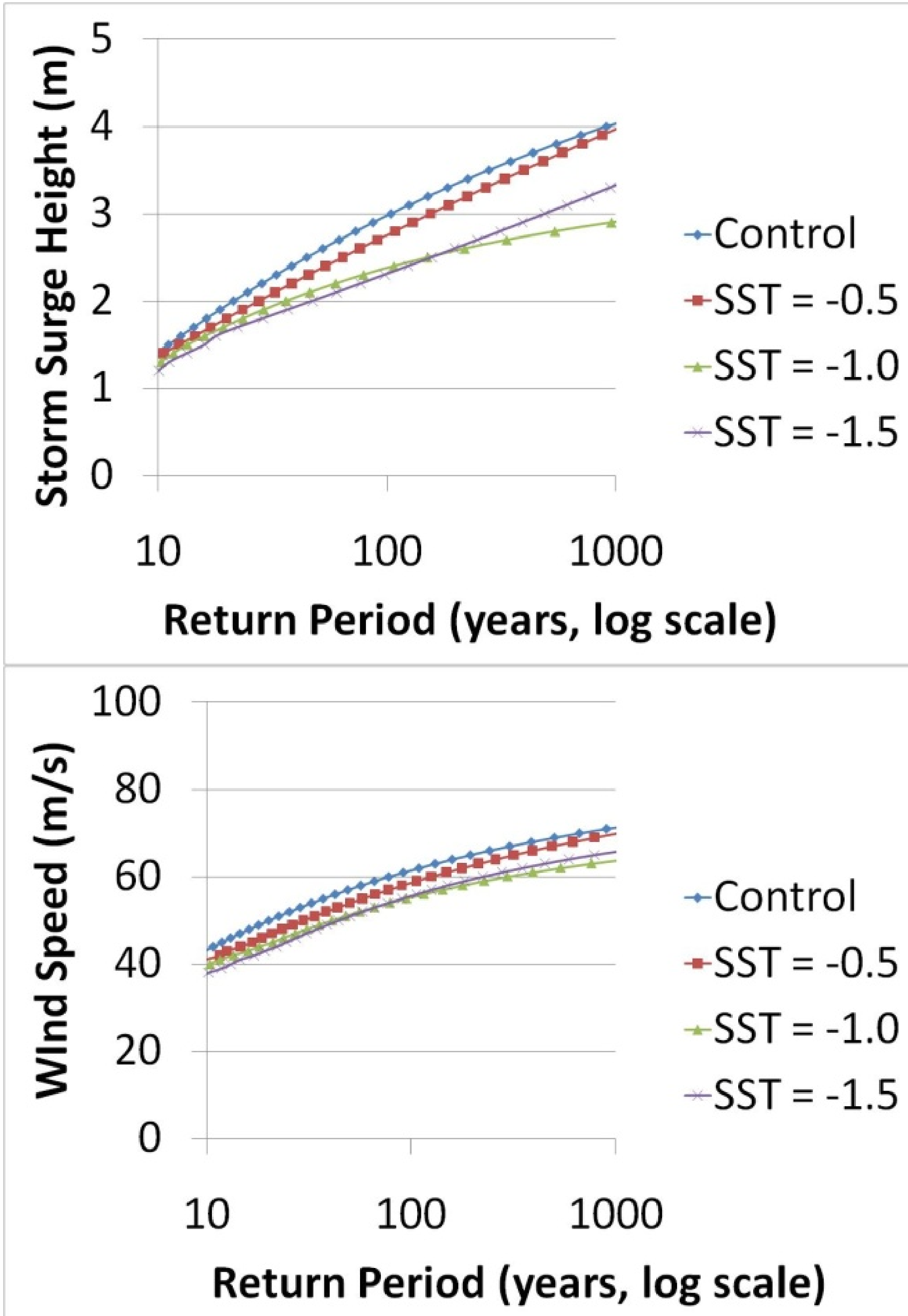


Figure 6.26. Storm surge (top) and wind (bottom) return level curves for Region 5.

Adaptation to reduce storm surge damages: Here I examine three strategies: elevating all residential buildings one foot, elevating all buildings to pile height, and building a surge barrier (or dike).

Recall from Chapter 2 that a lower bound cost for elevating a standard single family home is $40K plus $10K per foot raised up to nine feet. Thus a lower bound estimate to elevate all residential buildings one foot annualized over 30 years at a 5% discount rate is $6.6, $1.7, $4.9, $1.7, and $13.5 million respectively in Regions 1, 2, 3, 4, and 5, while a lower bound estimate to elevate all buildings to pile height is $13, $3.5, $9.4, $3.8, and $26.3 million respectively.

Next I examined surge barrier, or dike. The U.S. Army Corps of Engineers suggests building to a height that would protect against a 100 year event, which from our hurricane surge risk analysis is 1.1, 2.5, 3, 3, and 3 m respectively for Regions 1, 2, 3, 4, and 5. To fully protect the Regions, and assuming dikes would be placed in a line along the coast, these dikes would be of length 3, 4, 5, 5, and 6 km, respectively. As cost likely increases nonlinearly with dike height, the value in Chapter 2 of $4,000 per square meter overestimates costs for the heights of this study (1-3m). Assuming a range of $80-$4,000 per square meter, annualizing over 100 years at a 5% discount rate yields $0.01-1.2, $0.04-2.1, $0.06-3.3, $0.06-3.3, and $0.21-4.7 million respectively for Regions 1, 2, 3, 4, and 5.

Hurricane Modification: In this study, I used the Lin and Emanuel risk assessment model described in Section 3.4 to characterize the relationship between wind-wave pump induced SST change and TC characteristic changes.

As in Chapter 5, seasonal deployment, or covering a large area in front of Miami with pumps for the entire hurricane season, will decrease the SST by 1.0-1.5ºC and is estimated to cost between $0.9-1.5B annually. If pumps were to be deployed in the forecasted path of an intense TC, they would not have time to realize the full SST reduction, but we assume they could be deployed in a much smaller area without maintenance costs. In this case, it may be assumed that successful deployment in front of an approaching TC will decrease the SST by 0.5-1.0ºC and cost $400-700 million total per TC (see Chapter 5).

Additionally, these costs are levied to reduce TC damages over the entire area impacted by the hurricane; here we are particularly interested in the cost and benefit in each selected region. Therefore I distribute a fraction of the total hurricane modification cost to the five regions. Since wind damages are a nonlinear function of wind (in the order of cube of wind speed, *114*), the fraction of total cost depends on the time horizon examined by the policy maker. For instance, a 10 year time horizon would expect to have low winds, and fractional damages in the region would be low. However, a 1,000 year time horizon would have some very high wind events and, with the nonlinear increase of damages, a higher fraction of damages in the region.

For each time horizon, I assume that each region's fraction of total cost is equal to the fraction of the seasonal expected loss (value of damage) in the region compared to the total seasonal expected losses over the entire affected area. The expected seasonal loss is obtained by integrating the loss curve over the annual exceedance probability (the reciprocal of return period). First I calculated a cumulative damage up to the return period range X, weighting the damage of each return period Y by X/Y. Second I divided the cumulative damage by X to obtain the expected seasonal damage.

Damage and loss estimates are discussed in the next subsection. The calculated costs for seasonal deployment were $1.2-$5.6, $1.6-$8.0, $0.3-$2.4, $0.2 - $2.4, $0.4-4.2 million per season respectively in Regions 1, 2, 3, 4, and 5. Also applying the seasonal loss ratio, we estimated the costs for deployment in front of a storm to be $0.6-$2.8, $0.8-$4.0, $0.2-$2.2, $0.1-$1.2, $0.2-2.1 million per storm respectively.

6.1.3. Damage analysis and loss estimation

Finally, for each damage mitigation technique, I used the FEMA HAZUS-MH MR3 damage model and census data on the value of property at risk (*49*, *54*, Chapter 4), to calculate damages and aggregate total losses from wind and storm surge for each scenario.

I used the H-Wind feature in HAZUS-MH MR3 Hurricane Model (*49*) to aggregate losses from wind damage, including total loss, building loss, contents loss, inventory loss, relocation costs, income loss, rental income loss, wage loss, and direct output employment loss.

Following FEMA's Coastal Standard Operating Procedure (*102*), I used SLOSH output, subtracted the appropriate digital elevation model (see Chapter 4) and converted these data to a user defined flood grid. I then used the HAZUS-MH MR3 flood model (*54*) to aggregate total losses for storm surge damages for each return period for all scenarios. Damage values were smoothed along boundaries; further details are given in the Supporting Information.

6.2. Results

Following the method outlined above, I calculated return level curves of the wind speed, surge height, and damage value, as well as the seasonal expected net cost (damage reduction cost plus value of damage). Wind and storm surge analyses are presented separately.

First, I calculated the total damages that result with various adaptation and modification techniques as a function of return period (Figure 6.27-Figure 6.31). Scenarios examined included:

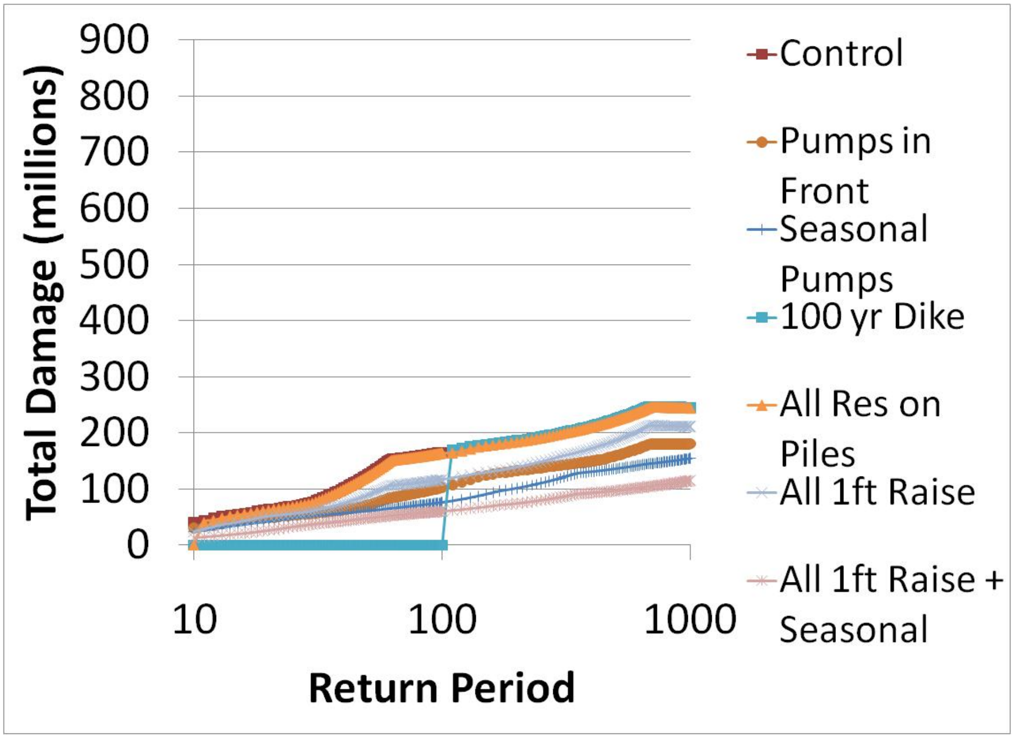
1) control with no damage abatement policies,
2) shutters on all residential windows and doors,
3) the full set of wind mitigation options available in HAZUS (shutters, improved roof-wall

connections, improvement of roof during replacement, and tie-downs),

4) raising all buildings one foot,
5) raising all residential buildings to pile height,
6) building a surge barrier,
7) deployment of wind-wave pumps to modify a specific storm,
8) seasonal deployment of wind-wave pumps, and
9) combinations of adaptation and modification.

Damage reduction values for pump deployment in front of specific storms or for an entire season were calculated by averaging the damages at each return period, respectively, over the 0.5ºC and 1.0ºC trials or 1.0ºC and 1.5ºC trial.

I find that HAZUS does not predict total destruction of property from either wind or storm surge alone even in a 1,000 year period. Since HAZUS is unable to combine wind and storm surge damage, we cannot rule out the possibility of total destruction for long return periods. While all areas experience much larger storm surge damages for short return periods, they experience more wind damages for long periods. Specifically, the return period at which wind damages become larger than storm damages in Region 1 is ~ 30 years; for other regions, the return period at which wind damages become larger than surge damages is just over 500 years. The switch of dominating hazard component results because a) the magnitude of both the storm surge and wind increases in a roughly linear manner with return period, and b) while surge damages are linear with storm surge height, wind damages increase as roughly the cube of the wind speed.



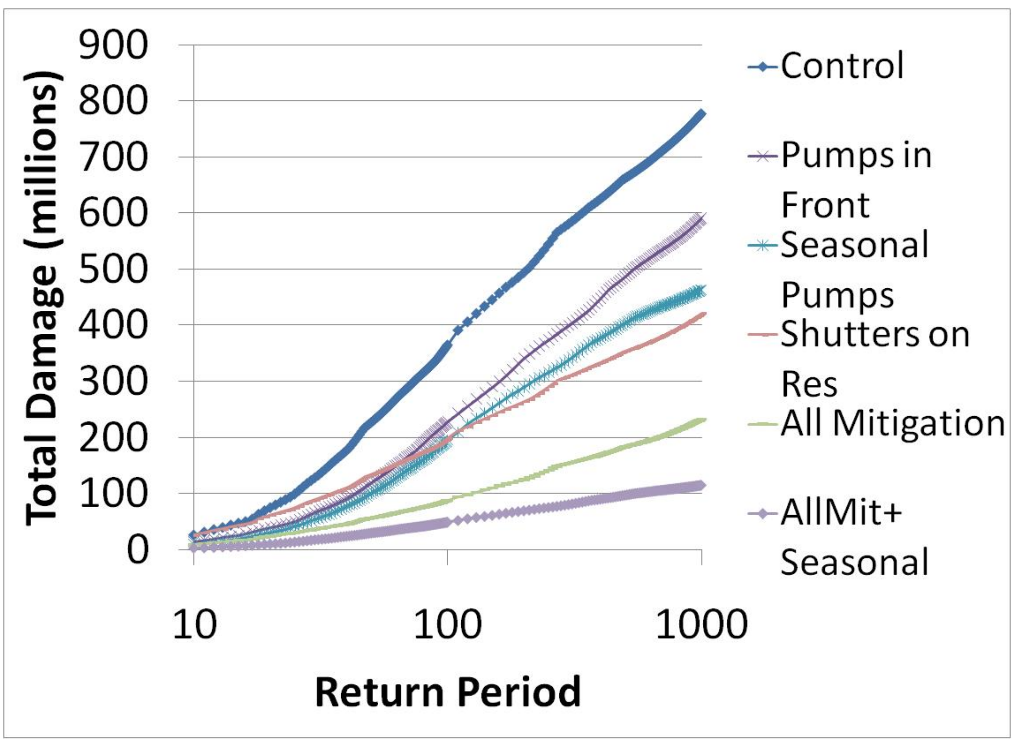


Figure 6.27. Damages methods combating storm surge damages (top) and wind damages (bottom) for Region 1.

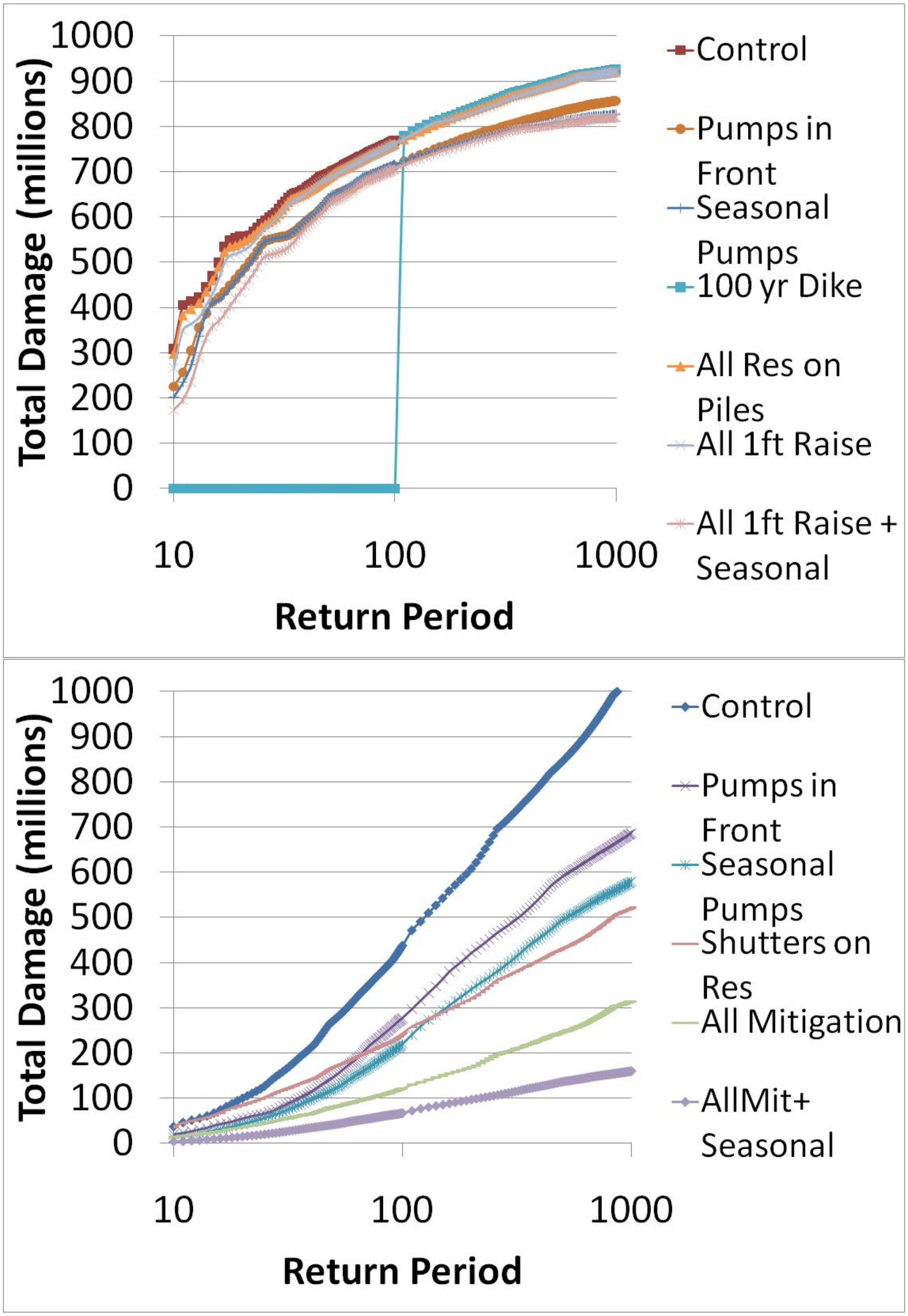
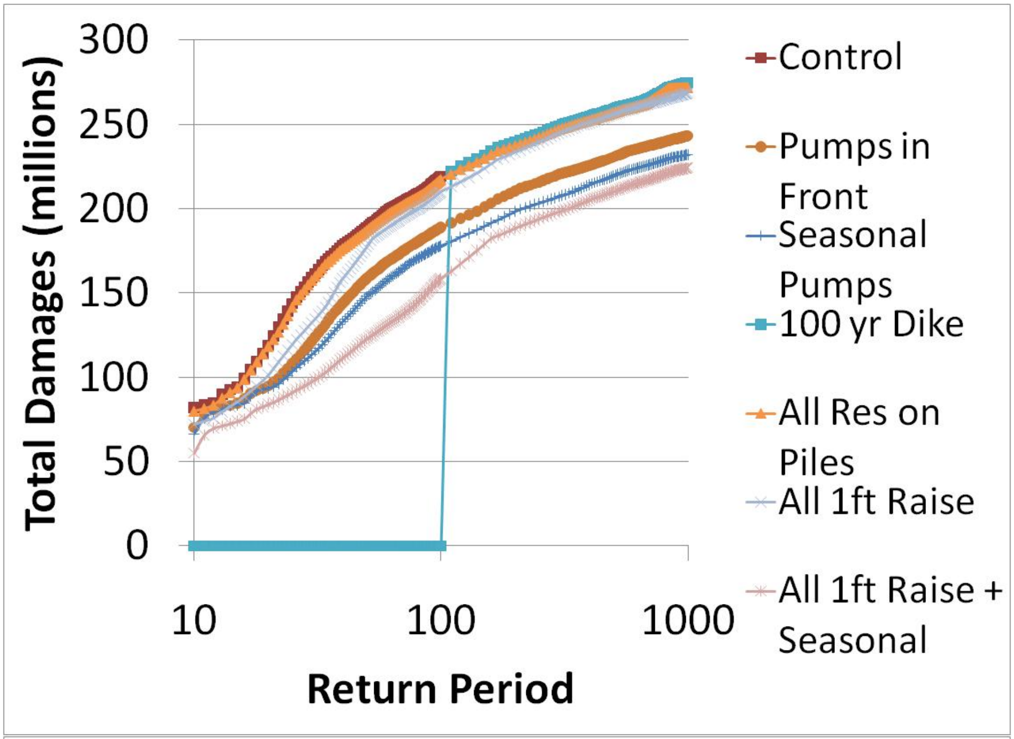


Figure 6.28. Damages methods combating storm surge damages (top) and wind damages (bottom) for Region 2.



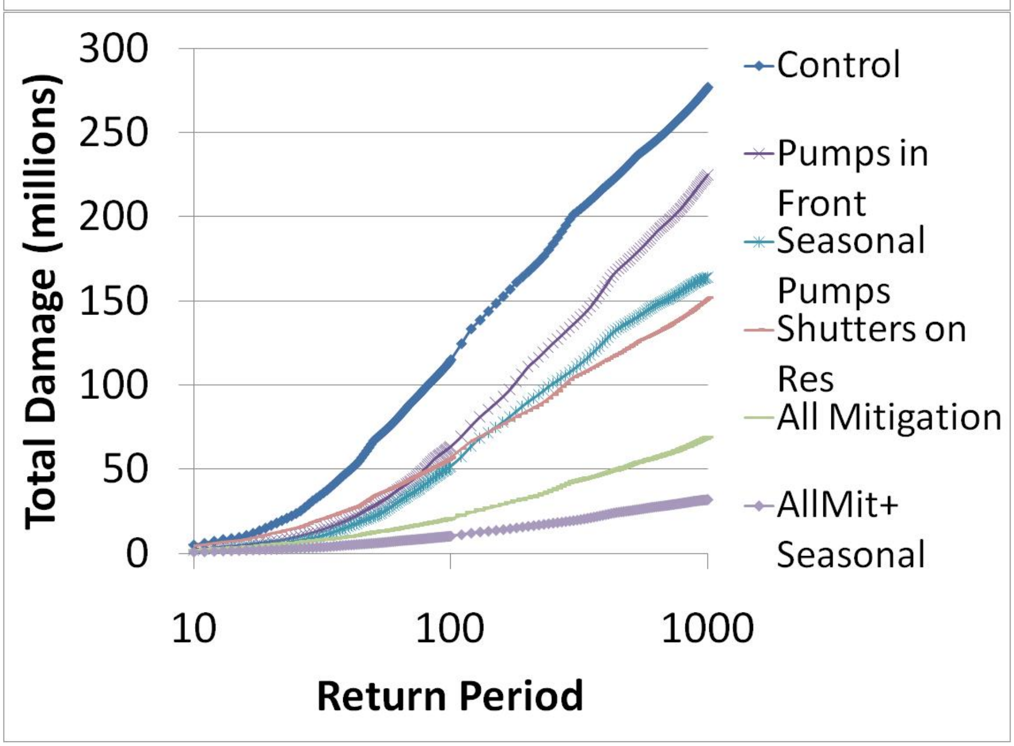


Figure 6.29. Damages methods combating storm surge damages (top) and wind damages (bottom) for Region 3.

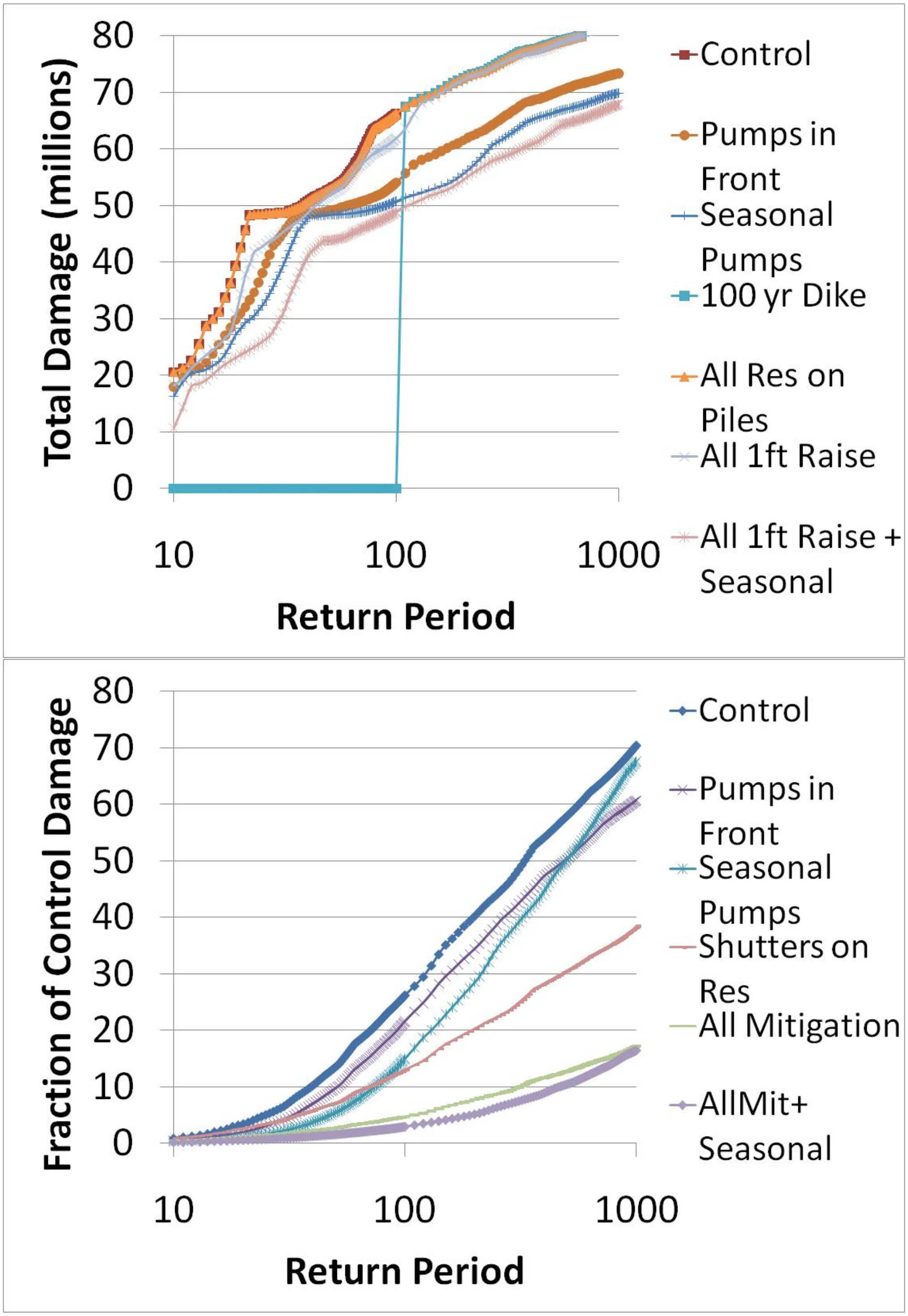


Figure 6.30. Damages methods combating storm surge damages (top) and wind damages (bottom) for Region 4.

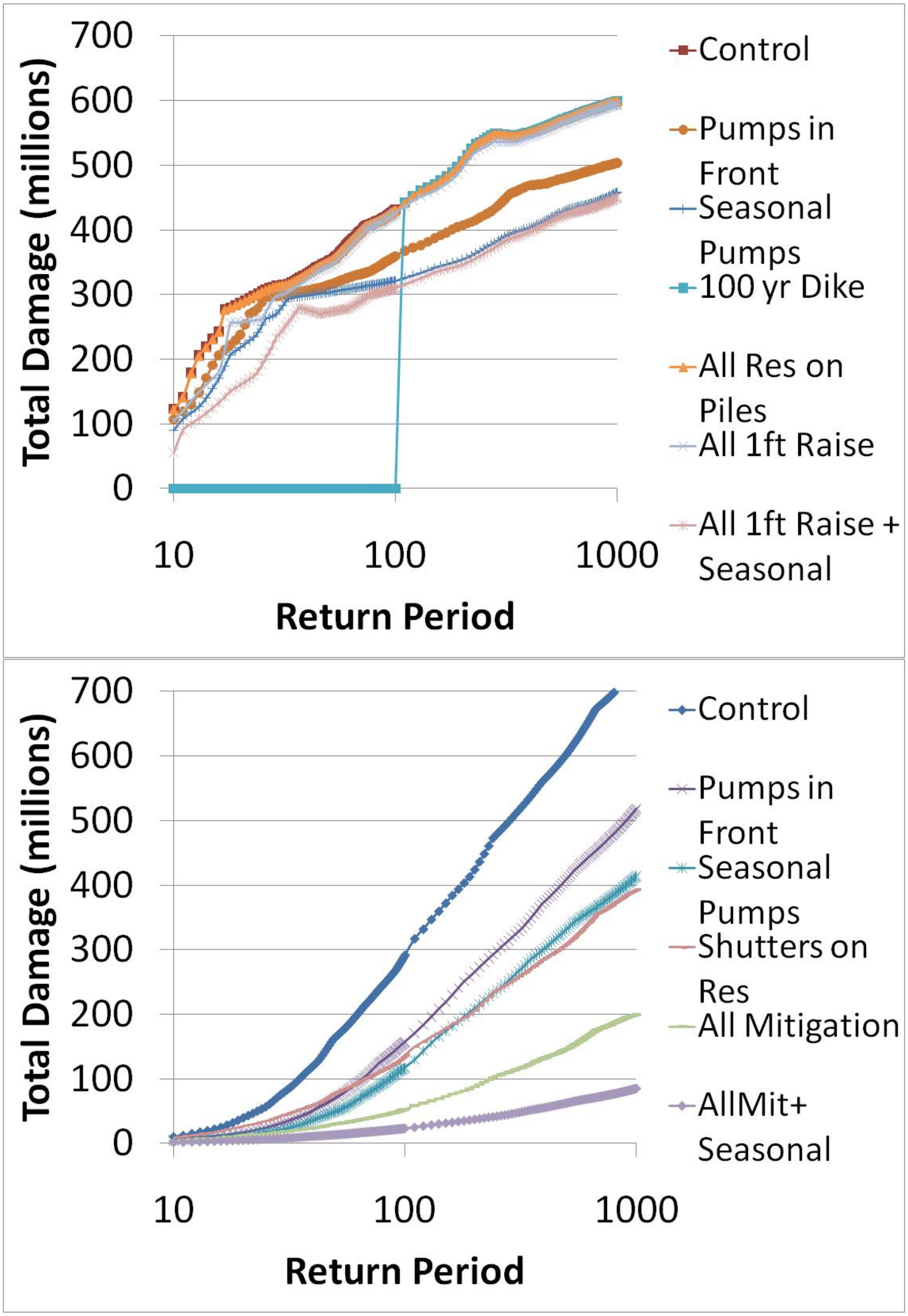


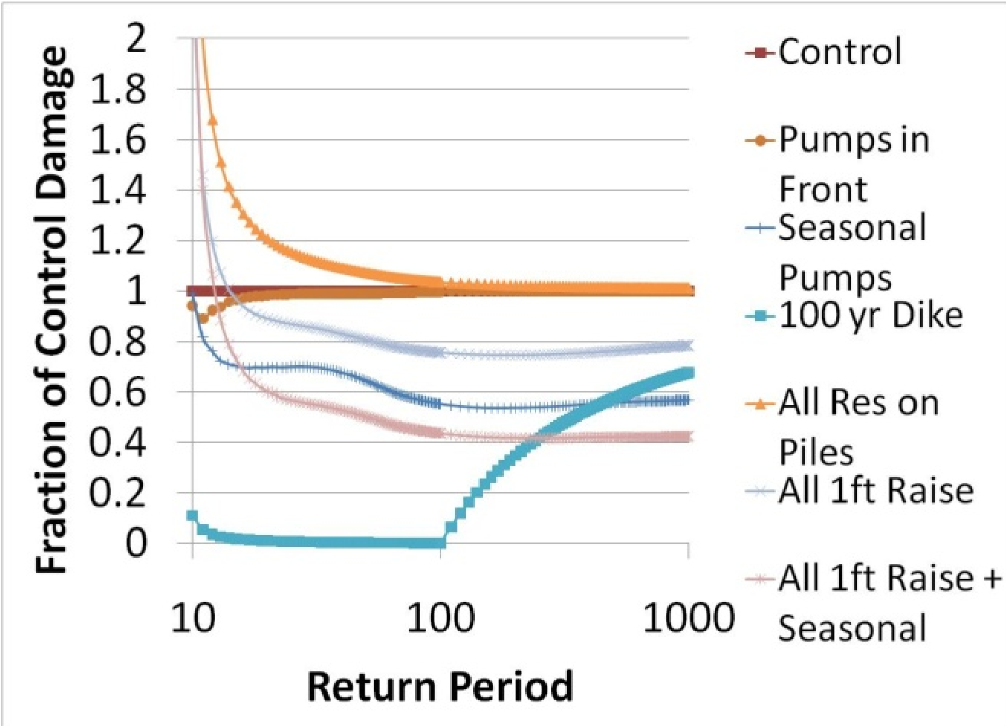
Figure 6.31. Damages methods combating storm surge damages (top) and wind damages (bottom) for Region 5.

Finally I calculated the seasonal expected net cost for each scenario, by adding the seasonal cost to the seasonal loss, as a function of time horizon considered. Figure 6.32- Figure 6.36 show the seasonal expected net benefit defined as the ratio of the seasonal net cost of each scenario over the control seasonal expected loss. Fractional values larger than one indicate a scenario with expected net costs larger than those for the control. High fractional values are expected at short return periods since scenario costs will not have been recuperated.

For wind damage reduction, the all-mitigation scenario dominates because benefits of additional mitigation techniques always outweigh their costs. For surge damage reduction, raising all buildings by one foot dominates raising all residential buildings to pile height because the former raises all buildings, whereas the latter only raises a few residential buildings not already at pile height. Seasonal deployment of wind-wave pumps dominates deployment in front of a specific storm because the former is more effective in reducing damages from each storm (due to 1.0-1.5ºC SST reduction instead of 0.5-1.0ºC reduction), and also protects against the entire season of storms instead of only a single storm. Even assuming deployment in front of a specific storm protects against the largest storm incident in each return period, on an expectation basis, damage reduction from one storm matters little compared to overall damages.

For storm surge adaptation, I find a surge barrier performs best except in Region 1 where a combination of raising all buildings by one foot and seasonal pump deployment is best for return periods longer than 200 years.

For wind adaptation, I find a combination of all mitigation possible in HAZUS and reliable seasonal deployment of wind-wave pumps is always the best choice (assuming that pump deployment and operation are reliable). If techniques are not combined, reliable seasonal deployment of wind-wave pumps performs best at short return periods, while all mitigation possible in HAZUS performs best at long return periods. The cross-over return period varies from 5-20 years depending on the region.



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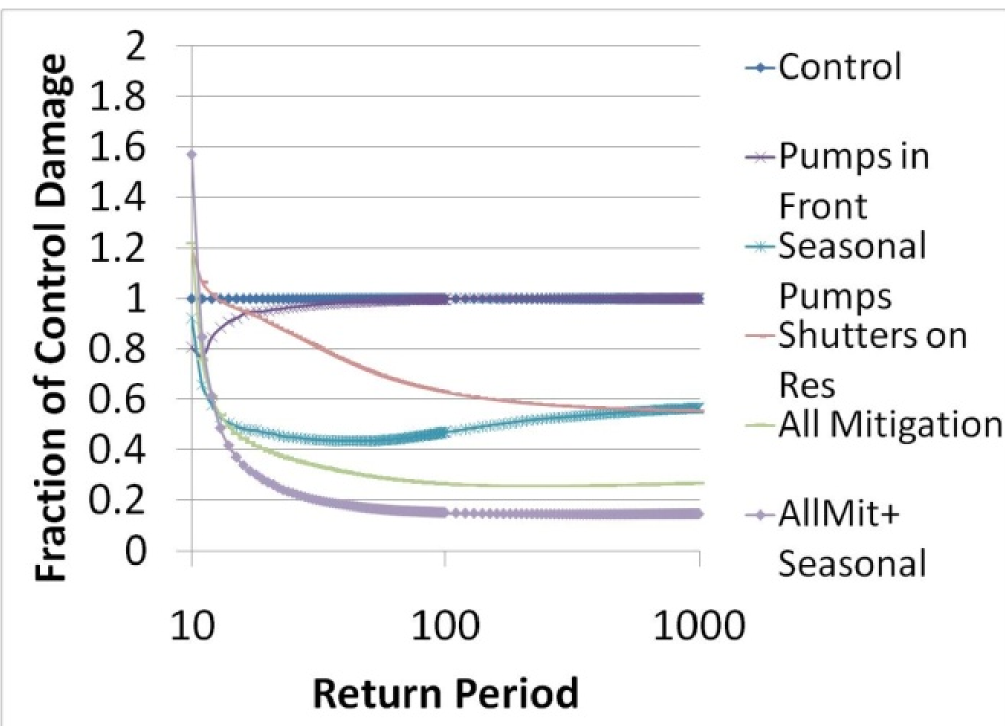


Figure 6.32. Net benefit for methods combating storm surge damages (top) and wind damages (bottom) for Region 1.

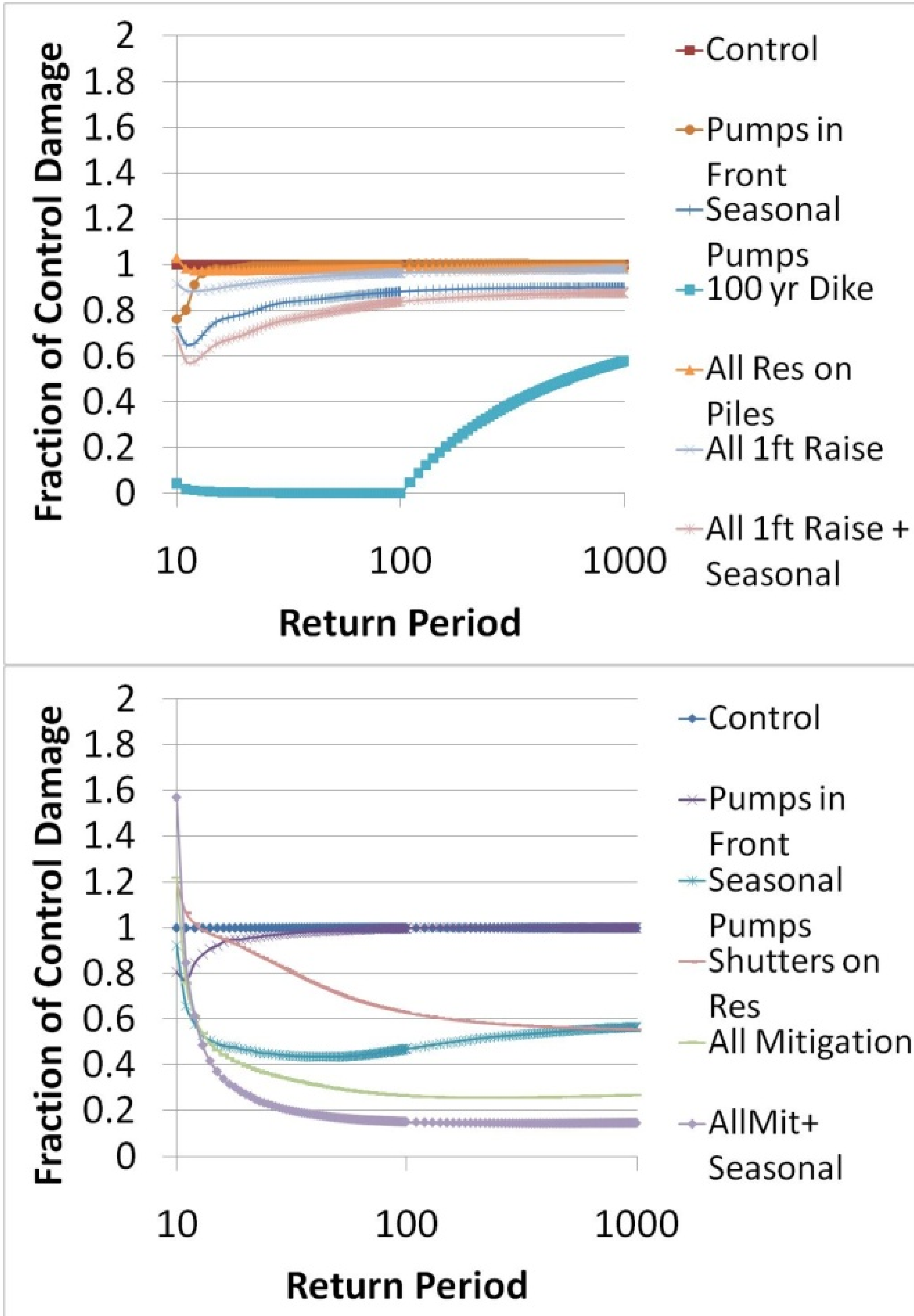


Figure 6.33. Net benefit for methods combating storm surge damages (top) and wind damages (bottom) for Region 2.

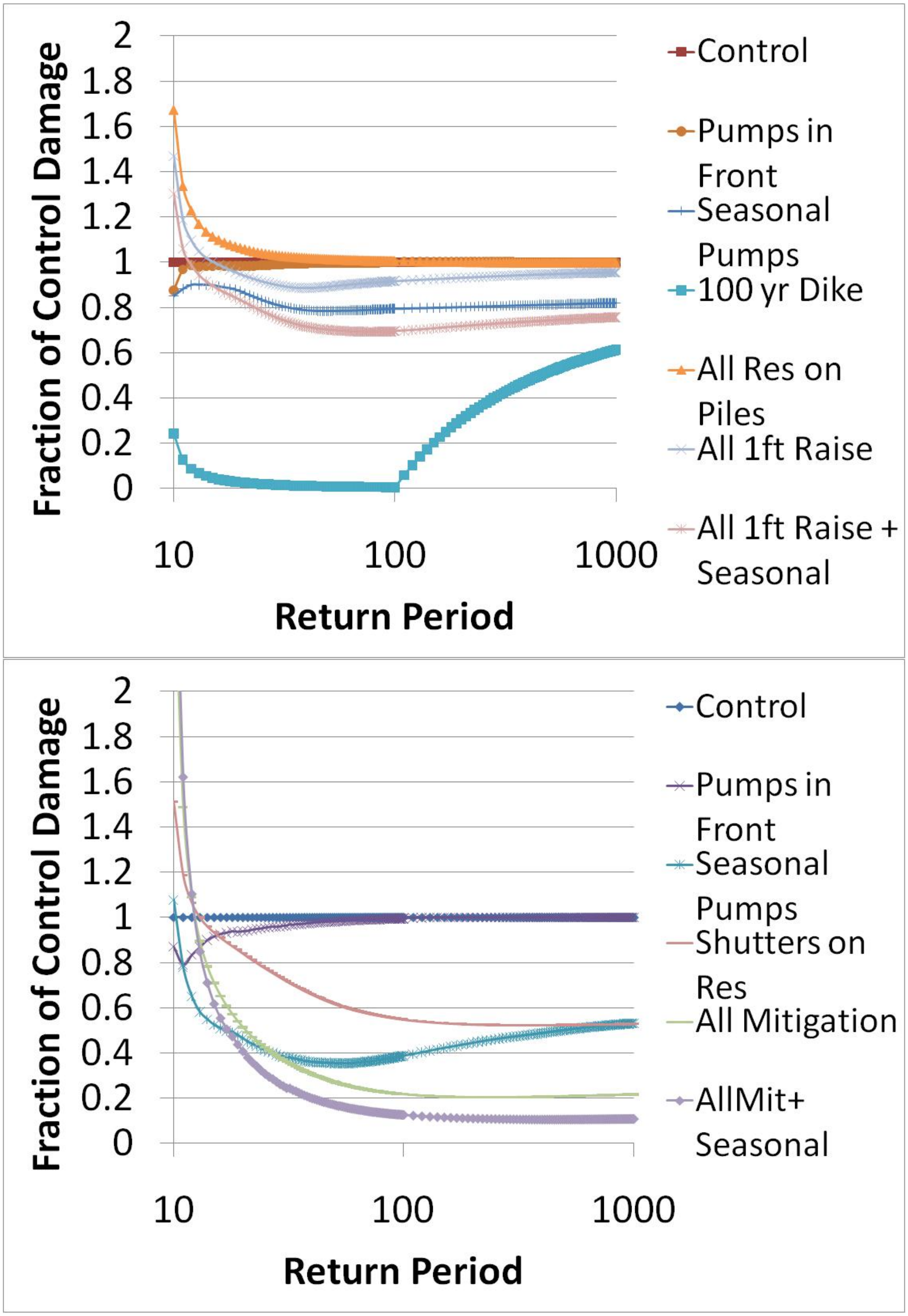
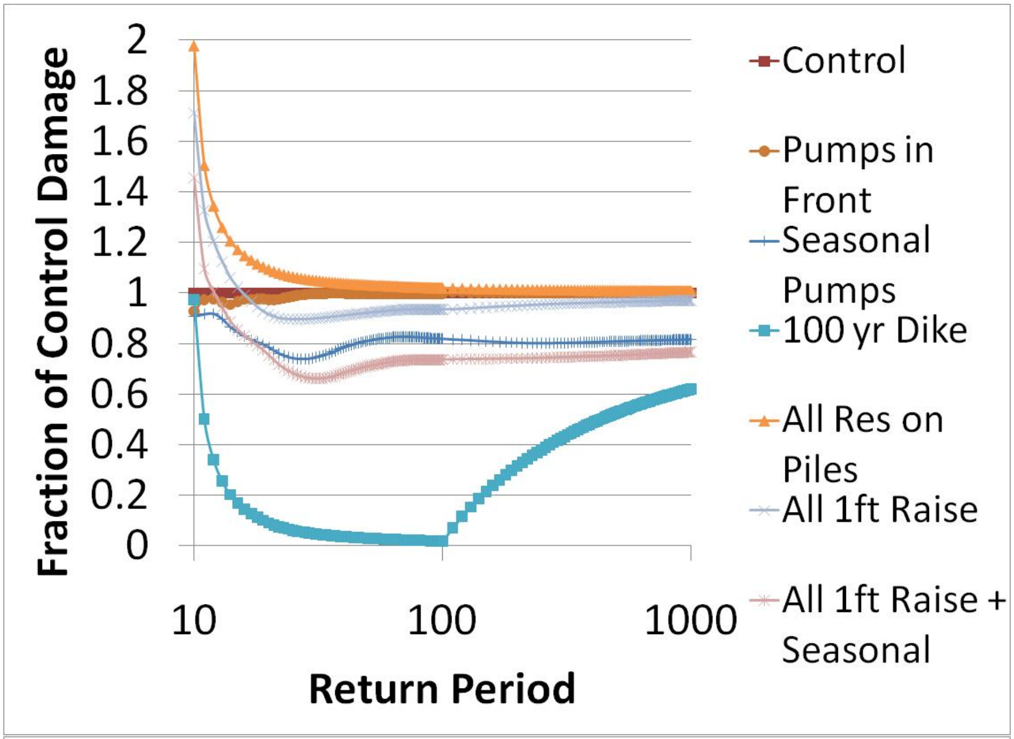


Figure 6.34. Net benefit for methods combating storm surge damages (top) and wind damages (bottom) for Region 3.



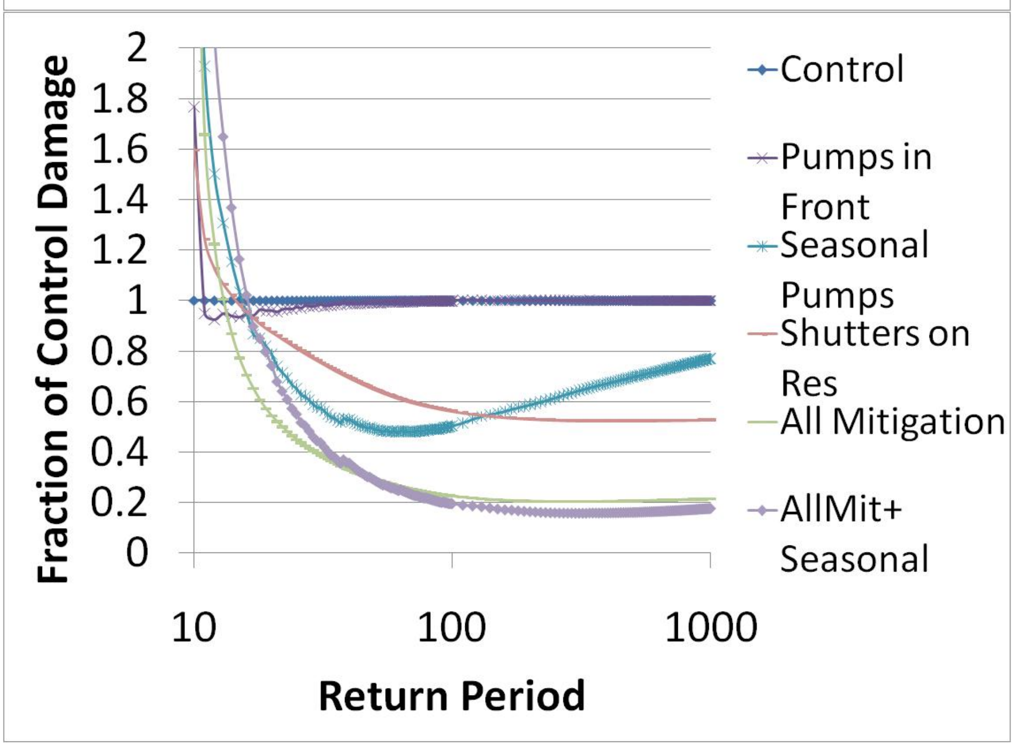


Figure 6.35. Net benefit for methods combating storm surge damages (top) and wind damages (bottom) for Region 4.

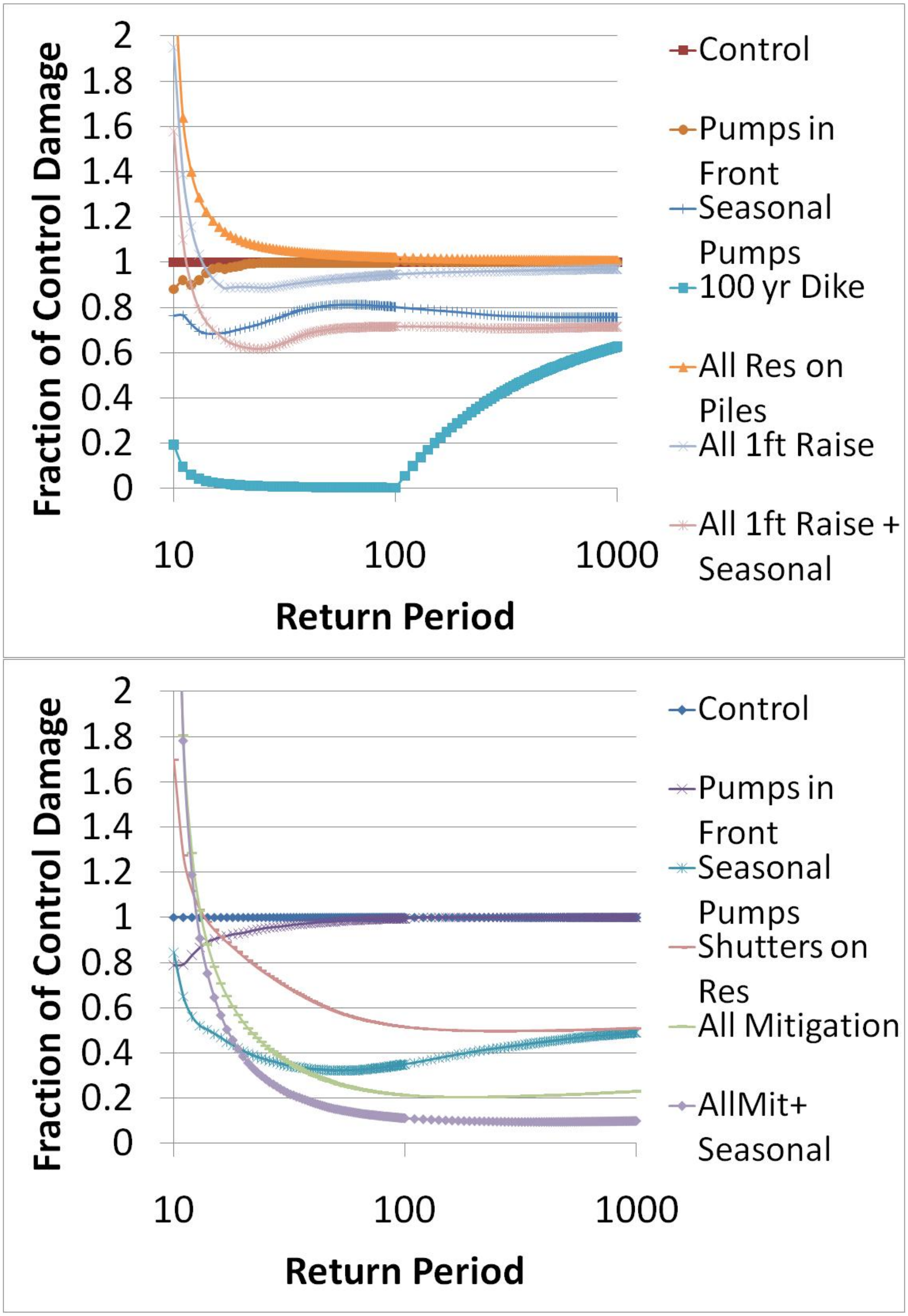


Figure 6.36. Net benefit for methods combating storm surge damages (top) and wind damages (bottom) for Region 5.

6.3. Discussion

Expected storm surge damages dominate expected wind damages in the coastal regions examined. However, storm surge and its response varies across the five regions we examined due to slight differences in topography, bathymetry, and coastal infrastructure. For instance, although Region 2 is “protected” from the open ocean by an archipelago, Region 1 has lower storm surge values. Thus the best method to reduce storm surge damages in Region 1 varies with return period, while the best method is always a surge barrier in Regions 2-5.

For wind, a portfolio of hurricane wind damage reduction techniques is preferred across the regions examined. While wind damages are not dominant in these regions, damages in areas outside of the floodplain will likely be dominated by wind damages. Hence a similar portfolio will likely be best in areas affected by hurricanes but outside of the flood plain.

6.3.1. Is there a “Typical Storm”?

After creating the event sets, it was plausible I could identify a “typical storm” for each return period. Thus I examined storms for the control scenario for Region 1. For each return period, I identified the storm closest to the return period value for wind and storm surge. Wind and storm surge extent are shown in Figure 6.37 and Figure 6.38. To see the effect of spatial variation, we calculated the total economic losses (over all five regions) for the “typical storms” selected for Region 1, as shown in Figure 6.39. Storm surge damages are nonlinear, but monotonically increasing. Wind damage is higher for the return period of 50 years than for longer return periods. This is because that the storm of the 50-year wind for Region 1 may be an extremely intensive wind storm for some other locations in the region.

These results indicate that since wind and storm surge vary greatly over large areas, there is hardly any "typical storm" for a return period over large areas. Local damage risks are not necessarily representative of the risks for larger areas, and therefore the best policy decisions to combat damages on the local level may be different from the best policy decisions at larger scales. In Chapter 5 I examined cumulative wind damage along an entire over-land track, but research on the spatial distribution of the hurricane wind and surge, and methods to combine the two, will be needed to predict long-term damages over large areas.

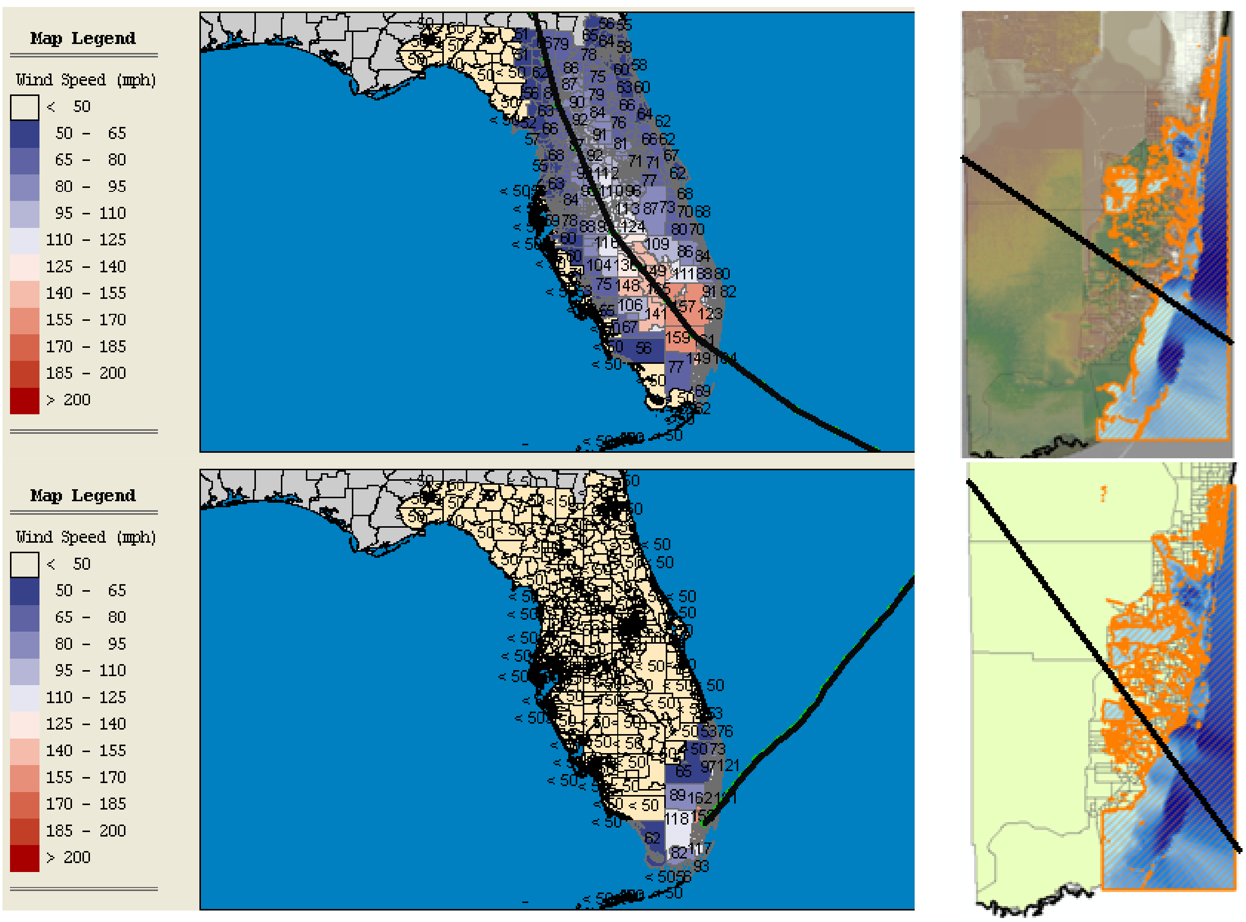


Figure 6.37. Wind speed (left) and storm surge (right) extents over the entire area for the "typical storm" for return periods of 50 years (top) and 100 years (bottom) with respect to the location of Region 1.

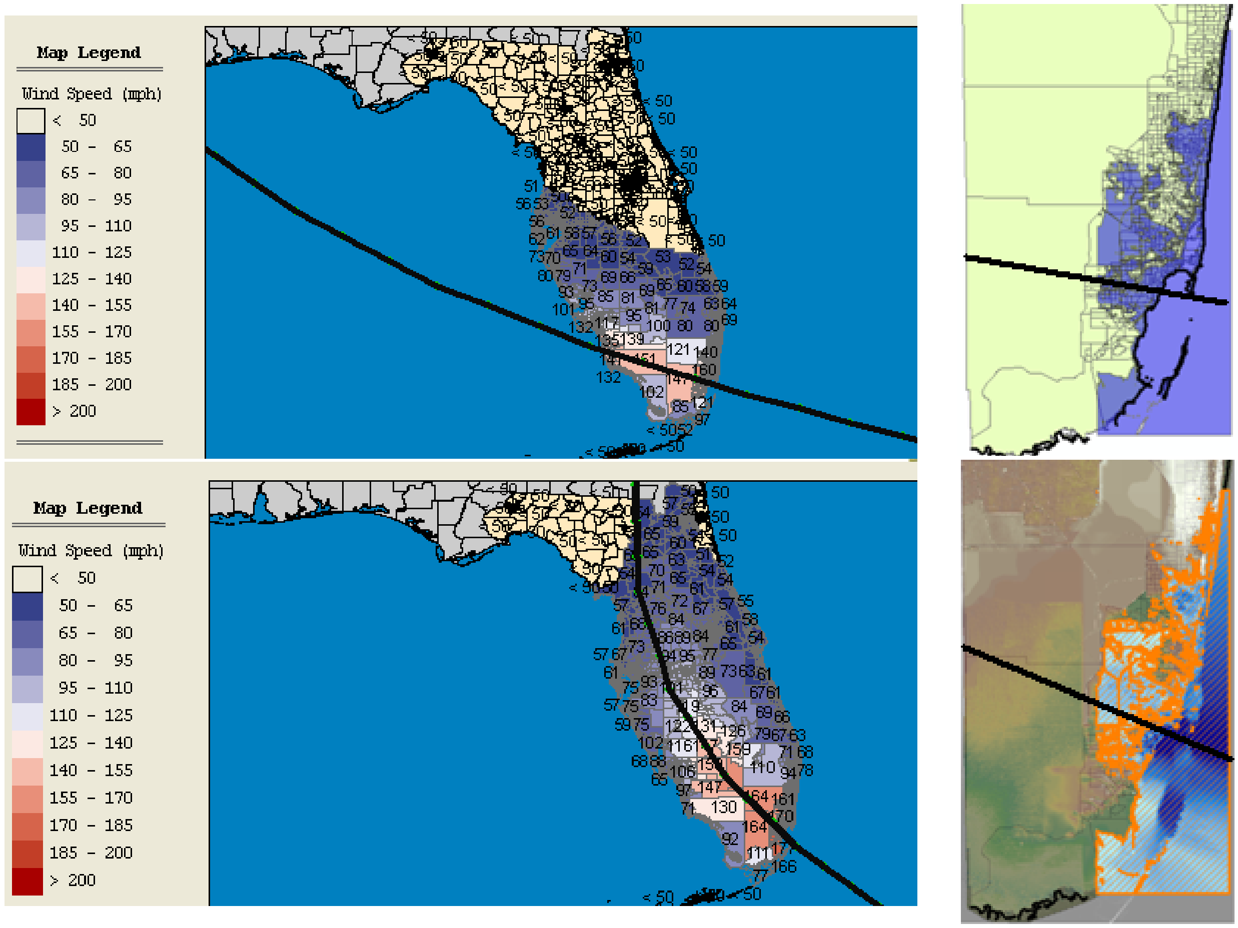


Figure 6.38. Wind speed (left) and storm surge (right) extents over the entire area for the "typical storm" for return periods of 500 years (top) and 1000 years (bottom) with respect to the location of Region 1.

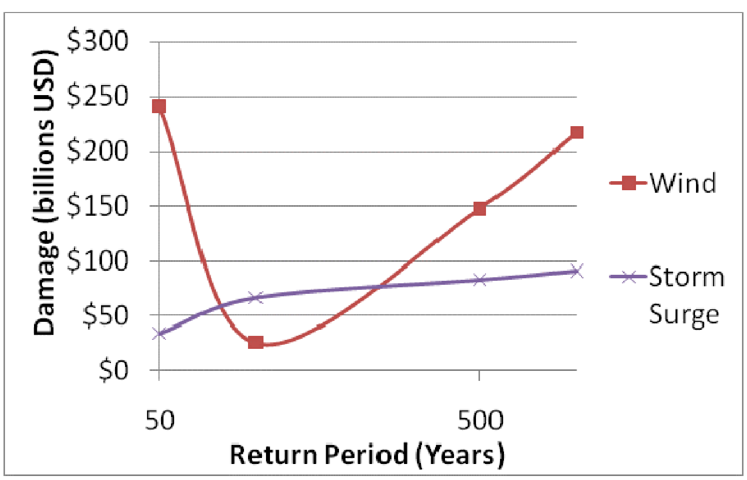


Figure 6.39. Total direct economic losses for the entire storm track for storms in Figure 6.37 and Figure 6.38. Recall all storms had damages in Region 1 matching the smoothed, monotonically increasing damage curve we calculated.

6.3.2. Can Wind and Storm Surge Damages be Combined?

The combination of wind and storm surge damage is also nonlinear and poorly understood (*36*). In some cases, the damages are less than the sum of the parts; for instance the same window might be broken from either wind or storm surge debris. In other cases the total damage is larger than the sum of the parts; a foundation weakened by storm surge might fail when the wind blows on the walls.

I suggest that damages by wind or storm surge would not prevent the other but might overlap; thus a lower bound damage value would be the maximum of either wind or storm surge damages. Table 6.9 gives aggregate damages values for wind only, storm surge only, the area of interest and total of all buildings, and three low bounding methods (by census block, by specific building type, and by both). Note when aggregating by the area of interest and total of all building types, we must choose either the total of all storm surge or wind damages; when aggregating at finer resolution, we can choose the maximum of the wind or storm surge in each sub-area. We find that examining damages on the finest resolution possible, census block and building type, consistently provides a damage estimate ranging from ~0.1 to 16% higher than either the wind or storm surge estimate alone. Most of the information is captured by aggregating at census block; dependency on census block occurs because storm surge damages dominate on the coast, while wind damages dominate inland. Dependency on building type occurs because some specific buildings suffer disproportionally more damage from one damage type than the other.

Due to the nonlinearities in combination in the coastal area we examined in this study, we can neither provide an upper bound lower than 100% nor make a statement about how double counting affects these conclusions. However, since storm surge damages dominate in these coastal regions, eventually a strategy of only protecting against wind damages will be overwhelmed by large storm surge losses. Further study of both the correlation between hurricane wind and surge and the correlation between wind and surge damages is needed to assess the likely efficacy of TC modification and adaptation.

Table 6.9. Aggregate Values in Millions USD for 50 year return period

		Region				
Damages	Aggregation Level	1	2	3	4	5
Wind Only		$227.05	$272.17	$52.16	$13.12	$164.50
Storm Surge Only		$124.72	$695.94	$188.51	$52.79	$351.31
Lower Bound: Maximum of wind and storm surge values	Area of interest, Total of All Buildings	$227.05	$695.94	$188.51	$52.79	$351.31
	Census Block, Total of All Buildings	$263.15	$734.89	$189.00	$53.13	$395.22
	Area of interest, Specific Building Type	$238.99	$697.85	$188.51	$52.79	$372.23
	Census Block, Specific Building Type	$264.76	$738.62	$189.00	$53.13	$395.30

Chapter 7. Public Perceptions

Portions of the discussion in this Chapter are based on Klima, K.; Bruine de Bruin, W.; Morgan, G.; Grossman, I. Public Perceptions of Hurricane Modification. Accepted 2011 at Risk Analysis.

Although research on modification is being done, no one has looked into how the public perceives this possibility and what kind of emotions might be involved if the government were to decide to do some experimental modification on an approaching hurricane. As with any new technology, the feasibility of implementing hurricane modification will depend on how people respond to the technology. For example, public resistance to nuclear power plants has likely been a key factor in limiting its contribution to the United States electricity mix to about 20% (*115*). Risk perception research has suggested that people respond more negatively to technologies that are perceived as novel and as having a large potential for catastrophes leading to a large number of deaths (*116*). Moreover, initial negative reactions may influence subsequent evaluations of a technology, with stronger negative affect being related to the perception of greater risk and less benefit (*117*). Especially with new technologies, people may lack sufficient understanding to evaluate their usefulness. In addition, hurricane modification raises serious questions about liability, ethics, and risk tolerance that do not arise in the absence of interventions to modify a storm (*30*). Hence, to foster an informed public discourse about whether to support hurricane modification, and, if so, how to deal with its consequences, policy makers need to effectively communicate the risks and benefits of hurricane modification (*118*).

To date, relatively little is known about how people will respond to the possibility of experiencing damages from a modified hurricane as compared to a hurricane that is left to run its natural course. Instead, most research to date has examined public perceptions of naturally occurring hurricanes, the associated emotions, and hurricane preparedness (*40*, *119, 120, 121, 122, 123, 124, 125, 126*). Recent work has reported that perceptions of hurricane risk are higher among Florida residents living in high-risk areas (*40*) and those who have previous experience with hurricanes (*127*). Willingness to prepare for future hurricanes is greater among people who have experienced disastrous hurricanes in the recent past (*128, 129, 130, 131*). The implementation of hurricane preparedness strategies such as hardening homes, creating home disaster kits, and planning for evacuation has increased among residents of those Florida and the Gulf coast areas that were threatened during the 2004 and 2005 seasons (*132*).

The prospect of hurricane modification may evoke feelings of anger and blame, especially when it is easier for people to generate a counterfactual in which a different action would have led to a better outcome (*133*). Indeed, social science research has suggested that counterfactual thoughts and related anger are more likely in unpleasant situations, such as accidents, that are caused by actions rather than inaction (a phenomenon known as omission bias, (*134*)), and by actions that are non-routine rather than routine (*135*). Because hurricane modification involves non-routine actions, residents who are affected by a hurricane after a hurricane modification attempt are likely to feel angry.

However, feelings of anger may be tempered if people perceive that chance played a role in producing the observed negative outcomes, of for example a car accident (*136*). Scientists agree that predicting the results of hurricane modification involves large uncertainty, both regarding the natural changes in hurricanes as well as the effect of the modification effort itself (*35*). As a result, hurricane modification efforts may leave the projected path and intensity of a hurricane unchanged, or might be followed by damages that are worse than originally projected – but no worse than what might have been experienced without modification. If residents of hurricane-prone areas understand the scientific uncertainty inherent in hurricane forecasts, they might be less angry about any negative outcomes experienced after hurricane modification – especially if the experienced damages were worse than initially predicted. Decreased anger may, in turn, lead to a decreased tendency to initiate legal action.

To improve people's understanding of the uncertainty inherent in predictions about hurricanes, forecasters typically include a "cone of uncertainty," which shows the projected track of the center of a hurricane three to five days into the future, surrounded by a highlighted area reflecting a margin of error. This margin of error is chosen such that two-thirds of similar past hurricanes fall within the cone of uncertainty. Because the potential deviation from the projected track increases when forecasting further into the future, the display of the margin of error looks like a cone (*137*). Based on archival research of Florida newspapers, responses to a National Weather Service request for comments on their cone of uncertainty graphic, and other survey research, it has been suggested that people underestimate the uncertainty presented in the cone-of-uncertainty graphics typically shown in hurricane forecasts, incorrectly assuming that they are safe if their area is not included (*138*). Given this misunderstanding, they could be expected to respond with anger and accusations of blame if hurricane modification results in efforts that are different from those that they thought to have been predicted.

Here, I examine public perceptions of hurricanes and hurricane modification efforts to alter projected paths and wind speed. I used Carnegie Mellon's mental models methodology to examine public perceptions (*118*), which has previously been used to examine people's beliefs about such diverse topics as sexually transmitted diseases (*139*), carbon capture and sequestration (*140*), radon in homes (*141*), and climate change (*142*, *143, 144*). Developed to inform the design of risk communication materials, this method aims to improve researchers' understanding of people's beliefs or "mental models" about the topic under consideration. To this end, it begins with a small set of formative "mental models interviews." Research questions are derived from these interviews and subsequently tested in surveys with larger samples that provide statistical power. For example, interviews about climate change first revealed the perhaps surprising misconception that nuclear power plants are a cause of climate change, which were then confirmed in survey research (*142*, *143, 144, 145*). Indeed, surveys that are based on formative interviews are more likely than conventional surveys to include questions about beliefs that are relevant to the target audience and use wording respondents understand (*146*).

In the first stage, I conducted a small set of semi-structured interviews with the aim of identifying people's relevant knowledge and beliefs, also referred to as their mental model, as well as the wording used to describe them. In the second stage, closed-form surveys were administered with a larger sample to examine how beliefs correspond to people's acceptance of hurricane modification techniques.

7.1. Formative interviews and resultant survey hypotheses

7.1.1. Sample

To inform the design of the survey about public perceptions of hurricane modification, I interviewed ten Miami Florida residents. The sample included five women and five men; seven who lived in houses, and three in apartments. All ten had a high school education, and four additionally held a college degree.

7.1.2. Procedure

Interviewees responded to an online ad targeting the Miami Florida area: "Researchers at

Carnegie Mellon University are conducting 45 minute telephone interviews to find out what people know about hurricanes. You will receive $50 for your participation. To be eligible, potential interviewees must (a) currently live in Florida, (b) be available for a 45 minute uninterrupted telephone interview, (c) be fluent in English, (d) be at least 18 years old, (e) be able to do the interview in a quiet room." Participants signed up through an online calendar and were given a toll-free telephone number to call at their scheduled time.

Following the mental models approach (*118*), the semi-structured interview protocol included general, nondirective questions guiding interviewees through topics relevant to hurricanes, damage reduction, and hurricane modification. To reveal the depth of interviewees' knowledge, I prompted for details on each issue that was raised in response to the standard protocol questions, while maintaining a friendly and nonjudgmental tone. After completing the interview, participants received a $50 Amazon gift certificate.

Appendix A contains the questions; below is a brief description.

As is common in the mental models approach, the interviews began by asking general questions, to avoid suggesting relevant topics or wording. The first question was "Could you start by telling me about the effects of hurricanes?" Participants were encouraged to expand on their own remarks. Subsequently, interviewees received more direct questions about *hurricanes and damages* (e.g., "What are the effects of hurricanes?") and *damage reduction* (e.g., "What can be done to avoid or prevent or reduce the damages caused by hurricanes?"), each of these questions were followed by encouragements to talk more.

Next, I examined interviewees' ability to understand hurricane *forecast uncertainty* by asking (a) "During hurricane season, how do you learn about when hurricanes are coming?", (b) "How good do you think hurricane forecasts are?" and (c) "How much of the problem is because scientists don't understand hurricanes, and how much is because sometimes nature can't be perfectly predicted?" The order of the two questions in this last prompt was varied across interviews.

Subsequently, interviewees were asked to define specific terms, such as "storm surge." Even if interviewees had not discussed hurricane modification, they were asked whether they had ever heard about "the possibility of changing hurricanes to reduce their damage" or "making the winds of the hurricane less strong, without changing the path of the hurricane." Those who gave an affirmative answer were encouraged to elaborate. Additionally, participants were asked whether undertaking such modifications "would be a good or a bad thing." All indicated how they would feel if faced with five different <u>hurricane modification scenarios</u> that varied their degree of success, including (a) scientists tried to slow down a hurricane but it ended up getting stronger, (b) scientists couldn't change a hurricane and it hit their area (without specifying whether scientists tried to change path or intensity); (c) a hurricane didn't hit their area but hit another area; (d) a hurricane that was headed for another area ended up hitting theirs (or: the interviewee's area); (e) a hurricane that was headed for another area significantly weakened, but the hurricane ended up hitting their area.

Finally participants reported demographic information.

7.1.3. Results

Given the very small sample size, the interview study was not designed to draw confident conclusions but to inform the phrasing of survey questions. I identified four key insights from the interviews, which I used to inform the design of the survey. Here I first discuss the background knowledge of the interviewees. Then I discuss results pertinent to the four following research questions:

1) Are people aware of the idea of hurricane modification and do they perceive it to be an ineffective strategy for damage reduction?
2) Is hurricane modification expected to cause changes in the expected path and/or strength of hurricanes?
3) After modification has been attempted, does a change in the projected path or strength of a hurricane evoke anger?
4) How is knowledge of forecast uncertainty related to anger about modification of the path and strength of hurricanes?

7.1.3.1 Background knowledge: Are the interviewees knowledgeable about hurricanes?

All ten interviewees had experienced hurricanes, with five specifically mentioning Hurricane Andrew. All discussed the damaging effects of hurricanes, with seven referring to wind damages (e.g. "windows shaking, it's like the worst rainstorm you've ever seen"), two of whom also mentioned rain (e.g. "it's like the worst rainstorm you've ever seen"). All of the ten interviewees had heard of a Category 3 storm, and after prompting, nine included wind speed in the description. Six interviewees had heard of storm surge; five interviewees suggested storm surge was synonymous to flooding, while only one recognized storm surge caused damages separately from floods.

All interviewees listed damage reduction strategies they could implement themselves to reduce damages from hurricanes. For instance, nine cited weatherproofing (hurricane shutters/windows, better roofs), six listed moving belongings indoors (secure patio furniture, removing things from the backyard, parking the car inside), five mentioned yard maintenance (trim trees), and six "hunkering down" (keep people/pets inside, away from non shuttered windows, stay off the streets afterward so the police/firemen can do their jobs, and in some cases evacuate). Interestingly, seven interviewees said that their general strategy for reducing damages was to "be prepared," which was explained as having enough food and water, as well as batteries and a generator. None mentioned strategies that they themselves or policy makers might implement to decrease flood damages. Three mentioned that policy makers might use regulations and building codes to encourage residents to protect themselves. As indicated above, only one discussed even a vague form of hurricane modification.

7.1.3.2 Are people aware of the idea of hurricane modification and do they perceive it to be an ineffective strategy for damage reduction?

When asked about strategies for reducing damages from hurricanes, none of the interviewees spontaneously mentioned hurricane modification as a strategy for damage reduction. Only one person referred to climate, but not people changing climate ("if the water is cold… [there] would probably be less of a chance of a hurricane"). After being prompted to generate more options, one interviewee mentioned "cool the oceans down", one suggested "stop global warming", and two discussed at length whether the Gulf oil spill would worsen the hurricane season. When asked whether they had "ever heard about the possibility of changing hurricanes to reduce their damage," five said no, questioning its effectiveness with statements such as "it will never be possible," "you can't change nature," and hurricanes are "too big and powerful to be changed." The other five interviewees said that they had heard about the possibility of changing hurricanes, but suggested implausible scenarios such as "putting giant fans on the coastline" or "in movies and stuff, like flying over the eye or something and dropping something" (*147*). None used the term "modification" in their response, but instead said "change." One interviewee stated "I think that [scientists and the government] would try their best if they could", and another said "It's just in the name of science, go ahead and try it." All other interviewees felt more negative about hurricane modification, for example stating that the government might be "using some kind of secret weapon or something."

7.1.3.3 Is hurricane modification expected to cause changes in the expected path and/or strength of hurricanes?

When discussing the idea of changing hurricanes to reduce damages, no interviewees explicitly interpreted hurricane modification as the possibility of changing the intensity. One interviewee assumed it was referring to efforts to change the direction (e.g. "you could change the path, that would be cool, you could steer it away from major population centers."). After being prompted, seven participants explicitly stated they had never heard of the possibility of "making the wind of a hurricane less strong without changing the path of a hurricane." All interviewees stated that "changing a hurricane to reduce its damage" was preferred to no change. Nevertheless, two interviewees expressed reservations that changing hurricane intensity may also have far reaching effect on the atmosphere (e.g. "For the people affected, good, but dealing with our atmosphere, and energy forces… unsure".)

When asked questions about scientists trying modification and the hurricane getting stronger or remaining unchanged while hitting their area, all interviewees seemed to perceive that the scientists had intentionally tried to steer the storm in the observed direction. Moreover, when asked about the scenario in which scientists tried to change the storm without succeeding, no one considered that the scientists might have been trying to reduce the intensity of the wind, or that the storm changed due to natural variability. Note that these responses were observed even after interviewees had been asked about the possibility of changing hurricane intensity. Hence, these findings suggest that it is more natural for people to think of hurricane modification as referring to changes in hurricane direction.

7.1.3.4 After modification has been attempted, does a change in the projected path or strength of a hurricane evoke anger?

Interviewees expressed anger when asked to discuss the possibility of a modified hurricane hitting their area. However, when prompted, interviewees classified strategies to reduce intensity as less negative than strategies for changing the path. If a modified hurricane “didn’t hit your area but hit another area,” eight interviewees expressed guilt and sorrow for residents in the affected area, one interviewee said “bad,” and one offered that “they should try and steer them away from bigger population centers. Not fair to those who live there, but better overall.” If a hurricane “that was headed for another area ended up hitting yours”, all interviewees expressed negative emotions including fear and anger, without expressly attributing blame. If a hurricane “that was headed for another area became significantly weakened, but the hurricane ended up hitting your area,” eight interviewees said this was acceptable, but two dissented (e.g. “Well, that’d be a lot better, but I’d still be mad.”) Only one interviewee considered relative damages: “It depends on if a weaker hurricane here does more or less damage than a stronger hurricane somewhere else”.

Although all interviewees seemed to react negatively to the suggested possibility of changing hurricanes to reduce damages, when explicitly asked, six agreed that there might be positive effects. Two of those indicated that it depends on the amount of damage reduction. Others repeated their initial concerns, including “you shouldn’t mess with weather, it might make things worse”, and “we have to be careful what we wish for, [hurricanes] play a cleansing force”.

7.1.3.5 How is knowledge of forecast uncertainty related to anger about modification of the path and strength of hurricanes?

Interviewees recognized the uncertainty inherent in hurricane forecasts when asked about it directly. Eight interviewees reported favorable impressions of forecasts; two made less positive statements such as "not as accurate as it should be." Nine of the ten interviewees were able to generate reasons to explain why forecasts were imperfect. In this context, four referred to the complexity of the weather and two referred to the limitations of forecast technology. When interviewees were explicitly asked whether uncertainty arises because scientists don't understand hurricanes or because nature can't be predicted, all said that nature cannot be predicted, regardless of choice order.

When asked if they would trust scientists' claims that the hurricane had become more intense due to natural variation rather than the modification effort, six interviewees agreed, with two adding that hurricanes are too big for scientists to change, thus expecting continued failure, and three adding the suspicion that "you'll always wonder if this was making careers." Of the remaining four, three indicated that they did not trust the scientists, with two reacting very angrily about the storm getting worse, and expressing attributions of blame. One interviewee was neutral.

However, interviewees did not apply the idea of natural variability in their later responses. Specifically, when asked about the scenario in which scientists tried to change the storm without succeeding, no one considered that the storm changed due to natural variability. Rather, interviewees forgot their previous assertion on forecast uncertainty and assumed that the path of a modified hurricane was determined by the modification. Thus it is unclear whether a) the interviewees understand uncertainty, and b) if there is a relation between understanding uncertainty and emotions of hurricane modification.

7.2. Surveys

Using insights and word choices provided by our interviewees, I conducted a survey with a larger sample, providing the statistical power to systematically examine the four research questions. Below, I present the demographics, survey questions, and the way they were designed to answer each research question. Survey questions adapted wording preferred by interviewees (*148, 149*); for instance, I carefully explained what I meant by modification (not steering, but making storm less intense) at an appropriate moment during survey.

7.2.1. Sample

A total of 157 individual participants completed the survey after correctly answering 2 questions that examined whether they were paying attention (e.g. "Which is the largest number in this set: 10, 20, 500, or 1,000?") and received a gift certificate that was mailed to their Florida address. On average, their mean (*M*) age was 40.20, which showed a standard deviation (*SD*) of 14.88, and their median income was in the $50,000-$74,999 category, with 66.7% being women, and 54.5% having a college degree. As a comparison, in 2010, the overall population of Florida had an average age of 38.7, median household income of $44,755, with 50.8% being women, and 25.6% having a college degree (*150*). Hence, by comparison, this sample is wealthier and includes slightly more women and college-educated participants.

Almost all (91.7%) reported having been in a hurricane. When reporting on their type of dwelling, 57.3% reported living in a single-story home, 17.8% in a multiple-story home, 8.9% in a condo, 8.3% in an apartment on or above the second story, 5.7% in a ground floor apartment, and .6% in a mobile home. When asked about the area in which they lived, 78.4% participants reported they lived in an urban area, 50.6% indicated it to be easily flooded, and 24.5% being less than a mile from the coast.

The New Environmental Paradigm Scale (NEP, *151*) had, after reverse coding, a Cronbach alpha = 0.80. Additionally, 97% correctly stated that hurricane categories are defined by how fast the storm's wind is blowing.

7.2.2. Procedure

Participants responded to a newspaper advertisement or an online advertisement targeting the Miami Florida area that read: "Researchers at Carnegie Mellon University are conducting 30-40 minutes online surveys to find out what people know about hurricanes. You will receive a $20 Amazon gift certificate for your participation. To qualify, you must: a) currently live in Florida, b) be available for a 30-40 minute survey, c) be fluent in English, and d) be at least 18 years old." They were directed to an online survey.

The survey text is given in Appendix B.

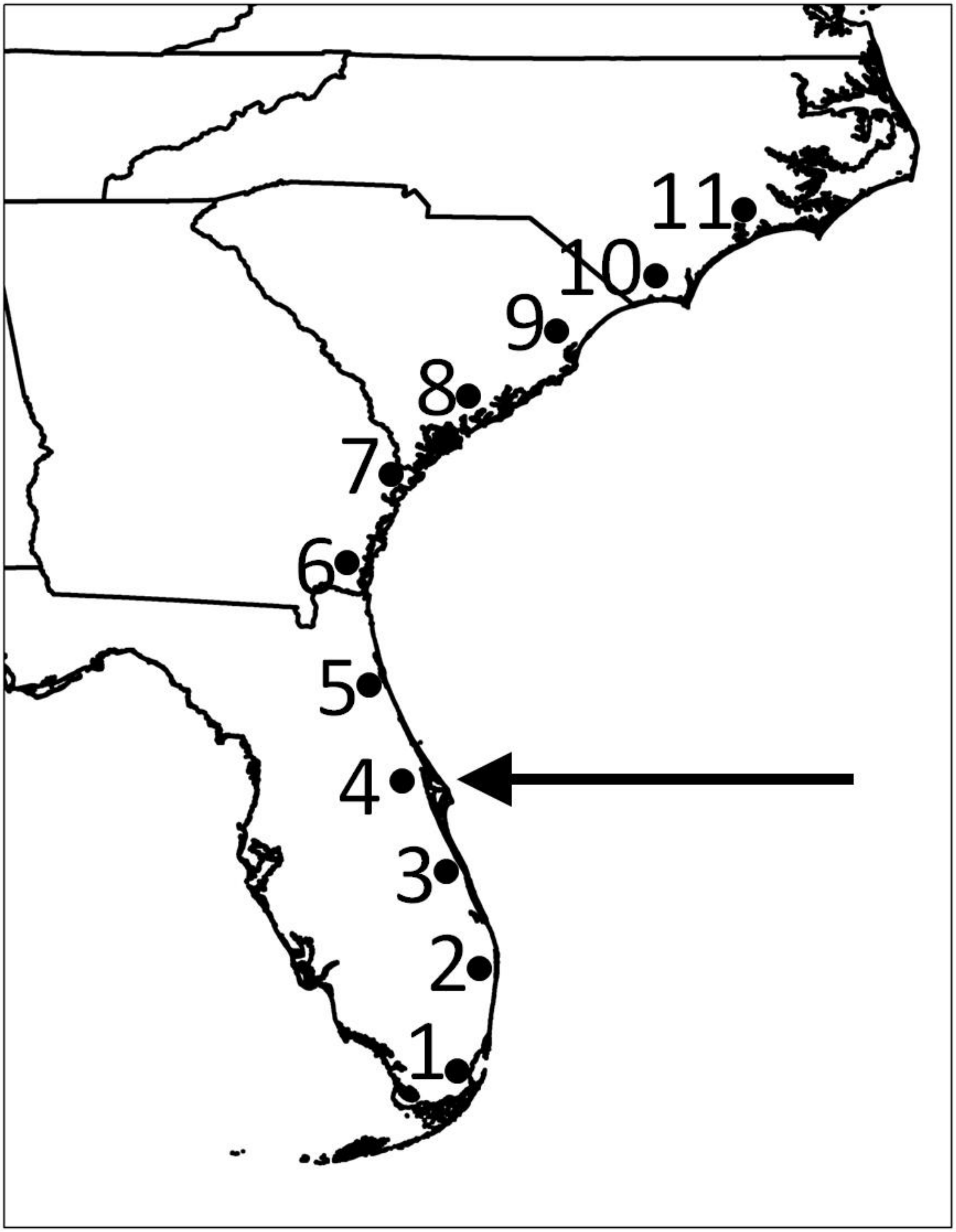
Participants were first asked an open-ended question about *damage reduction strategies*; "Please list all of the ways that you can think of that could avoid, prevent, or reduce the damages (property damages, economic losses, and anything else you can put a dollar value on) caused by hurricanes." They rated how effective 15 specific techniques are "in reducing damages (property damages, economic losses, and anything else you can put a dollar value on) for both a category 5 and a category 1 hurricane forecasted to make landfall in Miami, FL." The response scale ranged from 0 (=not effective at all in reducing damages) to 6 (=extremely effective in reducing damages).

To ascertain participants' understanding of how and why a single hurricane might change over its lifetime, participants were asked how much they agreed with several statements (0=completely disagree; 6=completely agree): "A hurricane forecast for [12 hours, 1 day, 3 days, or 1 week] is right at least half the time," "The cone of uncertainty shows how uncertain forecasts are," and "Hurricane forecasts are imperfect because [scientists don't completely understand hurricanes, technology is not advanced enough, weather changes randomly, and the media hypes up the possibility of a bad storm]," and "As a result of research, scientists will be better able to predict hurricanes [next year, in 10 years, in 100 years]."

Next, participants were asked questions about how a single hurricane might change over its lifetime. They received an unmodified scenario "The news forecasts that in 12 hours, a hurricane will make landfall at Location 4 on the map." This prompt was posed for both a Category 1 and 5 hurricane, and respondents were asked to indicate the expected landfall locations and hurricane categories (see Figure 7.40). The questions were repeated "assuming scientists try to change that hurricane to reduce damages" before participants were told anything about hurricane modification.

After hurricane modification had been introduced, participants were asked how much they agreed with eleven statements about hurricane modification adapted from the interviews reported in the interview, such as "We will never develop the technology to change a hurricane," and "Scientists will most likely try to change a hurricane to further their own career (0=completely disagree; 6=completely agree)".

Figure 7.40. Image presented with landfall location and wind speed questions.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Next, participants reported their anger at scientists in response to six different *hurricane modification scenarios* (0=not at all; 6=extremely), as well as other specific emotions not analyzed here. I systematically varied the damages that might have been experienced if scientists had not implemented hurricane modification and the hurricane would have continued along its projected path. That is, the scenarios described situations in which scientists tried to change a hurricane that ended up hitting the participants' area, when (a) that path had already been predicted or not, and (b) the damages due to storm intensity were the same, worse, or better than predicted.

Finally, participants answered three true/false statements referring to definitions of hurricane category, and reported their demographic information. The surveys took 30-40 minutes to complete. Once the survey was complete, interviewees received a $20 Amazon gift certificate.

7.2.3. Results

7.2.3.1 Are people aware of the idea of hurricane modification and do they perceive it to be an ineffective strategy for damage reduction?

To answer this research question, I present three analyses to suggest that people do not readily think of using hurricane modification for damage reduction. Moreover, they perceive it as a relatively ineffective strategy for damage reduction.

First, as in the interviews, before the concept was introduced, none of our survey participants listed hurricane modification in response to the open-ended question asking for strategies to avoid, prevent, or reduce damages caused by hurricanes. Only 2 of the 157 participants suggested that "perhaps scientists could help" with 20 others citing large-scale civil engineering efforts such as burying electrical lines underground or building a dam. All other responses referred to disaster preparedness strategies individuals could implement, and which followed the suggestions of the Florida Division of Emergency Management (*29*).

Second, Table 7.10 shows mean ratings for perceived effectiveness of different strategies to reduce damages from hurricanes, including hurricane modification. Strategies are ordered by their mean perceived effectiveness for reducing damages from category 5 storms, with mean perceived effectiveness for reducing damages from category 1 storms following the same approximate order. To systematically examine planned comparisons between the ratings of perceived effectiveness (for hurricane modification vs. each other type of damage reduction) by hurricane category (5 vs. 1), I conducted a repeated-measures Multivariate Analysis of Variance (MANOVA) F-test (*152*). As in the interviews, hurricane modification was rated as significantly less effective than each alternative, including "using spray to kill a mold" which is not actually a recommended strategy for reducing hurricane damages, with $F(1, 135)>13.16$, $p<.001$ for each planned comparison. A significant main effect of hurricane category showed that, overall, strategies were perceived as more effective against category 5 hurricanes than against category 1 hurricanes, $F(1, 135)=9.79$, $p<.01$. There was a significant interaction of hurricane category with planned comparisons for the following techniques: using metal roofs, using tie-down to strengthen wall to roof connections in buildings, bringing in loose lawn items, evacuating everyone but emergency personnel, and using a spray to kill mold. That is, each was perceived as substantially more effective than hurricane modification for protecting against damages from a category 1 than from a category 5 hurricane, with $F(1, 135)>4.86$, $p=.03$ for each.

Table 7.10. Mean (SD) ratings of the effectiveness of different strategies to avoid, prevent,

or reduce damages caused by hurricanes.

Strategy	M (SD) Effectiveness[a] Category 5	Category 1
Having buildings up to code	5.59*** (0.89)	5.36*** (1.18)
Cutting old tree branches	5.40*** (1.14)	5.26*** (1.26)
Bringing in loose lawn items	5.39*** (1.17)	5.29*** (1.27)
Putting the car in the garage	5.30*** (1.20)	5.18*** (1.40)
Using hurricane shutters	5.27*** (1.32)	5.16*** (1.46)
Being prepared (with enough food, water, and batteries)	4.96*** (1.71)	4.59*** (1.93)
Using tie-downs to strengthen wall to roof connections in buildings	4.82*** (1.41)	4.82*** (1.66)
Raising coastal buildings above ground level by struts or some other method	4.69*** (1.42)	4.54*** (1.75)
Having better dikes (walls that keep out the ocean)	4.48*** (1.66)	4.19*** (1.90)
Evacuating everyone but emergency personnel	4.47*** (1.71)	3.16*** (2.21)
Using metal roofs	4.23*** (1.72)	4.42*** (1.77)
Hunkering down (sheltering in place) in a secure part of the house	4.21*** (1.96)	4.08*** (2.09)
Building new buildings farther from the coast	4.10*** (1.80)	3.85*** (2.15)
Using a spray to kill mold	3.09 (2.17)	3.10*** (2.18)
A government attempt to change a hurricane to reduce damage	2.70 (2.22)	2.18 (2.18)

[a] M=mean; SD=standard deviation

Note: The response scale ranged from 0 (=not effective at all in reducing damages) to 6 (= extremely effective in reducing damages). Planned contrasts examined whether mean ratings were significantly different from hurricane modification within each hurricane category (*** p<.001; ** p<.01).

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Third, Table 7.11 shows participants' mean rating of agreement with five statements about the (in)effectiveness of hurricane modification, as adapted from the formative interviews. Positive statements about hurricane modification were reverse-coded to reflect agreement with its ineffectiveness. To examine which beliefs were held with relatively strong conviction, I used one-sample *t*-tests to test the difference of the mean rating from the midpoint (=3.0) of the scale, which ranged from 0 (=completely disagree) to 6 (=completely agree). As seen in Table 7.11, , the strongest agreement was with the reverse-coded statement "today, it is possible to change a hurricane to reduce its damage" as well as with "it is a bad idea to change a hurricane because it might make things worse" and "hurricanes are too big and powerful to ever be changed by humans." Cronbach's alpha across the five ratings was above .72, suggesting that their internal consistency was sufficient to conclude that they measured the same underlying construct, and to compute their overall mean (*153*, *154*). Table 7.11 shows that the overall mean was significantly above the scale midpoint, suggesting that participants agreed that hurricane modification would be ineffective.

Table 7.11. Agreement with interviewees' statements about the ineffectiveness of

hurricane modification.

Statement	M (SD) Agreement [a]
Today, it is possible to change a hurricane to reduce its damage (R)	4.68 *** (1.29)
It is a bad idea to change a hurricane because it might make things worse	3.59 *** (1.80)
Hurricanes are too big and powerful to ever be changed by humans	3.49 ** (1.83)
At some point in the future, it will be possible to change a hurricane to reduce its damage (R)	3.15 (1.66)
We will never develop the technology to change a hurricane	2.76 (1.77)
Overall	3.54 *** (1.18)

[a] *M*=mean; *SD*=standard deviation

Note: (R) refers to statements that were reverse-coded to denote agreement with the ineffectiveness of hurricane modification. The response scale ranged from 0 (= completely disagree) to 6(= completely agree). One-sample t-tests examined whether mean agreement with statements differed from the midpoint (=3), indicating beliefs held with stronger conviction (*** p<.001; ** p<.01).

Table 7.12. Participants' expectations for the landfall location and intensity of modified and unmodified hurricanes.

Type of hurricane	Initially projected intensity	Percent expecting change from initially projected landfall location	Percent expecting reduction from initially projected category
Unmodified	Category 5	4.3%	25.9%
Modified	Category 5	16.4% ***	40.5% **
Unmodified	Category 1	6.0%	6.4%
Modified	Category 1	16.4% *	0.9% *

Note: McNemar tests were used to test whether hurricane modification significantly affected the percent of participants reporting specific outcomes; t-tests were used to test whether hurricane modification significantly affected the number of selected outcomes (*** p<.001; * p<.05)

7.2.3.2 Is hurricane modification expected to cause changes in the projected path and strength of hurricanes?

Results suggest that participants expected modification to lead to changes in hurricane paths, but not necessarily to the reduction of storm strength. I examined, for unmodified and modified hurricanes of category 1 and category 5, whether or not participants included the forecasted landfall location and the forecasted hurricane category among their responses. To determine whether participants were more likely to expect a change from what was forecasted after a modified hurricane than after an unmodified hurricane, I conducted a McNemar change test, a non-parametric version of the paired-sample *t*-test. Table 7.12 shows that a significantly larger percent of participants expected that a modified hurricane rather than an unmodified hurricane would show diversion from the initially projected landfall location, whether the forecasted strengths were of category 5 or category 1. A significantly larger percent of participants expected the modified hurricane rather than the unmodified hurricane to show a reduction from the initially projected category 5 intensity. However, for hurricanes with a category 1 projection, more participants expected hurricane modification to increase rather than to decrease in intensity.

It is possible that participants may be more accepting of one kind of hurricane modification than another. Table 7.13 gives reported emotions about hurricane modification with effect not described, and with effect being a wind speed reduction. Participants have less negative emotions and more positive emotions about hurricane modification when the effect is specifically a wind speed reduction as opposed to not defined. I hypothesize that in the not defined scenario, participants were thinking of hurricane modification having the effect of a change in path, and thus would prefer a wind speed reduction over a change in path. Future research could test this hypothesis.

Table 7.13. Emotions about general hurricane modification.

Hurricane Modification Effect	*M* (*SD*) Emotion[a]		
	Angry at damages	Afraid	Happy
Not defined	1.48 (1.76)	2.70 (1.98)	2.87 (2.04)
Wind speed reduction	1.05 (1.52)	1.62 (1.85)	3.79 (1.86)

[a] *M*=mean; *SD*=standard deviation
Note: The response scale for the degree of experienced anger ranged from 0 (= not at all) to 6(= extremely).

7.2.3.3 After modification has been attempted, does a change in the projected path or strength of a hurricane evoke anger?

The results suggest that more anger is evoked when a hurricane's path or strength change from what was predicted before the modification attempt. Table 7.14 shows participants' reported emotions, as given in response to the six scenarios that described modified hurricanes hitting the participants' area, and which varied whether or not the path and direction differed from what was forecasted. As an initial indication of the relative strength of the reported anger, one-sample *t*-tests tested whether means were significantly different from the scale midpoint (=3). Table 7.14 shows that mean anger was significantly higher than the midpoint for only one scenario, in which the modified hurricane that hit participants' area was described having changed in path and increased in strength, as compared to what was forecasted. Table 7.14 also shows that mean anger was significantly below the scale midpoint for the one scenario in which both the path and the strength of the modified hurricane were the same as forecasted, and for the two in which the damages were less than expected. Across the six scenarios, reported anger showed sufficient internal consistency to allow for the computation of their overall mean, as seen in a Cronbach's

Table 7.14: Reported emotions in response to scenarios in which scientists tried to change a hurricane that hit their area.

Hurricane scenario		*M* (*SD*) Emotion[a]			
Path compared to prediction	Damage compared to prediction	Anger at scientists	Anger at damages	Afraid	Happy
Same	More	2.89 (2.10)	3.17 (2.07)	2.78 (2.14)	0.63 (1.18)
Same	Same	1.75 (1.86)***	2.19 (1.97)	2.18 (1.98)	1.00 (1.53)
Same	Less	1.03 (1.52)***	1.31 (1.58)	1.55 (1.78)	3.71 (2.08)
Different	More	3.48 (2.08)**	3.83 (2.03)	3.41 (2.19)	0.51 (1.19)
Different	Same	3.06 (2.10)	3.38 (2.08)	2.92 (2.02)	0.61 (1.14)
Different	Less	1.88 (1.80)***	2.32 (1.91)	2.25 (1.89)	2.17 (2.10)
Different	None (hit someone else)	1.86 (1.91)	2.01 (1.89)	2.19 (1.95)	1.80 (1.93)
Overall		2.36 (1.46)**			

[a] *M*=mean; *SD*=standard deviation

Note: The response scale for the degree of experienced anger ranged from 0 (= not at all) to 6(= extremely). One-sample *t*-tests examined whether mean anger differed from the midpoint (=3), indicating relative strength of the reported emotion ([***] $p<.001$; [**] $p<.01$).

alpha of .85 (*153*, *154*). The overall mean of anger was significantly below the scale midpoint, suggesting that participants experienced relatively limited anger when reading the hurricane modification scenarios.

To systematically examine the effects of changes from the initially forecasted path (yes or no) and from the initially forecasted damages (more, same, or less), I conducted a repeated-measures MANOVA (*152*) on reported anger at scientists. I found a significant main effect of whether or not the forecast predicted that the hurricane would hit the participants' area, $F(1,152)=67.38$, $p<.001$. Namely, participants reported significantly more anger at scientists when the modified hurricane hit their area but was not initially predicted to do so. There was also a main effect of damages, $F(2,151)=101.63$, $p<.001$, suggesting that participants reported increasingly more anger when there were more damages than predicted due to increased hurricane intensity. A significant interaction between whether or not the forecast was predicted to hit the participants' area and the degree to which the damages were different than expected, $F(2,151)=9.20$, $p<.001$)

showed that the most anger was reported in response to the scenario in which both the path and the intensity of the hurricane changed in a way that was worse than initially expected.

7.2.3.4 How is knowledge of forecast uncertainty related to anger about modification of the path and strength of hurricanes?

To address this research question, I first examined the extent to which participants recognized the uncertainty inherent in hurricane forecasts. Table 7.15 shows their mean ratings of agreement with statements about the uncertainty inherent in hurricane forecasts, ordered by their degree of agreement. Overall, participants agreed with the statements that "hurricane forecasts are uncertain because weather changes randomly," "the cone of uncertainty shows how uncertain forecasts are," and "hurricane forecasts are uncertain because the media hypes up the possibility of a bad storm." Beliefs in these three statements were held with relatively strong conviction, with one-sample t-tests showing that mean ratings were significantly higher than the scale midpoint (=3). Agreement was not significantly different from the scale midpoint for the two remaining statements (each p>.05), suggesting that participants were not as convinced that "hurricane forecasts are uncertain because technology is not advanced enough" or "because scientists don't completely understand hurricanes." Because Cronbach's alpha (*153*, *154*) showed relatively good internal consistency across these five statements (=.69), I computed their mean to reflect overall agreement with reasons for why forecasts are uncertain. That measure of overall recognition of forecast uncertainty was also significantly above the scale midpoint (=3), thus suggesting that participants generally tended to agree that hurricane forecasts are uncertain, $t(156)=8.71$, $p<.001$.

Unlike what I expected on the basis of the interviews, participants who more strongly agreed with statements that recognized the uncertainty inherent in forecasts reported more rather than less anger at scientists across hurricane modification scenarios. Indeed, Table 7.15 shows significant positive Pearson correlations between participants' overall recognition of forecast uncertainty measure with the mean anger reported across the hurricane modification scenarios and the overall uncertainty measure. The correlation was also significant for individual items, except for the one asking about the cone of uncertainty. Overall recognition of forecast uncertainty seemed differentially related to anger at scientists reported across hurricane modification scenarios. Specifically, it appeared that individuals who most recognized forecast

Table 7.15. Agreement with statements about the uncertainty inherent in hurricane forecasts.

Statement	*M* (*SD*) Agreement [a]	Relationship with overall anger across modification scenarios
Hurricane forecasts are imperfect because weather changes randomly	4.66^{***} (1.52)	$.18^{*}$
The cone of uncertainty shows how uncertain forecasts are	4.31^{***} (1.59)	.01
Hurricane forecasts are imperfect because the media hypes up the possibility of a bad storm	3.96^{***} (1.80)	$.18^{*}$
Hurricane forecasts are imperfect because technology is not advanced enough	3.06 (1.80)	$.22^{***}$
Hurricane forecasts are imperfect because scientists don't completely understand hurricanes	3.01 (1.88)	$.30^{***}$
Overall	3.80^{***} (1.15)	$.27^{**}$

[a] *M*=mean; *SD*=standard deviation
Note: The response scale ranged from 0 (= completely disagree) to 6(= completely agree). One-sample *t*-tests examined whether statements differed from the midpoint (=3), indicating beliefs held with stronger conviction, and Pearson correlations to examine the relationship with overall anger (*** $p<.001$; ** $p<.01$; * $p<.05$).

uncertainty were especially angry when damages were unexpectedly worse, for when their own area was unexpectedly hit (r=.22, p<.01) and hit as predicted (r=.26, p<.01). The same pattern held when damages stayed the same (r=.20, p=.01 when unexpectedly hit; r=.24, p<.01 when hit as predicted). However, these correlations were not as strong when the damages were less than predicted (r=13, p=.12 when unexpectedly hit; r=.17, p=.04 when hit as predicted).

Although overall perceptions of perceiving hurricane modification as ineffective were positively correlated to both overall anger about hurricane modification (r=.21, p<.01), and to recognizing forecast uncertainty (r=.18, p=.03), the observed relationship between anger and recognizing forecast uncertainty remained significant in partial correlations statistically controlling for perceptions of ineffectiveness (r=.24, p<.01). Additionally controlling for participants' age, gender, education, income, experience with hurricanes, area being prone to flooding, and distance being less than one mile from the coast had little to no effect on the reported correlation between overall anger across scenarios and overall recognition of forecast uncertainty (r=.21, p=.03). After adding all of these control variables, partial correlations of overall uncertainty with anger about individual hurricane modification scenarios also remained significant for those describing, compared to what was forecasted, an unchanged path with more damage (r=.22, p=.03), and a different path with more damage (r=.19, p=.05).

Moreover, the analyses suggest that recognizing forecast uncertainty mediated the effect of the degree to which damages were different from expected on reported anger at scientists. I added the overall agreement with statements recognizing uncertainty as a covariate to the MANOVA (*152*) that, as described above, examined the effect of whether or not the forecast was predicted to hit the participants' area (yes or no) and the effect of the amount of damages compared to prediction (more, same, or less) on anger at scientists. I then found a significant effect of recognizing uncertainty, $F(1, 151)=11.60$, p<.01, with the effect of predicted path showing reduced significance, $F(1, 151)=9.13$, $p<.01$, and the effect of increased damages and its interaction with the predicted path being no longer significant ($p>.05$). Even after controlling for perceptions of the ineffectiveness of hurricane modification and participant characteristics, uncertainty remained a significant predictor, $F(1, 104)=4.78$, $p=.03$. None of the control variables showed significance ($p>.05$), suggesting that they did not drive the mediation.

7.2.3.5 Other results: Attribution of damages

Overall, participants perceived significantly larger damages from hurricanes due to wind ($M=5.34$, $SD=1.00$) rather than other hurricane attributes, including debris ($M=4.85$, $SD=1.16$), flooding ($M=4.47$, $SD=1.73$), and rain ($M=3.78$, $SD=1.78$), with $F(1, 156)>26.87$, $p<.001$ for each. However, the 50.6% of participants who reported living in an area that easily flooded perceived higher flood damage ($r=-.39$, $p<.001$).

Table 7.16 gives the data on selected questions about damage attribution of different hurricane attributes. Respondents feel that wind causes the most damage in a hurricane and that maintaining buildings at code is very good for reducing wind damages. Additionally, respondents feel they have the best ability to prepare against debris.

Table 7.16. Selected questions about attribution between hurricane attributes. Scale: 0 = Causes the least damage or Not very well at all; 6 = Causes the most damage or Extremely

well.

Hurricane Attribute	*M* (*SD*) Attribute Rating[a] Damage likely caused by this attribute	Your ability to prepare against this attribute	Possible damage reduction through maintaining buildings at code
Wind	5.34 (1.00)	3.96 (1.79)	5.31 (0.97)
Debris	4.85 (1.16)	4.10 (1.69)	4.79 (1.39)
Flooding	4.47 (1.73)	3.20 (1.92)	4.40 (1.68)
Rain	3.78 (1.78)	4.08 (1.93)	4.87 (1.48)

[a] *M*=mean; *SD*=standard deviation
Note: The response scale ranged from 0 (= completely disagree) to 6(= completely agree).

7.3. Discussion

In this paper, I examined Florida residents' perceptions of hurricane modification techniques that aim to alter path and wind speed. Following the mental models approach (*118*), I conducted a survey study about public perceptions of hurricane modification that was guided by formative interviews on the topic. Below, I report on the four main findings.

First, I found that hurricane modification was perceived as a relatively ineffective strategy for reducing damages. Unprompted, none of the respondents mentioned hurricane modification for reducing damages. When asked, they rated hurricane modification as significantly less effective than other damage reduction strategies such as home hardening. In fact, participants' ratings of the effectiveness of hurricane modification techniques were not statistically different from their ratings of the effectiveness of a fictional technique described as "using a spray to kill mold." Possibly, hurricane modification is perceived as relatively ineffective because people are much less familiar with it than with other damage reduction strategies. When a new technology is still relatively unfamiliar, people's perceptions of it may be especially negative and unstable (*155*, *156*).

Second, while perceived as less effective than other strategies, hurricane modification was nevertheless expected to cause changes in storms. Participants expected that modified hurricanes would be more likely than unmodified hurricanes to divert from their initially projected landfall locations, and to show a reduction in intensity if the initial forecast predicted category 5. When the initial forecast predicted a category 1 storm, hurricane modification was expected to be counterproductive and increase storm intensity. Because the participants systematically expected changes from category 1 and category 5 projections to be larger for modified hurricanes than for unmodified hurricanes, I conclude that these results reflect actual effects of hurricane modification on reported expectations rather than just the mechanistic response bias referred to as regression towards the mean. This phenomenon occurs a result of measurement error, where initial observations of extreme values (e.g., very high blood pressure) tend to be less extreme in a subsequent observation (*157*, *158*), thus showing regression towards the mean. Such observations may lead researchers to erroneously conclude that their treatment (e.g., blood pressure medication) may have led to the observed change. To separate actual treatment effects from the mechanistic effects of regression towards the mean, it has been recommended to compare changes in a treatment group to changes in a no-treatment control group (e.g., patients with high blood pressure who do or do not receive the medication.) Because the response categories ranged from "less than category 1" to "category 5," participants had more ways to indicate that a projected category 1 storm would increase in strength rather than decrease in strength and that a projected category 5 storm would decrease in strength rather than increase in strength. As a result, responses may have been driven towards the middle of the response range. However, the conclusions are based on comparisons of participants' expectations for unmodified and modified hurricanes, which showed that participants systematically indicated that they expect larger changes with modified hurricanes than with unmodified hurricanes.

Third, more anger was evoked when a hurricane was described as having changed from the initially forecasted path or strength after an attempted modification. Participants expressed increased anger both when their area was hit by a modified hurricane that had been projected to go elsewhere and when the modified hurricane produced more damage than forecasted. In contrast, reported anger was weaker when hurricane modification was described as leaving the projected track unaltered, and leading to the projected damages or less. Hence, hurricane modification efforts that aim to reduce damages without changing paths may be better received than hurricane modification efforts that focus on diverting paths. Indeed, techniques aiming to change the path of hurricanes have been identified to cause especially complex questions about liability and ethics (*35*).

Fourth, unlike what I expected, participants who more strongly agreed with statements that recognized the uncertainty inherent in forecasts reported more anger toward scientists, across hurricane modification scenarios. Based on previous research about, for example, car accidents, we had expected that individuals who recognized the role of chance in forecasts of a hurricane's path and intensity would have shown less anger (*136*) Indeed, when chance is seen as producing a negative outcome, it is more difficult to make attributions of causality and blame. Possibly, the discrepancy in findings is due to the context of hurricane modification being systematically different from the context of car accidents. For example, as compared to cars, the risks related to hurricanes may be perceived as much less well-known, while triggering much more negative affect, feelings of lack of control, and fear of catastrophic outcomes. Risk perception research has suggested that each of these elements plays an important role in how people respond to risks – and possibly, any related uncertainty (*116*, *117*). Indeed, individuals who recognize the uncertainty inherent in hurricane prediction may have been less forgiving rather than more forgiving about the use of hurricane modification because they perceived hurricanes as too big and powerful to be reliably modified by humans.

However, while individuals' ability to recognize the uncertainty inherent in hurricane forecasts may have caused their increased feelings of anger toward scientists implementing hurricane modification, alternative explanations may apply. The correlation might also be explained by reverse causality, with individuals who feel more anger about hurricane modification possibly being more likely to question the certainty of hurricane forecasts. Additionally, even though I controlled for negative perceptions about the effectiveness of hurricane modification, demographic background, and experience with hurricanes, other unobserved variables may have affected the reported relationship between recognizing forecast uncertainty and anger about hurricane modification. For example, people who hold strong protective values related to nature and climate may be both more familiar with hurricane forecast uncertainty and more averse to hurricane modification. Indeed, research on the omission bias has suggested that protected values are related to being more negative about harmful acts of commission than about harmful acts of omission that produce the same negative results (*134*).

To examine the causal effect of recognizing uncertainty on feelings of anger, follow-up research should randomly assign participants to receive detailed information about forecast uncertainty, before asking how they feel about hurricane modification. Although my results suggest that it is incorrect to assume that hurricane modification will be more acceptable to individuals who recognize the role of uncertainty in forecasting hurricanes, it also seems premature to agree with those scientific experts who believe that providing members of the general public with information about uncertainty will increase distrust in science (*159*). Indeed, risk communication efforts in other domains have suggested that communicating about the uncertainty surrounding risks does not necessarily reduce people's willingness to accept those risks, and have provided guidelines about how to communicate quantitative risks (*118, 160, 161, 162, 163*).

One limitation of this study is that the sample was not randomly selected from residents of the state of Florida. Compared to the overall population of Florida, our sample is wealthier and more college-educated (*150*). While the relatively wealthy and college-educated participants may have been more familiar with hurricane modification than other Florida residents, they were clearly not well-informed. Thus, the results suggest that Florida residents likely need more information to make informed decisions about whether or not to support hurricane modification.

Any attempt to communicate the risks and benefits of hurricane modification should be designed to complement residents' mental models. (*118*). The survey presented here provides initial insights into people's knowledge and beliefs about hurricane modification, suggesting that they question its effectiveness, expect it to focus more on changing paths than on changing intensity, while also being angered more about changing paths than about changing intensity, especially when they recognize the uncertainty inherent in forecasts. If these results hold in follow-up research, policy makers who aim to facilitate informed public discourse about hurricane modification may specifically benefit from providing risk communications about hurricane modification techniques that bring the promise of reducing storm intensity without changing the projected path. It may be the case that effective risk communication about these hurricane modification techniques will increase acceptance of hurricane modification, even among individuals who recognize the inherent uncertainty.

Indeed, hurricane modification may be met with less public resistance if efforts focus on reducing storm intensity without changing the projected path. If the efficacy of those techniques can be increased, people may be willing to support hurricane modification. However, such an effort would need to be combined with open and honest communications to members of the general public. Lessons learned from the context of nuclear power (*115*) and other technologies associated with high risks suggest that dismissing the concerns of the general public will likely create a level of public distrust that will hamper any effort to successfully implement hurricane modification.

Chapter 8. Conclusions

Portions of the discussion in this Chapter are based on Klima, K.; Morgan, M.G.; Grossmann, I.; Emanuel, K. Does It Make Sense To Modify Tropical Cyclones? A Decision-Analytic Assessment. Engineering Science and Technology. 2011. 45:10 pp 4242–4248.

8.1. Summary

This thesis shows that the best method to reduce damages from hurricanes varies with the type of damages being considered. Damages in coastal areas near Miami-Dade County, Florida, are dominated by surge damages for short return periods, and wind damages for long periods. The return period at which the predominant damage mechanism switches is a highly specific function of location, ranging from 30-500 years. Although not examined in this thesis, it is likely that residents of areas farther inland away from bodies of water will be affected most by wind damages at almost all return periods. However, note that since storm surge is highly complex, and hurricane track post-landfall varies greatly, there is no "typical storm" for a return period over large areas. Thus the best policy decisions to combat damages on the local level will likely be different from the best policy decisions on the federal level. Further study on the spatial distribution of the hurricane wind and surge is needed to predict long-term damages over large areas.

If TC modification worked reliably and was deployed correctly against a particular storm, I find tropical cyclone modification may be more competitive than hardening. Examining seasonal wind damages, I find a portfolio of techniques including hardening and TC modification provides the lowest net cost. This occurs because both hardening and seasonal deployment of wind-wave pumps provides protection for average storms that might not be achieved if only the most intense storm is considered. However, examining seasonal storm surge damages, I find that dikes best reduce damage. It is unclear whether, when wind and storm surges are combined, a portfolio of techniques including TC modification will continue to provide the best net cost.

If hurricane modification were further developed into a feasible strategy for potentially reducing hurricane damages, residents of hurricane-prone areas would need to be able to make more informed decisions about whether or not to support its implementation. The work presented here provides initial insights into people's knowledge and beliefs about hurricane modification, suggesting that they question its effectiveness and expect it to focus more on changing paths than on changing intensity. People were also angered more about changing paths than about changing intensity, especially when they recognize the uncertainty inherent in forecasts.

8.2. Discussion

Although hurricane modification has been shown to be cost effective, much more research is needed before implementation. Clearly it is premature at this stage to call for the development of an operational program. If and when subsequent modeling studies and field trials have examined reliability, navigation impacts, drifting, and similar issues, and suggest that such a program might be justified, a wide range of institutional, operational and other issues will need to be addressed. An examination of damages at the census tract level reveals that large damage reductions occur in areas where property values are very high (e.g., containing multi-million dollar houses and condos). If and when a policy choice between hurricane modification and hardening arises, issues of social equity must be carefully considered.

Tradeoffs exist between having one or many decision makers. A program of modification allows one player (likely the government) to unilaterally make a decision. This could spark fear, anger, and resentment among inland residents who subsidize coastal residents. In contrast, a program of hardening allows each home or business owner to prepare as a function of their own risk tolerance level and available monetary incentives. However, absent extensive inspection and enforcement, 100% compliance is unlikely.

There is also the issue of liability (*35, 164*). A modified TC might no longer be considered an "act of God", raising the possibility of domestic and international liability claims against those who deployed the intervention. Liability could extend beyond immediate TC induced destruction. TCs transport a tremendous amount of heat, moisture, and energy, and any disruption to this process could have large negative consequences for at least some parties, including a loss of rain for farmers or impacts on the global climate. It may be that hurricane modification can be compared to other natural catastrophes such as earthquakes, floods, fires (*165*) so that sovereign immunity would apply. However, this area of law remains relatively unexplored.

Joan Vogel (Vermont School of Law, personal communication) and John Echeverria (Georgetown, personal communication) suggest preventing law suits by creating a Hurricane Modification Program that would provide increased compensation to those affected by the storm. However, here a problem of statutory design arises. First, a program supporting a highly unpredictable process like hurricane modification, *regardless of compensation*, can be very scary to citizens. The program must be structured to ease residents' fear. Second, *even if the alternative is worse*, it is politically unattractive to cause deaths. Although value of life arguments have been made in favor of some government programs such as vaccinations, it is unclear how these arguments would apply to hurricane modification techniques.

8.3. Future Work

Several more concrete possibilities of future research exist.

First, the combination of wind and storm surge damage is nonlinear and poorly understood (*36*). Since storm surge damages dominate for these coastal locations, an attempt to solely protect against wind damages may be overwhelmed by the large storm surge losses. Preliminary work in Chapter 6 examines the combination of wind and storm surge, but much more work is needed.

Second, other hurricane modification techniques should be examined. While those in Project HURRMIT will surely be interesting, and in some cases beneficial to aerosol research, I argue that it would be more interesting to study a steering mechanism. Although the public policy work indicates that steering a TC might not be acceptable to residents, Kevin Sharp's preliminary investigations into altering TC tracks suggest that a steering technique may be beneficial (*166*). Policy questions here include: How certain would a steering technique need to be before it could be justified? When/how would it need to be implemented? What issues of equity and responsibility are involved (in steering a storm from a high density high income community to a low density low income community; in failing and inadvertently steering a storm over a city, etc.)

Third, the public perceptions work in Chapter 7 provides a basis of work demonstrating the need for effective risk communication regarding hurricane modification. A much larger and more comprehensive study could be conducted of the four main findings. For instance, follow-up research testing the causal effect of recognizing uncertainty on feelings of anger at scientists. could randomly assign participants to receive detailed information about forecast uncertainty, before asking how they feel about hurricane modification. Additionally, the research could more fully define exactly what type of modification would be acceptable. Questions should help identify risk communication strategies. Any strategies identified should be combined with open and honest communications to members of the general public.

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Appendix A: Interview Protocol

General guideline

- Be friendly, polite, and show genuine interest in what the interviewee is saying.
- Encourage the interview to talk more, rather than less.
- Do not rush through the interview.
- Stick to the interview protocol, but follow up on answers that seem incomplete or unclear.
- Avoid sharing your own answers, beliefs, definitions, and wording.
- Never finish an interviewee's sentence, even if he or she has trouble finding the correct word to use.
- Never cut off an interviewee's answer.
- Never show frustration with non-talkative interviewees.
- Keep subjects from straying into sensitive areas.

Basic Prompts

- Why do you say that?
- Anything else?
- Can you tell me more about _____________?
- Can you explain how/why?
- Does ___________ bring anything else to mind?
- If you were going to explain hurricanes to someone else, is there anything you would say differently or add to what you have said?
- The last sentence uttered by the interviewee as a question.

0. OVERVIEW

In this interview, I will ask you questions about hurricanes. We are doing these interviews to research what people think about hurricanes and their effects. There are no right and no wrong answers, we are just interested in your thoughts. Please avoid discussing sensitive, identifiable information. If you feel uncomfortable answering any question, we can skip it and go on to the next one.

Do you have any questions?

Let's start now.

1. GENERAL KNOWLEDGE

Could you start by telling me about the effects of hurricanes?
Standard prompts
[We assume that hurricane damages will be discussed.]
[If none are listed] Can you think of any good effects from hurricanes?

2. DAMAGES

a. What can be done to avoid or prevent or reduce the damages caused by hurricanes? Are there any other ways to reduce the damages caused by hurricanes?

   [For each strategy, ask, using the interviewee's own wording:]
   Please explain a bit more how [doing this] that will help.
   What damages will [doing this] help to reduce?
   Why might people decide not to [do this]?
   Who should be responsible for [doing this]?
   [We assume that mitigation techniques will be discussed.]

b. Of the several things you listed that will reduce the damages caused by hurricanes, which ones work best? *[Repeat these strategies again, in interviewees' original wording, to remind interviewees which ones they mentioned]*

3. CHANGE

a. During hurricane season, how do you learn about when hurricanes are coming?
   [No answer is okay.]

b. How good do you think hurricane forecast are?
   Why are hurricane forecasts not perfect?
   [Only if not brought up] How much of the problem is because scientists don't understand hurricanes, and how much is because sometimes nature can't be perfectly predicted?

4. DEFINITIONS

a. Hurricanes get classified by numbers. For example, a weather forecaster might say this is a *category 3 hurricane*.
   Have you heard about this?
   Tell me roughly what you think it means.
   What does a higher number mean?

b. Hurricanes can do damage from something called *storm surge*.
   Have you heard about this?
   Tell me roughly what you think that means.

5. MODIFICATION

a. Have you ever heard about the possibility of changing hurricanes to reduce their damage? What have you heard about it?
   [Standard prompts]
   If people could change hurricanes, do you think that would be a good or bad thing?
   What might be a good effect of changing hurricanes?
   What might be bad effect of changing hurricanes?

b. Now let's talk about the possibility of making the winds of the hurricane less strong, without changing the path of the hurricane.

   Have you heard about this? *[If yes, what have you heard about it, and from where did you learn this?]*

   If it would be possible to make the winds of a hurricane less strong without changing their path, do you think that would be a good or bad thing?
   What might be a good effect of doing this?
   What might be bad effect of doing this?

c. Now imagine a situation in which scientists try to slow down a hurricane but it ends up getting stronger. Scientists all agree that nothing they did could have made the winds stronger. They argue that the storm got stronger just because of natural variability. Tell me how you feel about this situation.

d. Now imagine a situation in which a hurricane is headed towards the area in which you live. Scientists try to change a hurricane to save your area. How would you feel if…..
   i. …the scientists couldn't change the hurricane and it hit your area anyway?
   ii. …the hurricane didn't hit your area but hit another area?
   iii. … a hurricane that was headed for another area ended up hitting yours?
   iv. ...a hurricane that was headed for another area significantly weakened, but the hurricane ended up hitting your area.

6. **DEMOGRAPHICS**
   a. Where do you live? *House, Apartment, Mobile Home, No Residence, Other*
   b. What is your zip code? *[So I can define coastal or inland]*
   c. How many people were living or staying your household on April 1, 2010? How many were children?
   d. What is the highest degree or level of school you have completed?
   e. Did you look anything up before this interview? If yes, what and where?
   f. Have you been in a hurricane?

7. **ENDING**
   a. Do you have any questions for me?

Appendix B: Survey Questions

Welcome

This survey is part of a Carnegie Mellon University study. It takes about 35-40 minutes to complete.

There are no right and no wrong answers, we are just interested in your thoughts. Your responses will remain anonymous. Please go through the questionnaire a page at a time. Once you have completed a page, please do not return to previous pages.

At the end of the survey you will be asked to leave a Florida street address (P.O. Box not acceptable). The address is for payment purposes only; we will send you an Amazon gift certificate for $20, but not send you anything else.

If you have concerns about this questionnaire you may contact: cmuhurricanestudy@gmail.com .

Please answer the eligibility questions below:

1.) What is your age?

____

2.) What state do you live in?

____

Part I: This section asks you about the effects of hurricanes.

3.) Please list all of the ways that you can think of that could avoid, prevent, or reduce the damages (property damages, economic losses, and anything else you can put a dollar value on) caused by hurricanes. Please list one per line up to ten causes.

: ________________________

: ________________________

: ________________________

: ________________________

: ________________________

: ________________________

: ________________________

: ________________________

: ________________________

: ________________________

Part II: This section contains **OPINION** questions about how well you think different methods work to avoid or reduce the damages that hurricanes can cause. Some of these things you may have already mentioned, but for completeness please answer each question anyway. In answering each question, assume that only the action described will be taken. Consider each action separately from the rest. If it would matter to your answer, assume that the action is being taken in Florida. Please answer each question below by checking the one box that best describes what you think.

First you will be asked about a Category 5 hurricane, and then about a Category 1 hurricane.

4.) The news forecasts that a **CATEGORY 5 HURRICANE** will make landfall in Miami, Florida. In your opinion, how effective in reducing damages (property damages, economic losses, and anything else you can put a dollar value on) would it be to do the following actions in Miami, Florida?

	Not effective at all in reducing damages 0	**1**	**2**	**3**	**4**	**5**	**Extremely effective in reducing damages 6**	**Decline to answer**
a. Using hurricane shutters	( )	( )	( )	( )	( )	( )	( )	( )
b. Using metal roofs	( )	( )	( )	( )	( )	( )	( )	( )
c. Using tie-downs to strengthen wall to roof connections in buildings	( )	( )	( )	( )	( )	( )	( )	( )
d. Being prepared (with enough food, water, and batteries)	( )	( )	( )	( )	( )	( )	( )	( )
e. Having buildings up to code	( )	( )	( )	( )	( )	( )	( )	( )
f. Raising coastal buildings above ground level by struts or some other method	( )	( )	( )	( )	( )	( )	( )	( )
g. Bringing in loose lawn items	( )	( )	( )	( )	( )	( )	( )	( )
h. Cutting old tree branches	( )	( )	( )	( )	( )	( )	( )	( )
i. Putting the car in the garage	( )	( )	( )	( )	( )	( )	( )	( )
j. Evacuating everyone but emergency personnel	( )	( )	( )	( )	( )	( )	( )	( )
k. A government attempt to change a hurricane to reduce damage	( )	( )	( )	( )	( )	( )	( )	( )
l. Hunkering down (sheltering in place) in a secure part of the house	( )	( )	( )	( )	( )	( )	( )	( )
m. Having better dikes (walls that keep out the ocean)	( )	( )	( )	( )	( )	( )	( )	( )
n. Using a spray to kill mold	( )	( )	( )	( )	( )	( )	( )	( )
o. Building new buildings farther from the coast	( )	( )	( )	( )	( )	( )	( )	( )

5.) The news forecasts that a **CATEGORY 1 HURRICANE** will make landfall in Miami, Florida. In your opinion, how effective in reducing damages (property damages, economic losses, and anything else you can put a dollar value on) would it be to do the following actions in Miami, Florida?

	Not effective at all in reducing damages 0	**1**	**2**	**3**	**4**	**5**	**Extremely effective in reducing damages 6**	**Decline to answer**
a. Using hurricane shutters	( )	( )	( )	( )	( )	( )	( )	( )
b. Using metal roofs	( )	( )	( )	( )	( )	( )	( )	( )
c. Using tie-downs to strengthen wall to roof connections in buildings	( )	( )	( )	( )	( )	( )	( )	( )
d. Being prepared (with enough food, water, and batteries)	( )	( )	( )	( )	( )	( )	( )	( )
e. Having buildings up to code	( )	( )	( )	( )	( )	( )	( )	( )
f. Raising coastal buildings above ground level by struts or some other method	( )	( )	( )	( )	( )	( )	( )	( )
g. Bringing in loose lawn items	( )	( )	( )	( )	( )	( )	( )	( )
h. Cutting old tree branches	( )	( )	( )	( )	( )	( )	( )	( )
i. Putting the car in the garage	( )	( )	( )	( )	( )	( )	( )	( )
j. Evacuating everyone but emergency personnel	( )	( )	( )	( )	( )	( )	( )	( )
k. A government attempt to change a hurricane to reduce damage	( )	( )	( )	( )	( )	( )	( )	( )
l. Hunkering down (sheltering in place) in a secure part of the house	( )	( )	( )	( )	( )	( )	( )	( )
m. Having better dikes (walls that keep out the ocean)	( )	( )	( )	( )	( )	( )	( )	( )
n. Using a spray to kill mold	( )	( )	( )	( )	( )	( )	( )	( )
o. Building new buildings farther from the coast	( )	( )	( )	( )	( )	( )	( )	( )

Part III: Hurricanes cause damage through rain, flooding, wind, and debris. This section asks **OPINION** questions. Please answer each question below by checking the one box that best describes what you think.

6.) Suppose a hurricane hits **YOUR AREA**, causing damage. How much of this damage is likely caused by each of the following?

	Causes the least damage 0	**1**	**2**	**3**	**4**	**5**	**Causes the most damage 6**	**Decline to answer**
a. Rain	( )	( )	( )	( )	( )	( )	( )	( )
b. Flooding	( )	( )	( )	( )	( )	( )	( )	( )
c. Wind	( )	( )	( )	( )	( )	( )	( )	( )
d. Debris	( )	( )	( )	( )	( )	( )	( )	( )

7.) How well could you **PREPARE YOURSELF** against damages from each of the following if a hurricane hits your area?

	Not very well at all 0	**1**	**2**	**3**	**4**	**5**	**Extremely well 6**	**Decline to answer**
a. Rain	( )	( )	( )	( )	( )	( )	( )	( )
b. Flooding	( )	( )	( )	( )	( )	( )	( )	( )
c. Wind	( )	( )	( )	( )	( )	( )	( )	( )
d. Debris	( )	( )	( )	( )	( )	( )	( )	( )

8.) How well would **MAINTAINING BUILDINGS AT CODE** help to reduce damages from each of the following if a hurricane hits your area?

	Not very well at all 0	**1**	**2**	**3**	**4**	**5**	**Extremely well 6**	**Decline to answer**
a. Rain	( )	( )	( )	( )	( )	( )	( )	( )
b. Flooding	( )	( )	( )	( )	( )	( )	( )	( )
c. Wind	( )	( )	( )	( )	( )	( )	( )	( )

d. Debris	( )	( )	( )	( )	( )	( )	( )	( )

Please look at the figure, then scroll down. Answer each question below by checking the one box that best describes what you think.

[1]

9.) An example hurricane forecast is shown above. Please fill in the one box that best describes how much you agree or disagree.

	Completely disagree	**1**	**2**	**3**	**4**	**5**	**Completely agree**	**Decline to answer**
a. A hurricane forecast for **12 HOURS** into the future is right at least half the time.	( )	( )	( )	( )	( )	( )	( )	( )
b. A hurricane forecast for **ONE DAY** into the future is right at least half the time.	( )	( )	( )	( )	( )	( )	( )	( )
c. A hurricane forecast for **3 DAYS** in the future is right at least half the time.	( )	( )	( )	( )	( )	( )	( )	( )
d. A hurricane forecast for **ONE WEEK** in the future is right at least half the time.	( )	( )	( )	( )	( )	( )	( )	( )

10.) The cone of uncertainty (the shaded grey area around the hurricanes in the image above)

[1] Figure from Max Mayfield on the Weather Channel (guy cited by interviewee), http://maxmayfieldshurricaneblog.files.wordpress.com/2010/07/td3-cone-from-11-am-thursday-july-22-2010.jpg%3Fw%3D426%26h%3D239&imgrefurl=http://newsodrome.com/search/landfall_news/tropical-storm-bonnie-s-cone-of-uncertainty-19081487&usg=__Z3ePb9nEh_IoaSrs9sfeLazK06g=&h=239&w=426&sz=23&hl=en&start=0&zoom=1&tbnid=0sLLUQD3q_iznM:&tbnh=162&tbnw=201&prev=/images%3Fq%3DNHC%2Bcone%2Bof%2Buncertainty%26um%3D1%26hl%3Den%26client%3Dfirefox-a%26sa%3DN%26rls%3Dorg.mozilla:en-US:official%26biw%3D1280%26bih%3D641%26tbs%3Disch:1&um=1&itbs=1&iact=hc&vpx=137&vpy=112&dur=614&hovh=167&hovw=299&tx=176&ty=72&ei=xqFuTMfRL8H58AaBoemBCw&oei=xqFuTMfRL8H58AaBoemBCw&esq=1&page=1&ndsp=15&ved=1t:429,r:0,s:0

shows how uncertain forecasts are.

Completely disagree ❍---❍---❍---❍---❍---❍---❍ Completely agree ❍ Decline to answer

11.) Hurricane forecasts are imperfect because...

	Completely disagree	**1**	**2**	**3**	**4**	**5**	**Completely agree**	**Decline to answer**
a. Scientists don't completely understand hurricanes.	( )	( )	( )	( )	( )	( )	( )	( )
b. Technology is not advanced enough.	( )	( )	( )	( )	( )	( )	( )	( )
c. Weather changes randomly.	( )	( )	( )	( )	( )	( )	( )	( )
d. The media hypes up the possibility of a bad storm.	( )	( )	( )	( )	( )	( )	( )	( )

12.) As a result of research, scientists will be able to predict hurricanes better…

	Completely disagree	**1**	**2**	**3**	**4**	**5**	**Completely agree**	**Decline to answer**
a. Next year.	( )	( )	( )	( )	( )	( )	( )	( )
b. In 10 years.	( )	( )	( )	( )	( )	( )	( )	( )
c. In 100 years.	( )	( )	( )	( )	( )	( )	( )	( )

Part IV: This section contains **OPINION** questions about how a single hurricane might change over its lifetime. Please answer each question below by checking the box or boxes that best describes what you think. You may check one box, several boxes, or all boxes.

First you will be asked about a Category 5 hurricane, and then about a Category 1 hurricane.

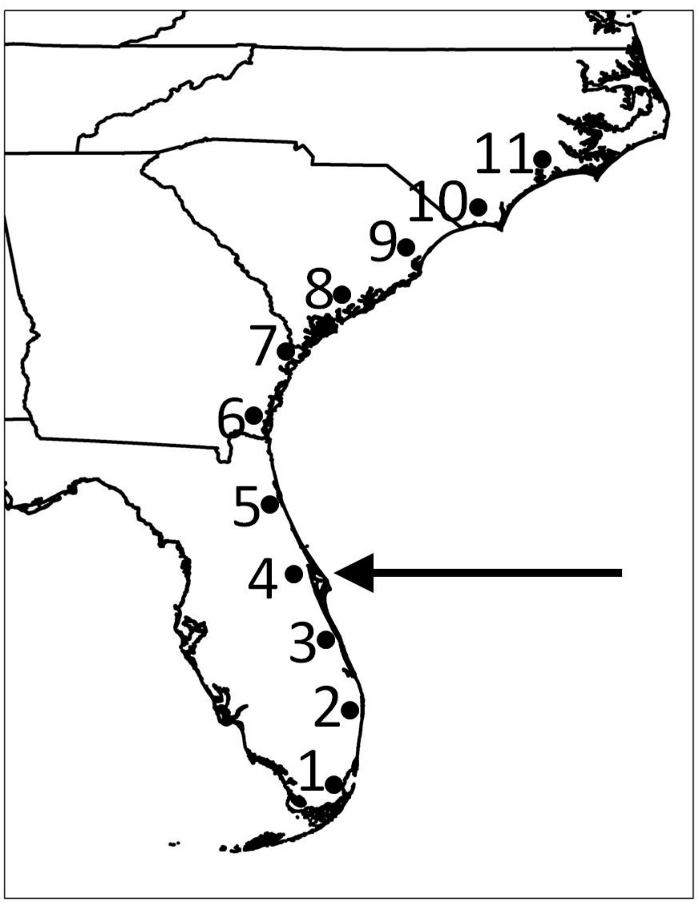
13.) The news forecasts that in 12 hours, a hurricane will make landfall as a **CATEGORY 5 HURRICANE** at Location 4 on the map (i.e. the center of the hurricane will pass over Location 4).

Check the boxes where you think the hurricane could make landfall. You may check one, several, or all boxes.

- ❍ South of Location 1
- ❍ Location 1
- ❍ Location 2
- ❍ Location 3
- ❍ Location 4
- ❍ Location 5
- ❍ Location 6
- ❍ Location 7
- ❍ Location 8
- ❍ Location 9
- ❍ Location 10
- ❍ Location 11
- ❍ North of Location 11
- ❍ Will not make landfall

Check the boxes which you think could describe the hurricane at landfall. You may check one, several, or all boxes.

- ❍ Below Category 1
- ❍ Category 1
- ❍ Category 2
- ❍ Category 3
- ❍ Category 4
- ❍ Category 5



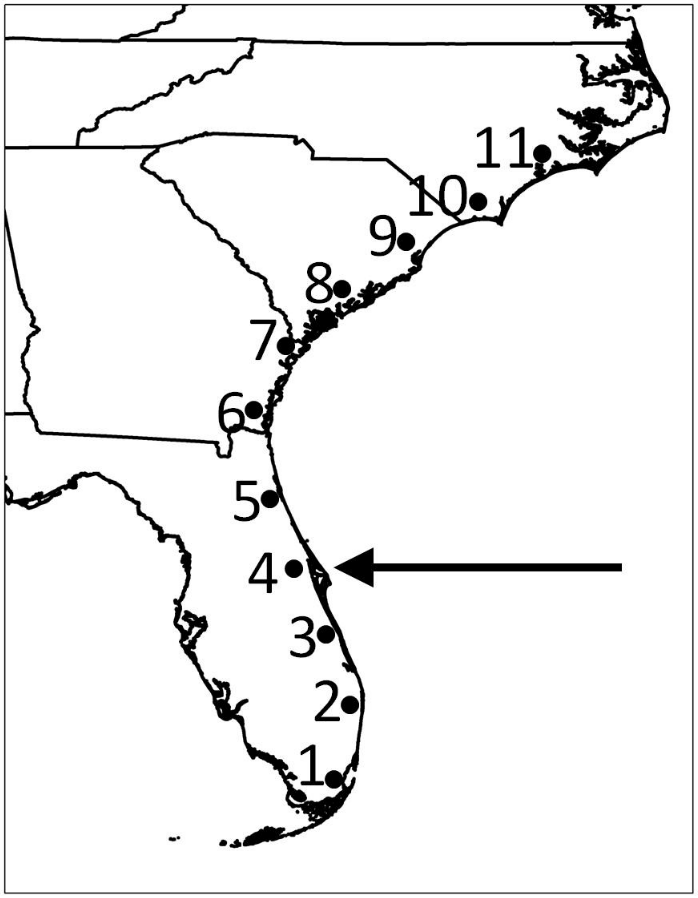
14.) The news forecasts that in 12 hours, a hurricane will make landfall as a **CATEGORY 1 HURRICANE** at Location 4 on the map (i.e. the center of the hurricane will pass over Location 4).

Check the boxes where you think the hurricane could make landfall. You may check one, several, or all boxes.

❍	South of Location 1	❍	Location 7
❍	Location 1	❍	Location 8
❍	Location 2	❍	Location 9
❍	Location 3	❍	Location 10
❍	Location 4	❍	Location 11
❍	Location 5	❍	North of Location 11
❍	Location 6	❍	Will not make landfall

Check the boxes which you think could describe the hurricane at landfall. You may check one, several, or all boxes.

❍	Below Category 1	❍	Category 3
❍	Category 1	❍	Category 4
❍	Category 2	❍	Category 5



Part V: This section contains **OPINION** questions about how a single hurricane might change over its lifetime assuming scientists try to change that hurricane to reduce damages. Note, you don't know how or what the scientists are doing, just that their goal is to reduce damages. If it would matter to your answer, assume that the action is being taken in the open ocean prior to landfall. Please answer each question below by checking the box or boxes that best describes what you think. You may check one box, several boxes, or all boxes.

Just tell us how the storm **MIGHT CHANGE**…. **NOT** how you want the storm to change. Later we will ask you questions about your feelings.

First you will be asked about a Category 5 hurricane, and then about a Category 1 hurricane.

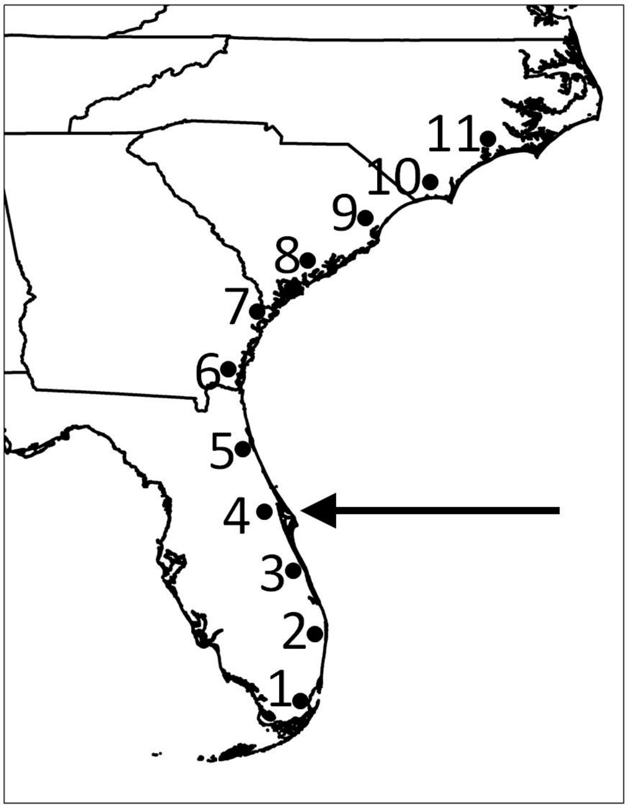
15.) The news forecasts that in 12 hours, a hurricane will make landfall as a **CATEGORY 5 HURRICANE** at Location 4 on the map (i.e. the center of the hurricane will pass over Location 4). Scientists try to change the hurricane to reduce damages.

Check the boxes where you think the hurricane could make landfall. You may check one, several, or all boxes. Just indicate how the storm **MIGHT CHANGE**…. **NOT** how you want the storm to change.

❍	South of Location 1	❍	Location 7
❍	Location 1	❍	Location 8
❍	Location 2	❍	Location 9
❍	Location 3	❍	Location 10
❍	Location 4	❍	Location 11
❍	Location 5	❍	North of Location 11
❍	Location 6	❍	Will not make landfall

Check the boxes which you think could describe the hurricane at landfall. You may check one, several, or all boxes. Just indicate how the storm **MIGHT CHANGE**…. **NOT** how you want the storm to change.

❍	Below Category 1	❍	Category 3
❍	Category 1	❍	Category 4
❍	Category 2	❍	Category 5


11
10
9
8
7
6
5
4
3
2
1

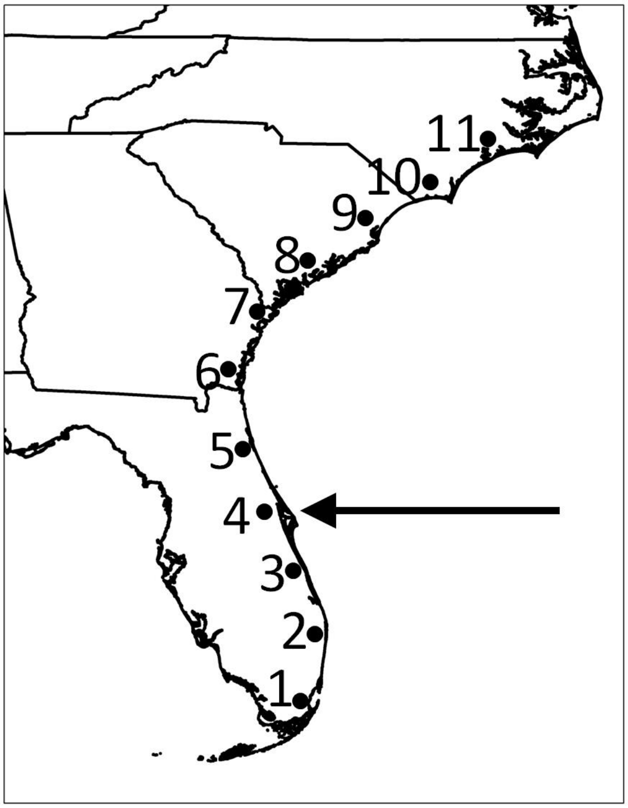
16.) The news forecasts that in 12 hours, a hurricane will make landfall as a **CATEGORY 1 HURRICANE** at Location 4 on the map (i.e. the center of the hurricane will pass over Location 4). Scientists try to change the hurricane to reduce damages.

Check the boxes where you think the hurricane could make landfall (not where you want it to make landfall). You may check one, several, or all boxes. Just indicate how the storm **MIGHT CHANGE**…. **NOT** how you want the storm to change.

❍	South of Location 1	❍	Location 7
❍	Location 1	❍	Location 8
❍	Location 2	❍	Location 9
❍	Location 3	❍	Location 10
❍	Location 4	❍	Location 11
❍	Location 5	❍	North of Location 11
❍	Location 6	❍	Will not make landfall

Check the boxes which you think could describe the hurricane at landfall. You may check one, several, or all boxes. Just indicate how the storm **MIGHT CHANGE**…. **NOT** how you want the storm to change.

❍	Below Category 1	❍	Category 3
❍	Category 1	❍	Category 4
❍	Category 2	❍	Category 5



Part VI: This section asks **OPINION** questions about changing hurricanes. Please answer each question below by checking the one box that indicates how strongly you agree or disagree.

17.) For each statement below, please check how much you agree or disagree.

	Completely disagree	**1**	**2**	**3**	**4**	**5**	**Completely agree**	**Decline to answer**
a. Today, it is possible to change a hurricane to reduce its damage.	( )	( )	( )	( )	( )	( )	( )	( )
b. At some point in the future, it will be possible to change a hurricane to reduce its damage.	( )	( )	( )	( )	( )	( )	( )	( )
c. Hurricanes are too big and powerful to ever be changed by humans.	( )	( )	( )	( )	( )	( )	( )	( )
d. We will never develop the technology to change a hurricane.	( )	( )	( )	( )	( )	( )	( )	( )
e. It is a bad idea to try to change a	( )	( )	( )	( )	( )	( )	( )	( )

hurricane because you shouldn't mess with the weather.								
f. Hurricanes play a necessary role in the environment, and therefore should not be changed.	( )	( )	( )	( )	( )	( )	( )	( )
g. It is a bad idea to change a hurricane because it might make things worse.	( )	( )	( )	( )	( )	( )	( )	( )
h. Scientists will most likely try to change a hurricane to further their own career.	( )	( )	( )	( )	( )	( )	( )	( )
i. Scientists will most likely try to change a hurricane to help people.	( )	( )	( )	( )	( )	( )	( )	( )
j. If the government tries to change a hurricane, they are trying to help the general public.	( )	( )	( )	( )	( )	( )	( )	( )
k. The government will use the ability to change storms as a weapon.	( )	( )	( )	( )	( )	( )	( )	( )

Part VII: This section contains **OPINION** questions on how you feel about changing hurricanes to avoid, prevent, or reduce damages. In answering each question, assume that only the action described will be done. Consider each action separately from the rest. If it would matter to your answer, assume that the action is being taken in the open ocean prior to landfall. Please answer each question below by checking the one box for each part (a, b, c, d) that best describes how you feel.

18.) Thinking about the possibility of changing a hurricane to avoid or prevent or reduce damages makes me:

	Not at all 0	**1**	**2**	**3**	**4**	**5**	**Extremely 6**	**Decline to answer**
a. Afraid	( )	( )	( )	( )	( )	( )	( )	( )
b. Angry	( )	( )	( )	( )	( )	( )	( )	( )
c. Happy	( )	( )	( )	( )	( )	( )	( )	( )

19.) Suppose scientists find a way to make the winds of a hurricane less strong without changing anything else. Thinking about this makes me:

	Not at all 0	**1**	**2**	**3**	**4**	**5**	**Extremely 6**	**Decline to answer**
a. Afraid	( )	( )	( )	( )	( )	( )	( )	( )
b. Angry at scientists	( )	( )	( )	( )	( )	( )	( )	( )
c. Angry at damages	( )	( )	( )	( )	( )	( )	( )	( )
d. Happy	( )	( )	( )	( )	( )	( )	( )	( )

For the questions on this page, imagine a situation in which a hurricane is **HEADED TOWARD WHERE YOU LIVE.** Scientists try to change the hurricane to save your area. Please check one box for each part (a, b, c, d) that best describes how you feel.

20.) Suppose the hurricane hits your area, and it causes the same amount of damage that was being predicted before scientists tried to change the storm. Thinking about this makes me:

	Not at all 0	**1**	**2**	**3**	**4**	**5**	**Extremely 6**	**Decline to answer**
a. Afraid	( )	( )	( )	( )	( )	( )	( )	( )
b. Angry at scientists	( )	( )	( )	( )	( )	( )	( )	( )
c. Angry at damages	( )	( )	( )	( )	( )	( )	( )	( )
d. Happy	( )	( )	( )	( )	( )	( )	( )	( )

21.) Suppose the hurricane hits your area, and it causes more damage than was being predicted before scientists tried to change the storm. Scientists all agree that nothing they did could have made the winds stronger. They argue that the storm got stronger just because of natural weather changes. Thinking about this makes me:

	Not at all 0	**1**	**2**	**3**	**4**	**5**	**Extremely 6**	**Decline to answer**
a. Afraid	( )	( )	( )	( )	( )	( )	( )	( )
b. Angry at scientists	( )	( )	( )	( )	( )	( )	( )	( )
c. Angry at damages	( )	( )	( )	( )	( )	( )	( )	( )
d. Happy	( )	( )	( )	( )	( )	( )	( )	( )

22.) Suppose the hurricane hits your area and causes less damage than was being predicted before scientists tried to change the storm. Thinking about this makes me:

	Not at all 0	**1**	**2**	**3**	**4**	**5**	**Extremely 6**	**Decline to answer**
a. Afraid	( )	( )	( )	( )	( )	( )	( )	( )
b. Angry at scientists	( )	( )	( )	( )	( )	( )	( )	( )
c. Angry at damages	( )	( )	( )	( )	( )	( )	( )	( )
d. Happy	( )	( )	( )	( )	( )	( )	( )	( )

Note: This question is on the previous page.

23.) Suppose after the scientists try to change the storm, the hurricane doesn't hit your area, but it does hit another area. Thinking about this makes me:

	Not at all 0	**1**	**2**	**3**	**4**	**5**	**Extremely 6**	**Decline to answer**
a. Afraid	( )	( )	( )	( )	( )	( )	( )	( )
b. Angry at scientists	( )	( )	( )	( )	( )	( )	( )	( )
c. Angry at damages	( )	( )	( )	( )	( )	( )	( )	( )
d. Happy	( )	( )	( )	( )	( )	( )	( )	( )

For the questions on this page, imagine a situation in which a hurricane is **HEADED SOMEWHERE ELSE.** Scientists try to change the hurricane to save that area. Please check one box for each part (a, b, c, d) that best describes how you feel.

24.) Suppose the hurricane doesn't hit that area, but hits your area. The storm causes the same amount of damage that was being predicted before scientists tried to change the storm. Thinking about this makes me:

	Not at all 0	**1**	**2**	**3**	**4**	**5**	**Extremely 6**	**Decline to answer**
a. Afraid	( )	( )	( )	( )	( )	( )	( )	( )
b. Angry at scientists	( )	( )	( )	( )	( )	( )	( )	( )
c. Angry at damages	( )	( )	( )	( )	( )	( )	( )	( )
d. Happy	( )	( )	( )	( )	( )	( )	( )	( )

25.) Suppose the hurricane doesn't hit that area, but hits your area. The storm causes more damage than was being predicted before scientists tried to change the storm. Scientists all agree that nothing they did could have made the winds stronger. They argue that the storm got stronger just because of natural weather changes. Thinking about this makes me:

	Not at all 0	**1**	**2**	**3**	**4**	**5**	**Extremely 6**	**Decline to answer**
a. Afraid	( )	( )	( )	( )	( )	( )	( )	( )
b. Angry at scientists	( )	( )	( )	( )	( )	( )	( )	( )
c. Angry at damages	( )	( )	( )	( )	( )	( )	( )	( )
d. Happy	( )	( )	( )	( )	( )	( )	( )	( )

26.) Suppose the hurricane doesn't hit that area, but hits your area. The storm causes significantly less damage that was being predicted before scientists tried to change the storm.

	Not at all 0	**1**	**2**	**3**	**4**	**5**	**Extremely 6**	**Decline to answer**
a. Afraid	( )	( )	( )	( )	( )	( )	( )	( )

b. Angry at scientists	( )	( )	( )	( )	( )	( )	( )	( )
c. Angry at damages	( )	( )	( )	( )	( )	( )	( )	( )
d. Happy	( )	( )	( )	( )	( )	( )	( )	( )

Part VIII: This section asks general **TRUE/FALSE** questions. Please answer each question below by checking the one box that best describes what you think.

27.) a. Hurricane categories are defined by how fast the storm's wind is blowing.

❍ True ❍ False ❍ Decline to answer

How confident are you in your answer to 27a?

Not confident at all ❍---❍---❍---❍---❍---❍---❍ Extremely confident ❍ Decline to answer

28.) a. Hurricane categories are defined by the size (i.e. the width) of the storm.

❍ True ❍ False ❍ Decline to answer

b. How confident are you in your answer to 28a?

Not confident at all ❍---❍---❍---❍---❍---❍---❍ Extremely confident ❍ Decline to answer

29.) a. Hurricane categories are defined by the amount of damage the storm could cause.

❍ True ❍ False ❍ Decline to answer

b. How confident are you in your answer to 29a?

Not confident at all ❍---❍---❍---❍---❍---❍---❍ Extremely confident ❍ Decline to answer

Part IX: Listed below are statements about the relationship between humans and the environment. For each statement below, please check the box that indicates how strongly you agree or disagree.

30.) For each statement below, please check how much you agree or disagree.

	Completely disagree	**1**	**2**	**3**	**4**	**5**	**Completely agree**	**Decline to answer**
a. We are approaching the limit of the number of people the earth can support.	( )	( )	( )	( )	( )	( )	( )	( )
b. The balance of nature is very delicate and easily upset.	( )	( )	( )	( )	( )	( )	( )	( )
c. Humans have the right to modify the natural environment.	( )	( )	( )	( )	( )	( )	( )	( )
d. Humans were meant to rule over the rest of nature.	( )	( )	( )	( )	( )	( )	( )	( )
e. When humans interfere with nature it often produces disastrous consequences.	( )	( )	( )	( )	( )	( )	( )	( )
f. Plants and animals exist primarily to be used by humans.	( )	( )	( )	( )	( )	( )	( )	( )
g. To maintain a healthy economy we will have to develop a "steady state" economy where industrial growth is controlled.	( )	( )	( )	( )	( )	( )	( )	( )
h. Humans must live in harmony with nature in order to survive.	( )	( )	( )	( )	( )	( )	( )	( )
i. The earth is like a spaceship with only limited room and resources.	( )	( )	( )	( )	( )	( )	( )	( )
j. Humans need not adapt to the natural environment because they can remake it to suit their needs.	( )	( )	( )	( )	( )	( )	( )	( )
k. There are limits to growth beyond which our industrialized society	( )	( )	( )	( )	( )	( )	( )	( )

cannot expand.								
l. Mankind is severely abusing the environment.	( )	( )	( )	( )	( )	( )	( )	( )

Part X: General Information about you (all answers will be kept confidential)

31.) Highest level of education: ❍ some high school

❍ completed high school
❍ some college or trade school
❍ completed undergraduate college in math/science
❍ completed undergraduate college not in math/science
❍ graduate school in math/science
❍ graduate school not in math/science
❍ decline to answer

32.) Age (Leave blank if you decline to answer): ___________________________________

33.) Gender:
❍ Male
❍ Female
❍ Decline to answer

34.) Zipcode (Leave blank if you decline to answer): ________________________________

35.) Do you live within a mile of the coast?
❍ Yes
❍ No
❍ Decline to answer

36.) Do you live in an area easily flooded?
❍ Yes

❍ No

❍ Decline to answer

37.) What kind of area do you live in?

❍ Coastal urban area

❍ Coastal rural area

❍ Inland urban area near a lake, river, or stream

❍ Inland rural area near a lake, river, or stream

❍ Inland urban area NOT near a lake, river, or stream

❍ Inland rural area NOT near a lake, river, or stream

❍ Decline to answer

Note these questions are on the same webpage as the previous page.

38.) Where do you live?

- ❍ Single Story House
- ❍ Multiple Story House
- ❍ Condo
- ❍ Ground Floor Apartment
- ❍ Apartment, Above Ground Floor
- ❍ Mobile Home
- ❍ RV
- ❍ No residence
- ❍ Other
- ❍ Decline to answer

39.) What is your household's annual income?

- ❍ Less than $10,000
- ❍ $10,000 to 24,999
- ❍ $25,000 to 49,999
- ❍ $50,000 to 74,999
- ❍ $75,000 to 99,999
- ❍ $100,000 to 149,999
- ❍ $150,000 to 299,999
- ❍ $300,000 or more
- ❍ Decline to answer

40.) How many people were living or staying in your household (Leave blank if you decline to answer.)?

Total on April 1, 2010?: ______________________

How many were children?: ______________________

How many were elderly, infirm, or handicapped?: ______________________

35.) Have you experienced a hurricane?

- ❍ Yes
- ❍ No
- ❍ Decline to answer

If yes, please list the storms you can remember (up to 10):

Your Location	Year	Hurricane Name
(list up to 10)		

Thank you very much for your help with this study. All answers will be kept confidential.

Final Steps

43.) Please enter the next number in this sequence:

1,2,3,4,5,6....

____

44.) Which is the largest number in this set?

- ❍ 1
- ❍ 20
- ❍ 500
- ❍ 1,000

Email Address

Thank you for taking our survey. Your response is very important to us. All answers will be kept confidential.

In order to process your gift certificate, please enter your email address.

Email address:: ________________________

To mail you the $20 gift certificate, we need your Florida street address (P.O. Box not acceptable). This is for payment purposes only, we will not send you anything else. You have *two* options to send us your mailing address. Please choose *one* of the following:

1) From the email address you entered above, please email your street address to cmuhurricanestudy@gmail.com .

2) Click "Next". You will be automatically routed to the Address Submission Link. This page make take up to 5 minutes to load; please be patient. If the page does not load, please copy and paste the following link into your browser: https://www.surveygizmo.com/s3/391118/Address-Submission

Thank you for taking our survey. Your response is very important to us. All answers will be kept confidential.