Does It Make Sense to Modify Tropical Cyclones? A Decision-Analytic Assessment

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ABSTRACT: Recent dramatic increases in damages caused by tropical cyclones (TCs) and improved understanding of TC physics have led DHS to fund research on intentional hurricane modification. We present a decision analytic assessment of whether it is potentially cost effective to attempt to lower the wind speed of TCs approaching South Florida by reducing sea surface temperatures with wind-wave pumps. Using historical data on hurricanes approaching South Florida, we develop prior probabilities of how storms might evolve. The effects of modification are estimated using a modern TC model. The FEMA HAZUS-MH MR3 damage model and census data on the value of property at risk are used to estimate expected economic losses. We compare wind damages after storm modification with damages after implementing hardening strategies protecting buildings. We find that if it were feasible and properly implemented, modification could reduce net 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. Damage from storm surge is modest in the scenario studied, but might be abated by modification.

KEYWORDS: Tropical cyclone; hurricane modification; hurricane hardening; adaptation, hardening; decision analysis; HAZUS; wind-wave pumps; shutters.

BRIEF: A proposed modification strategy could result in lower net losses for very intense hurricanes, while conventional hardening strategies are more economical for average storms.

Introduction

Intense tropical cyclones (TCs) are called hurricanes in the Atlantic and typhoons in the West Pacific. 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 (*1*). Additionally, over 1200 deaths are attributable to Katrina (*2*). Researchers have also identified many environmental impacts of hurricanes (*3, 4*). Annual losses are now estimated to average about $10-billion/year (*5*).

Given increasing coastal population, studies suggesting an upward shift of the average intensity of TCs with global warming (*6*), and work linking observed hurricane intensities to observed global warming (*7*), future damage rates from TCs are expected to increase. However, due to the suggested ~25% reduction in number of TCs, (*7*) it may be a few hundred years before global warming induced increases in hurricane damages may be detectable (*8*).

Several methods exist to reduce TC damages. Hardening structures includes applying storm shutters, reinforcing roofs, and using stronger building materials. The insurance industry calls hardening "hurricane hardening", while the Intergovernmental Panel on Climate Change (IPCC) would call hardening "adaptation". Currently, several hardening strategies have been adopted in various locations along the U.S. Atlantic coast (*9*).

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 (*10*). Since then, understanding of physics and track prediction has improved. For instance, we now have improved insight about how sea surface temperature relates to TC intensity (*11*). 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 (*12*). The U.S. Department of Homeland Security (DHS) and the

American Meteorological Society have recently devoted renewed attention to TC modification (*13, 14*), and DHS has funded an effort to identify and evaluate hurricane modification strategies through Project HURRMIT (*15*). Despite continued study, there are many extremely serious concerns with the implementation and effectiveness of any modification technique (see Supporting Information for discussion of one example).

Suppose that a strategy can 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 (*16*) by considering a range of average property damages with a 5% upper bound of approximately $250-million 1969USD. 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.

Here we compare hardening structures and hurricane modification for a hypothetical strong storm that makes landfall in Miami-Dade County, Florida. First, we define a control scenario using census data on property value at risk and prior distributions on changing storm behavior calculated from historical data. Second, we 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 we do not assess the actual performance of arrays of wind-wave pumps. Rather, we 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?. We then calculate the net benefits as a function of wind damages and technique costs. Finally, we explore the possibility that modification might be unreliably deployed.

Methods

We 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, we first characterize future evolution of the storm using discretized probability distributions for TC characteristics. For most of the Andrew-like storms examined in this paper, storm surge is a small component of the total damages. This occurs due to coastal bathymetry features such as the steep continental shelf and because most of the populated area of southeast Florida lies at an elevation above that affected by storm surges (see Supporting Information). 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 we focus on wind damages only.

Given the set of ways the hurricane could evolve, we calculate a range of possible wind damages with a three-step model. First we calculate a wind field at census block level for each of the possible hurricane tracks with FEMA's HAZUS-MH MR3 (*17*, *18*) hurricane model. Next, we use the wind field and HAZUS empirical wind damage functions to calculate wind damages for each building type. We 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, we alter empirical wind damage functions. To calculate the effects of hurricane modification, we alter hurricane tracks as informed by data from a hurricane downscaling technique driven by NCEP/NCAR reanalysis data from 1980-2005. While we have focused on a particular hurricane modification technique, our methodology could be applied to a range of impact categories and hardening options.

1. Creation of the family of unmodified TCs

We 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 over water, making landfall, and moving across land using Atlantic TC GIS data from the HURDAT database of the NOAA Coastal Services Center for the period 1953-2004, when aircraft reconnaissance was regular (*19*,*20*). We identified all hurricanes that crossed the line connecting (30ºN,70ºW) to (25ºN,75ºW) and made landfall on the U.S. mainland. We 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, we 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). Next, we 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. Finally, we characterized TC evolution over the first 12 hours on land (20 TCs). Complete tables are given in the Supporting Information.

To create a probabilistic range of control TCs, we chose a base TC and then applied the priors as shown in Figure 1. Because we were interested in strong hurricanes that may make landfall between Miami and Jacksonville, we used the 1992 track of Hurricane Andrew. To obtain tracks with a range of interesting landfalls, we rotated the eye bearing of this track by 11 degrees clockwise over the last 5 data points. We refer to the resulting hurricane tracks as "Andrew-like" TCs.

Next, we 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.

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

2. Modifying hurricanes with wind-wave pumps

Theory indicates that a TC is sustained through a "Carnot-like cycle", in which the storm draws heat from the ocean surface (*21*). The effect of a local change in SST (i.e. under the eyewall) is much larger than that of a global change (*11*). 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 upwelling pumps have been demonstrated to be capable of bringing deep, cooler ocean water to the surface (*22, 23*), 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 (*22*) of the same magnitude as natural TC induced upwelling (*24*); since pumps draw water from a different depth, the cooling should be additive to the cooling affected by the TC itself, and should have few additional environmental consequences (Supporting Information).

Pumps could be deployed for different durations and over different suitable regions. While difficulties in pump implementation exist, the purpose of this paper 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. Extended discussion on uncertainties, optimal configurations, deployment techniques, and other issues is given in the Supplemental Information. For this study, we consider sea surface temperature (SST) reductions and costs from 300m long pumps spaced 333m apart as listed below.

Seasonally and regionally. We 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.

In front of an approaching TC. If we had perfect knowledge of the TC track up until the area to be cooled and further assumed that the hurricane moved in conformity with our estimated priors, then pumps could deployed in a square 150kmX150km area (eddies are much smaller). We 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.

To characterize the effect of an SST decrease on the control hurricanes, we used data from a hurricane downscaling technique driven by NCEP/NCAR reanalysis data from 1980-2005 (*25, 26*) (see Supporting Information). We found a change in SST decrease only affects wind speed (and thus radius to maximum winds), not translational speed or eye bearing. Using model data, we regressed the fractional wind speed reduction against the change in SST, maximum 1 minute sustained wind speed at 10m height, and time spent in the altered SST area. We 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).

3. Hardening structures against TCs

Other strategies can decrease damages caused by hurricanes. Some options for "hurricane proofing", or hurricane hardening techniques, include adding storm shutters, strengthening roofs, assuring that structures have a negative load path to ground, and elevating buildings on pilings. These techniques are "tried-and-true", 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.

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) (*27*), 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 55 km/hr). Unshuttered windows with a lifetime of 15-50 years may last hundreds of years if shutters are correctly employed (*17, 28*). 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 *(17)*.

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 *(17)*, 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 (*9*).

Roof Wall Connections: This technique 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 the walls. In new homes, improved architectural design increases the uplift resistance. For existing houses, roof-wall and roof-truss connections can be strengthened with 0.125" straps and 8D nails (*27*). 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 (*9*).

We 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.

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.

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.

4. HAZUS-MH MR3 description

To estimate direct economic losses from TCs, we use FEMA's publically available HAZUS-MH MR3 hurricane model with their default input data (*17*). HAZUS uses general building stock data from the 2000 U.S. Census Bureau, commercial data by Dun and Bradstreet (2006) (*29)*, and RSMeans Residential Cost Data (2006) for calculations at census tract level (*30*). The HAZUS hurricane model modifies NHC data by decreasing wind values to roughly 90% of the given values. This occurs 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 (*31*).

Although HAZUS has been independently verified against insurance values (*17*), we performed our own validation of predicted wind damage versus historical damage information for Hurricane Wilma. General loss trends are similar, with differences attributable to storm surge/flood damages (see Supporting Information).

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.

In cases 2 and 3, the SST change only modifies track wind speed, and therefore the effect of the SST decrease is superimposed on the control priors. Note 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.

We 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 (*32*). This suggests that an action taken to protect one city (a deployment area "protecting Miami") may have far reaching benefits.

Figure 2A-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.

Figure 2C 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. We 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.

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

In the modification trials, time spent in the cooled SST area greatly affects wind speed and damage reduction, seasonal deployment results in a larger damage reduction than deployment in front of a TC, and 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 (roof-wall connections, hardening in roof replacement, tie-downs). Technique effectiveness appears to be slightly improved when multiple techniques are used.

Figure 3 shows aggregated total direct economic losses. Figure 4 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.

We 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. 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.

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.

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 or hardening arises, issues of social equity should 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 are several TC damage mechanisms that have not been considered in this work. Storm surge and rainfall damage are a small portion of the total damages from Andrew-like storms of the type examined here (see Supporting Information). 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 large slow-moving storms, flooding damage from rainfall may be significant. Neither of these additional damage mechanisms change the conclusions we reach about physical damage from wind. Modeling these other damage mechanisms present significant technical challenges to be addressed in future work.

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" the wind-wave pump 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.

Finally there is the issue of liability (*16*). 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 so that sovereign immunity would apply. However, this area of law remains relatively unexplored.

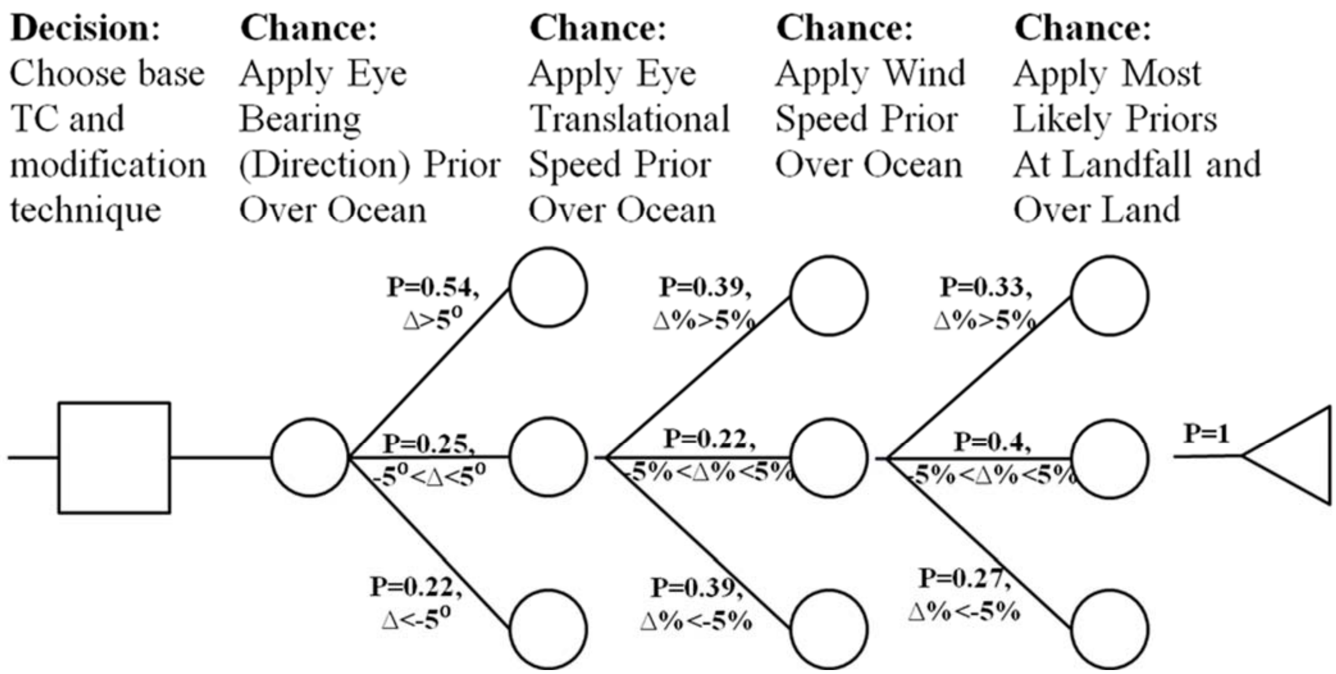

Figure 1. Schematic indicating how the discretized prior probabilities are applied. Data are from National Hurricane Center historical tracks (1953-2004). Circles indicate choice nodes, and branches indicate the available choices. Δ indicates an absolute or a percent change of characteristic over 12 hours.

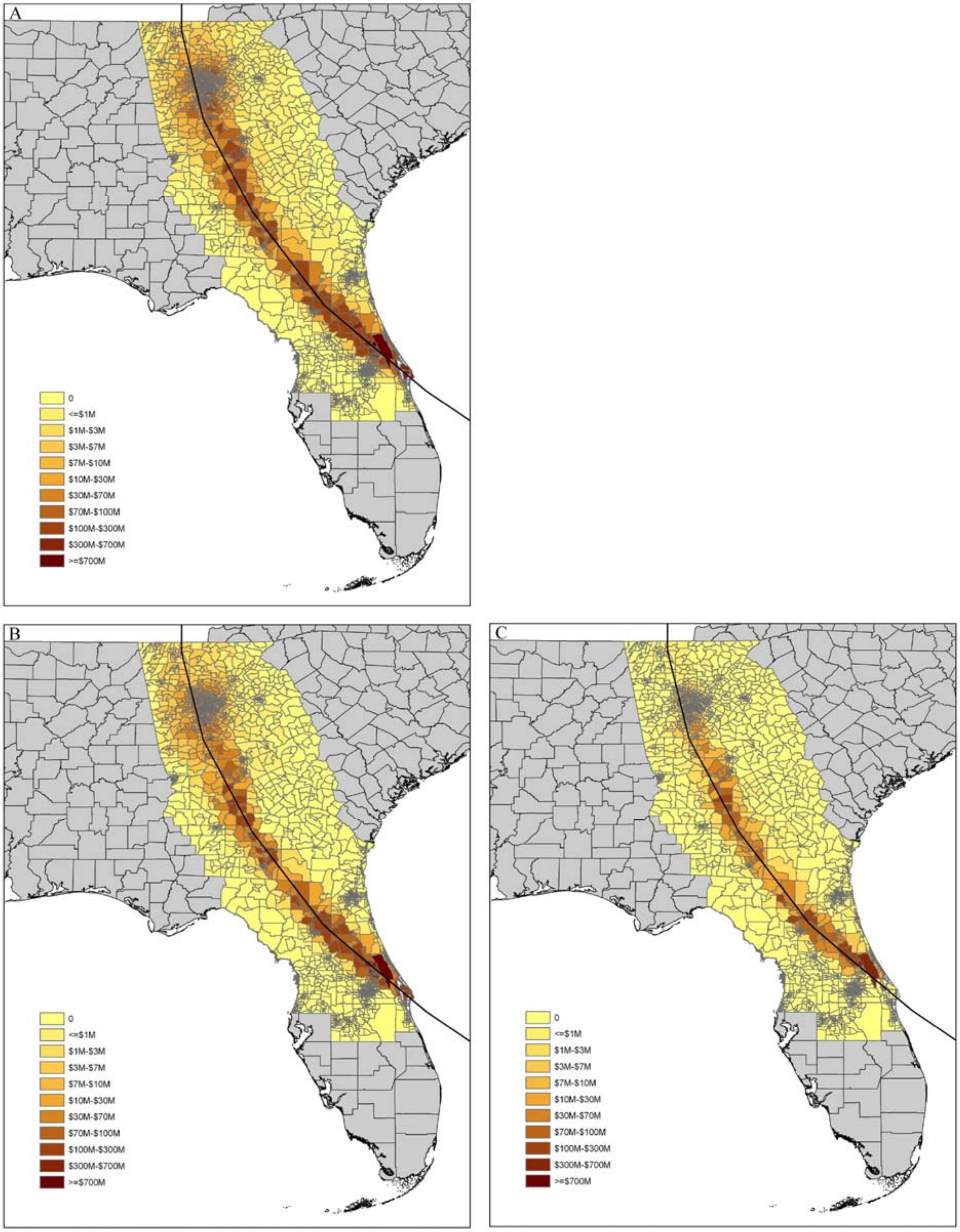

Figure 2. Total direct economic losses (log USD 2002) for the most likely technique. A: the most probable control trial (no wind speed change). B: Difference between control trial and the same trial with a 1°C SST decrease. C: Difference between control trial and the same trial with shuttering of all Florida and Georgia homes. Wind fields are given in the Supporting Information.

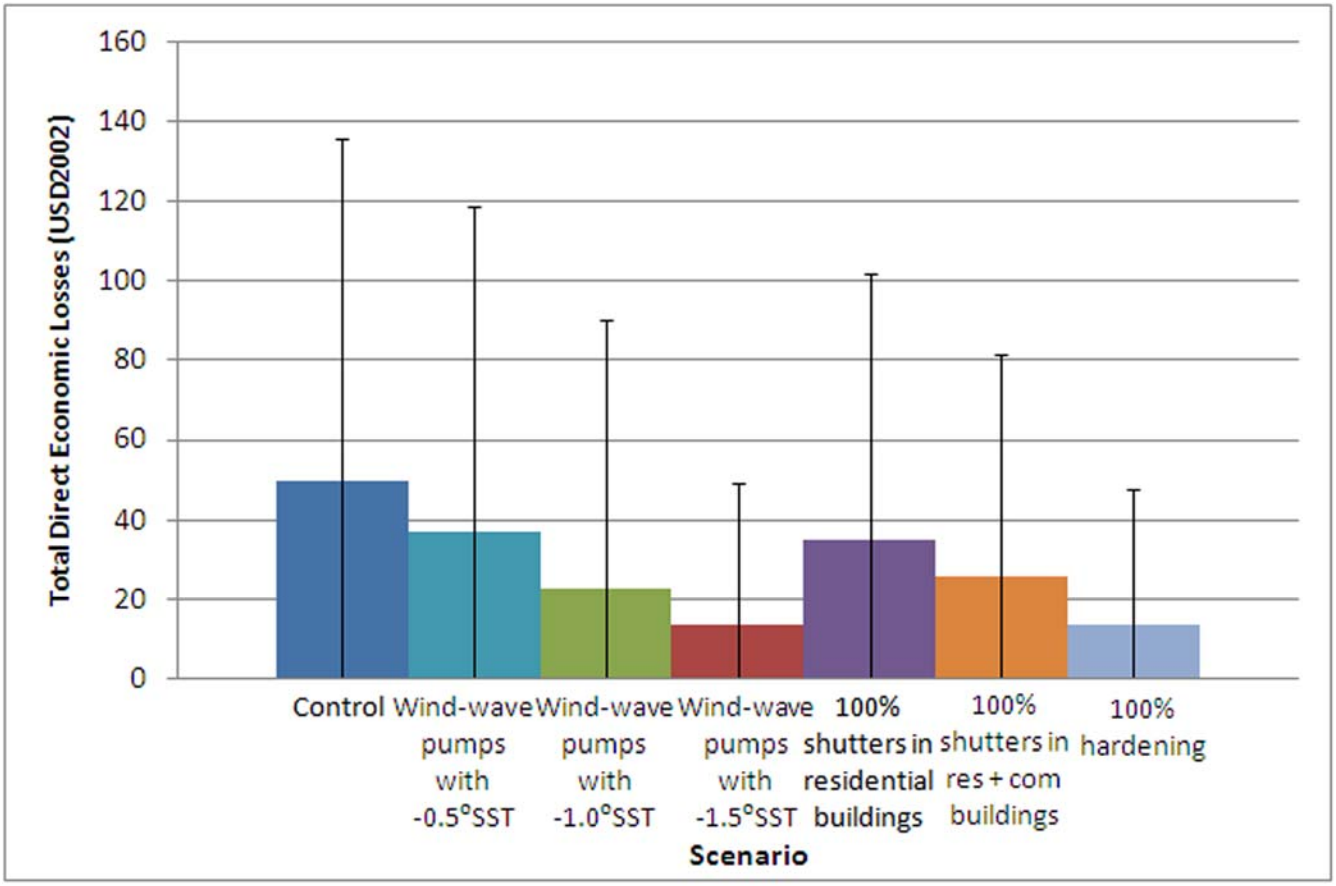

Figure 3. Aggregated total direct economic losses for each trial (billions USD 2002). Bars denote the average weighted value, whiskers the 5th and 95th percentiles.

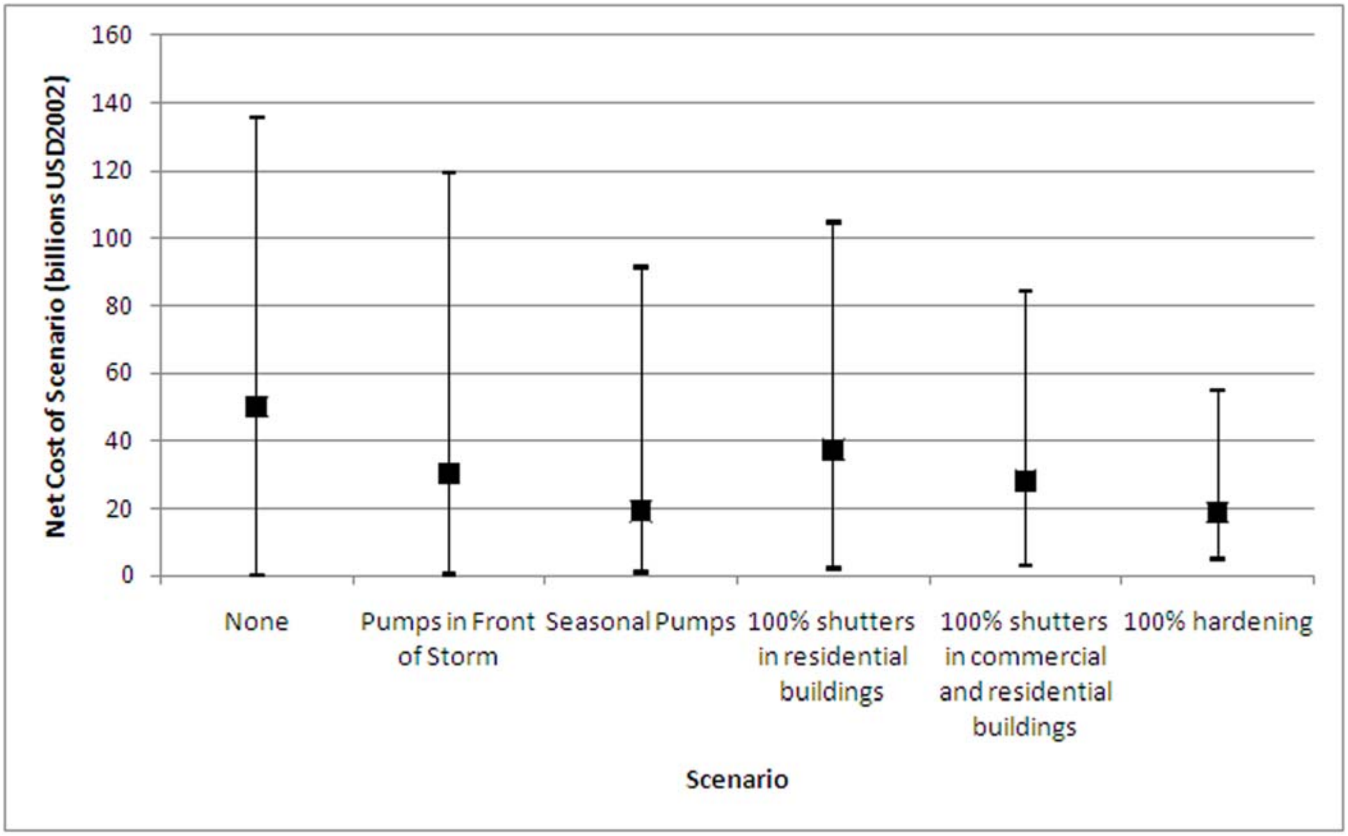

Figure 4. Aggregated net costs for each trial (billions USD 2002). Bars denote the average weighted value, whiskers the 5th and 95th percentiles.

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SUPPORTING INFORMATION AVAILABLE: The supporting information contains details on the wind-wave pump technique, validation of the HAZUS model, discussion on why storm surge damages can be neglected, and the complete tables of probabilities and total direct economic losses.

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