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Hurricane Modification and Adaptation in Miami-Dade County, Florida

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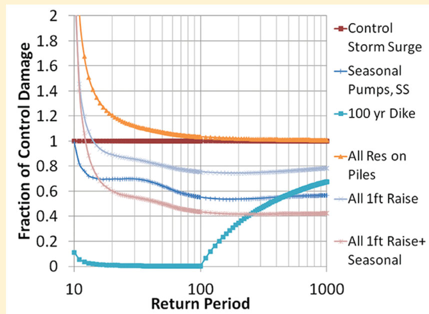
Supporting Information

ABSTRACT: We investigate tropical cyclone wind and storm surge damage reduction for five areas along the Miami-Dade County coastline either by hardening buildings or by the hypothetical application of wind-wave pumps to modify storms. We calculate surge height and wind speed as functions of return period and sea surface temperature reduction by wind-wave pumps. We then estimate costs and economic losses with the FEMA HAZUS-MH MR3 damage model and census data on property at risk. All areas experience more surge damages for short return periods, and more wind damages for long periods. The return period at which the dominating hazard component switches depends on location. We also calculate the seasonal expected fraction of control damage for different scenarios to reduce damages. Surge damages are best reduced through a surge barrier. Wind damages are best reduced by a portfolio of techniques that, assuming they work and are correctly deployed, include wind-wave pumps.



INTRODUCTION

Annual losses from tropical cyclones (TCs) in the United States are estimated to average about $10-billion/year.[1] Damages can be caused by wind, storm surge, and floods. Some U.S. coastal areas experience high TC wind speeds and contain geophysical features vulnerable to storm surges and flooding.[2] Since the Miami-Dade County coastline contains a range of topography, bathymetry,[3] and infrastructure [4,5] with different susceptibilities to TCs, optimal policy choices regarding methods to reduce TC damages depend strongly on locale.

Various adaptation techniques, including "hardening", are available to reduce damages from TCs.[6−8] Many techniques are recognized by Florida residents,[9] and can remain in place for many years. Some techniques, such as installing storm shutters, strengthening roofs, and providing structures a negative load path to ground, protect buildings against wind and windborne debris.[7] Other techniques, such as elevating structures on pilings and building dams or dikes, help protect buildings against water damage.

Strategies to reduce the intensity of a TC, while still hypothetical, offer a very different approach to reducing damages. An early project on "hurricane modification", Project Stormfury, ended in 1983 due to lack of results.[10] However, recent years have witnessed a renewed interest in TC modification.[11−13] One technique, wave-driven upwelling pumps, has been demonstrated to be capable of bringing deep, cooler ocean water to the surface,[14,15] thereby decreasing local sea surface temperature (SST). Preliminary assessments suggest that, given reliable deployment, an array of wind-wave pumps over a 150 km square region along the east coastline of Miami-Dade County, Florida can reduce TC intensity and may offer a cost-effective method to reduce wind-induced damages.[16] However, this technique's ability to reduce storm surge damage is less clear and will likely be a strong function of location.

Here we use a risk assessment model to compare wind and storm surge damage reduction from wind-wave pumps and adaptation strategies for five areas along the Miami-Dade County coastline. For each area, we estimate the storm surge height and wind speed as functions of return period and SST reduction. For each damage mitigation technique, we estimate costs and, using the FEMA HAZUS-MH MR3 damage model and census data on the value of property at risk, we estimate expected economic losses for a range of storm surge heights and wind speeds.

METHODS

Five regions along the Miami-Dade County coastline were chosen to reflect a range of topographies, bathymetries, and infrastructure, Figure 1. Regions 1, 2, and 5 are the full census tracts 12086004101, 12086006701, 12086010605, respectively, in which buildings values total $1.4, $2.2, and $1.3 billion, respectively, in 2006. Regions 3 and 4 are, respectively, the northern and southern parts of census track 12086008000,

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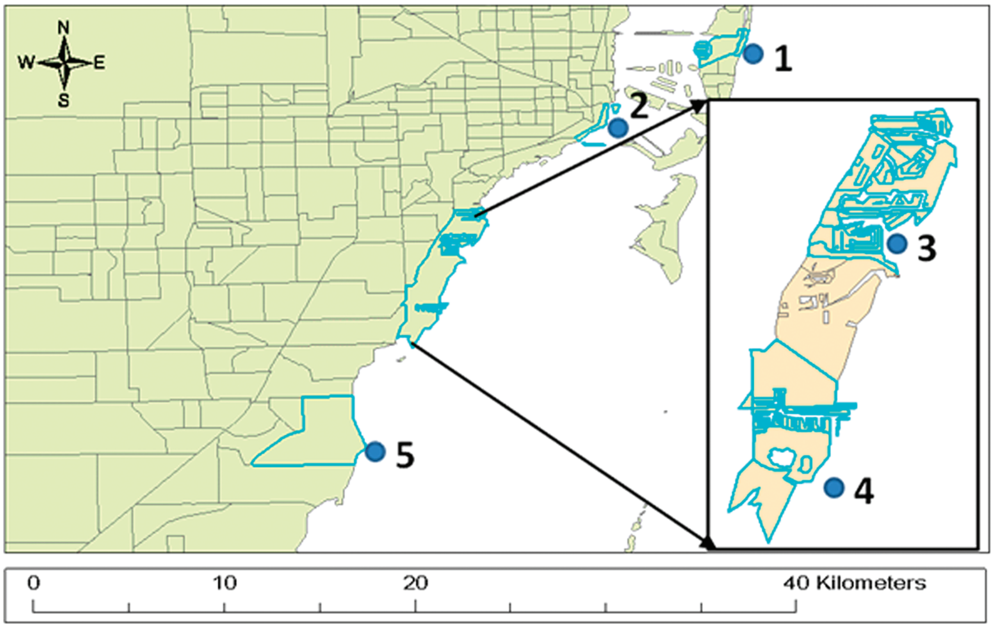

Figure 1. The five regions along the Miami-Dade County coastline with varying topographies, bathymetries, and housing types examined in this study. Regions 1, 2, and 5 include the full census tract (12086004101, 12086006701, 12086010605, respectively), while Regions 3 and 4 are, respectively, the northern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

containing buildings worth, respectively, \$600 and \$160 million in 2006.

We created damage scenarios for each region in three steps. First we used a risk assessment method to estimate the wind speed and storm surge height as functions of TC return period and SST reductions by wind-wave pumps. Second, we identified several possible scenarios of adaptation and hurricane modification and calculated implementation costs. Third, we used FEMA's HAZUS-MH MR3[17,18] to calculate damages and aggregate total losses from the wind and storm surge for each scenario.

In contrast to previous work that considered only wind damages,[16] this method yields wind and storm surge damages for a range of return periods. Additionally, damage reductions from adaptation and modification can be combined.

1. TC Wind and Surge Risk Assessment. To investigate the risks of TC wind and surge and how they may be reduced by lowering SST through using wind-wave pumps, we adapted a risk assessment method previously applied to study storm surge risk for New York City.[19] We generated large numbers of synthetic TCs for the study area under different SST conditions, and conducted storm surge simulation for each storm. Return level curves were then estimated for the wind and surge as functions of return period and SST reduction for each region.

The hurricane model applied uses large-scale TC environments, which may be estimated from observations or climate modeling, to generate synthetic TCs.[20,21] Output does not rely on the limited historical track database, but is in statistical agreement with the observations.[20] For this study, we generated a control set of 500 TCs for the study area under current climate conditions. The annual frequency of such TCs was estimated to be 0.41. To study the modification of the TCs by wind-wave pumps, we simulated another three 500-TC sets, for each of the SST reductions of 0.5, 1.0, and 1.5 °C,[16] yielding an annual frequency of 0.36, 0.33, and 0.3, respectively.

We applied the Sea, Lake, and Overland Surges from Hurricanes (SLOSH) model[22] with a grid for Miami basin to simulate storm surges for all 2000 synthetic tracks. SLOSH is currently used by the National Hurricane Center to provide real-time TC storm surge guidance. The performance of the SLOSH model has been evaluated using observed storm surges from past TCs; the accuracy of the surge heights predicted by the model is reported to be within 20% when the TC is adequately described.[22,23]

For each of the five selected regions and for each SST reduction, we calculated the wind speed and storm surge height at a coastal point near the region. We 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/surge return level curves (or, equivalently, exceedance probability curves), representing the long-term TC risk, were estimated by combining the probability density function (PDF) of the wind speeds/surge heights and the annual TC frequency. The PDF of the TC wind and surge is often associated with a long tail where infrequent storms cause catastrophic damage. Therefore, we modeled the tail of each PDF with a generalized pareto distribution (GPD) using the maximum likelihood method,[24] and the rest of the distribution, where the data are abundant, with nonparametric density estimation, similarly to other studies on TC climatology.[25,26] We calculated the statistical confidence intervals of the estimated return level curves with the Delta Method.[24]

2. Cost Analysis for Adaptation and Hurricane Modification Scenarios. We examine two hardening methods to reduce wind damages, three adaptation techniques to reduce storm surge damages, and one hurricane modification technique. Here we detail costs for these scenarios.

Hardening to Reduce Wind Damages. Previous work described methods to increase wind resistance of buildings, such as installing shutters on all windows and doors as well as employing all wind hardening techniques (shutters, improved roof-wall connections, improvement of roof during replacement, and tie-downs).[16] According to the building data in HAZUS, adding corrugated aluminum shutters to windows and doors of all nonshuttered 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 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.

Adaptation to Reduce Storm Surge Damages. FEMA maintains extensive information on ways one can protect property from floods and storm surges.[27−31] 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, they must be elevated or in some other way protected from future water damages when repaired.[27] The highest foundation height described in HAZUS is pile foundation height.[18] Here we examine two strategies: elevating all residential buildings one foot and elevating all buildings to pile height.

The cost of elevating a building varies with building characteristics. A Florida construction company suggested we estimate a lower bound cost for elevating a standard single family home as \$40 K plus \$10 K per foot raised up to nine feet. The approximate 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. 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.

A third technique to reduce storm surge damages involves large scale civil engineering of the coast through coastal reinforcement, the raising of quaysides, or the building of dikes and levees. Here we consider the cost of installing a surge barrier. Optimal design depends on local bathymetry and storm climatology.[32] The U.S. Army Corps of Engineers suggests a surge barrier 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. Costs of these structures are uncertain because of cost of maintenance. Recently, \$14.45 billion USD2010 was allocated to build the Hurricane and Storm Damage Risk Reduction System, approximately 560 km of 6 m high levees in New Orleans,[33] suggesting a cost of \$4,000/sq-meter. As cost likely increases nonlinearly with dike height, this value overestimates costs for the heights of this study (1−3 m). Assuming a range of \$80−4,000/sq-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. Note this surge barrier would cause heightened flooding at its edges if it were simply terminated at the ends of our study region.

Hurricane Modification. We examined the hurricane modification technique of using wind-wave pumps to raise colder deep water to the surface and decrease SST.[14] Previous work suggests along the east coast of Miami-Dade County, the wind-wave pumps can realize an SST reduction sufficient to decrease TC intensity;[12] we use the risk assessment method described above to characterize this relationship. Seasonal deployment, or covering a large area in front of Miami (25−27 °N, 78−80 °W) with pumps for the entire hurricane season, will decrease the SST by 1.0−1.5 °C and is estimated to cost between \$0.9−1.5 billion annually.[12] After a storm passes re-equilibration time is less than 6 h,[12] so it is very unlikely that the pumps will be less viable on a second storm. If pumps were to be deployed ∼3 days ahead of 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 (roughly over a 150 km^2 region) and without maintenance costs. In this case, it may be assumed that successful deployment in front of an approaching TC will decrease the SST by 0.5−1.0 °C and cost \$400−700 million total per TC.[12]

However, these costs are levied to reduce TC damages over the entire area impacted by the hurricane; here our focus is the cost in each selected region. Therefore we distribute a fraction of the total hurricane modification cost to the five regions. We 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). (Damage and loss estimates are discussed in the next subsection.) The calculated costs for seasonal deployment are \$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 estimate 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.

3. Damage Analysis and Loss Estimation. To estimate total losses, we use FEMA's publically available HAZUS-MH MR3 model with default input data. HAZUS uses general building stock data from the 2000 U.S. Census Bureau, commercial data by Dun and Bradstreet (2006),[4] and RSMeans Residential Cost Data (2006) for calculations at the census tract level.[5] Wind damages and storm surge damages were calculated in two different submodels of HAZUS.

We used the H-Wind feature in HAZUS-MH MR3 Hurricane Model[17] 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,[34] we subtracted the appropriate digital elevation model (DEM) in the North American Datum of 1983 (NAD83) (ref 35 and Supporting Information) and converted these data to a user defined flood grid. We then used the HAZUS-MH MR3 flood model[18] to aggregate total losses for storm surge damages for each return period for all scenarios. Damage values were smoothed along boundaries (Supporting Information).

RESULTS

Following the method outlined above, we calculated return level curves of the wind speed and surge height, the value of

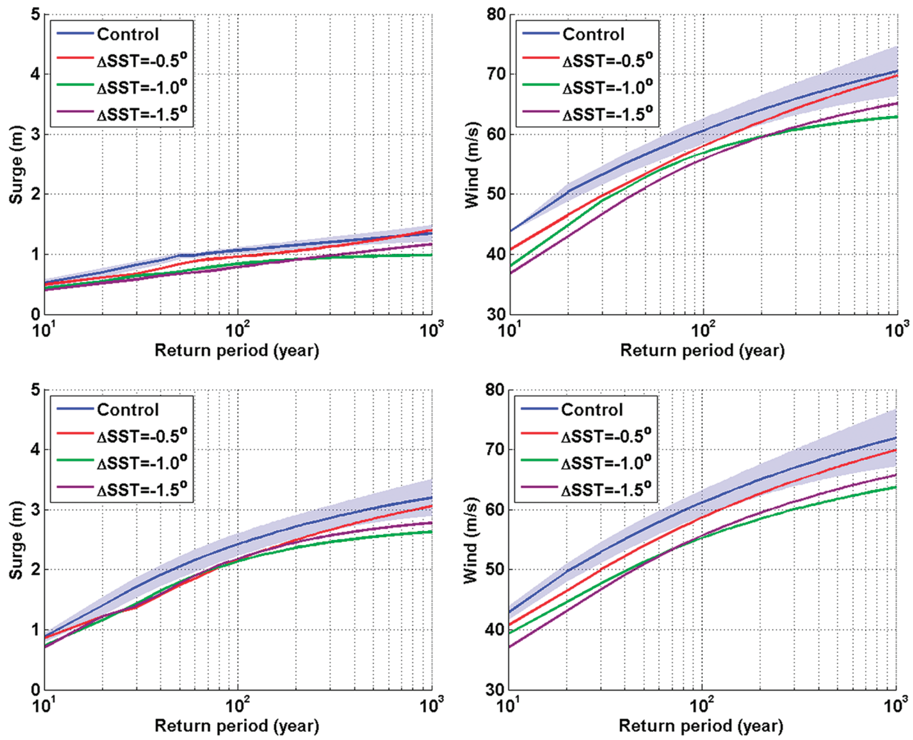

Figure 2. Storm surge and wind return level curves for Region 1 (top) and 2 (bottom). Legend indicates SST reduction from control. The shading shows the 90% confidence interval for the control scenario.

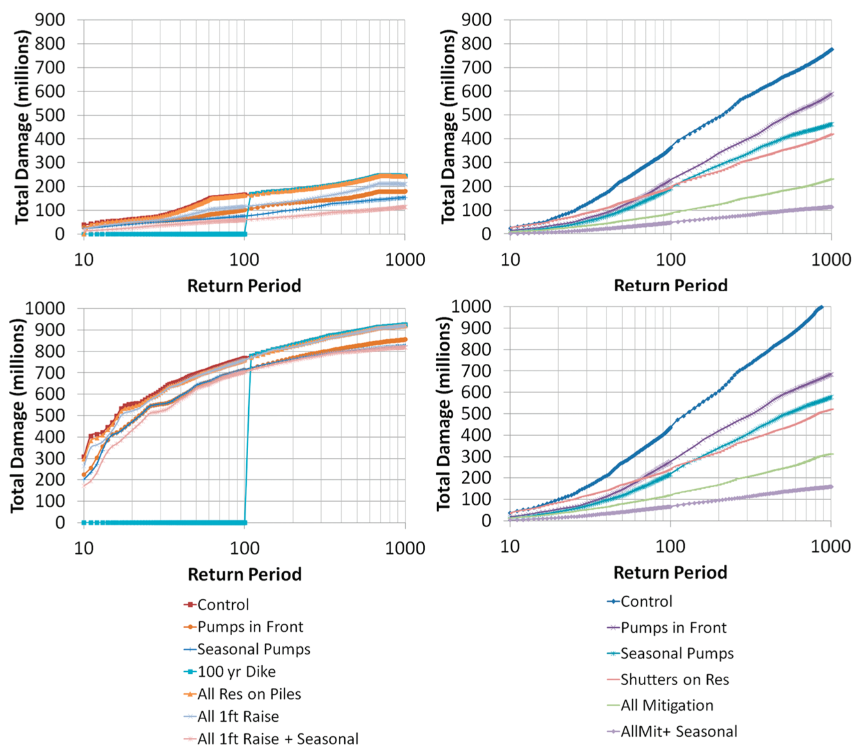

Figure 3. Total damages for scenarios combating storm surge (left) and wind damages (right) for Region 1 (top) and 2 (bottom).

damage of each scenario, and the seasonal expected net cost of each scenario (damage reduction cost plus value of damage). Wind and storm surge analyses are presented separately.

First, we calculated return level curves of the wind speed and the surge height as functions of return period and SST reduction. Figure 2 shows the return level curves for Region 1 and 2. Curves for Regions 3−5 are provided in the Supporting Information. 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

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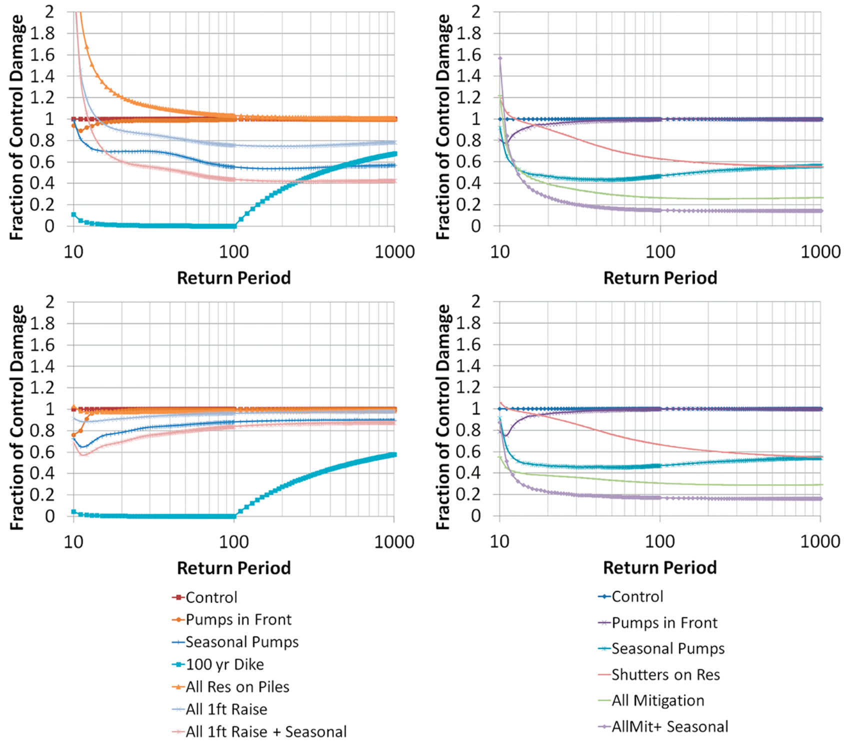

Figure 4. Seasonal expected fraction of control damage for scenarios combating storm surge (left) and wind damages (right) for Region 1 (top) and 2 (bottom).

TC modification for this region; further reduction of SST may have little impact on storm intensity. At greater SST reduction, the boundary layer becomes stable and frictional effects become more confined to a thin boundary layer, enabling the vortex in the free atmosphere to spin down less rapidly.

Next we calculated the total damages that result with various adaptation and modification techniques as a function of return period using the wind and surge return level curves in Figure 2. Scenarios examined included (a) control with no damage abatement policies, (b) shutters on all residential windows and doors, (c) the full set of wind mitigation options available in HAZUS, (d) raising all buildings one foot, (e) raising all residential buildings to pile height, (f) building a surge barrier, (g) deployment of wind-wave pumps to modify a specific storm, (h) seasonal deployment of wind-wave pumps, and (i) combinations of adaptation and modification. Damage 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 0.5 and 1.0 °C trials or 1.0 and 1.5 °C trial. Damage values are given in Figure 3 and in the Supporting Information; note the benefit of each scenario, although not given here, would be the difference between the control and the specific scenario. We find that HAZUS does not predict total destruction of property from either wind or storm surge alone even in a 1000 year period. Since HAZUS is unable to combine wind and storm surge damages, 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 surge 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 between dominating hazard component results because (a) the magnitude of storm surge and wind both increase in a roughly linear manner with return period, and (b) while surge damages are linear with the storm surge height, wind damages increase as roughly the cube of the wind speed.

Finally we calculated the seasonal expected fraction of control damage for each scenario. We calculated the seasonal expected total damage as an integration of the damage curve in Figure 3 up to each return period. Next we calculated seasonal net costs for each scenario by adding the seasonal expected total damage to the seasonal implementation cost (described in Methods, and $0 in the control case). Then we calculated the seasonal expected fraction of control damage as the ratio of the seasonal net cost of each scenario to the control seasonal total damages. Figure 4 shows, for Region 1 and 2, the seasonal expected fraction of control damage. The seasonal expected fraction of control damage curves for Regions 3−5 are similar (Supporting Information). 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 (or the extremes will not have been expected to happen).

For wind damage reduction, the all-mitigation scenario dominates because benefits of additional mitigation technique 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 1.0−1.5 °C SST reduction instead of 0.5−1.0 °C 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 a period, on an expectation basis, damage reduction from one storm is often small compared to overall damages.

For storm surge adaptation, we 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, we find a combination of all mitigation possible in HAZUS and seasonal deployment of wind-wave pumps is always the best choice (assuming that pump deployment and operation are reliable). If techniques are not combined, seasonal deployment of wind-wave pumps performs best at short return periods (or when small to moderate events are considered), while all mitigation possible in HAZUS performs best at long return periods (or when the extremes are also considered). The switch between scenarios varies from return periods of 5–20 years depending on the region.

DISCUSSION

Expected storm surge damages dominate expected wind damages in the coastal regions examined. However, the storm surge and its response varies across the five regions we examined due to 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.

Since storm wind and surge vary greatly over large areas, there is hardly any "typical storm" for a return period over large areas (Supporting Information). 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 previous work[16] we examined cumulative wind damage along an entire overland 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.

The combination of wind and storm surge damage is also nonlinear and poorly understood.[6] A lower bound can be placed on the total damages (Supporting Information), but 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 better assess the likely efficacy of TC modification and adaptation.

ASSOCIATED CONTENT

Supporting Information

Raster download information for the five regions, the smoothing of HAZUS storm surge damage values, the storm surge and wind return level curves for Regions 3–5, the damages for each scenario for Regions 3–5, the seasonal expected net cost of each scenario for Regions 3–5, the inability to identify typical storms for each return period, and an attempt to combine wind and storm surge damages using lower bound estimates. This material is available free of charge via the Internet at http://pubs.acs.org.

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