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HURRICANE EVACUATIONS AS A METRIC FOR SOCIETAL VULNERABILITY

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Abstract

Analyses of the variations in societal vulnerability to hurricanes and the impacts of hurricane forecasts help to mitigate vulnerability are the subject of this research. An index of societal variability is developed based on the idealized costs of evacuation owing to hurricane landfall. Evacuation populations are chosen as a forecast metric because evacuation zones combine information about hurricane track and intensity, population density and the areas of greatest vulnerability due to coastal bathymetry and topography (which affect storm surge) and available evacuation routes. Thus, idealized evacuation statistics capture the societal impact of forecast and realized storm track and intensity.

For the initial analysis, the study focuses on the forecasts of the seven hurricane landfalls in Florida during the 2004 and 2005 hurricane seasons using the National Hurricane Center (NHC) best track for validation. The official forecast was compared with operational model forecasts that were available at the time. Forecasts of minimum pressure, wind intensity, and landfall coordinates are compared with conditions at landfall. A vulnerability index value for the total cost of an evacuation is computed, taking into account both the cost of evacuating the population of a region, including "correct" evacuations and over-warning, and the costs incurred by not evacuating a population actually impacted at landfall. These measures are compared with the cost of a perfect forecast. Analyses of this index are completed for forecasts in six-hour intervals from the initial NHC tropical storm watch declaration up to landfall.

A Tropical Cyclone Game (TCG), a descendent of the Hurricane Game developed at Colorado State in the 1980s, was developed to provide a more nuanced perspective on evacuations due to approaching hurricanes. This model includes parameterizations of

population awareness and likelihood of evacuation in the presence of an approaching storm. Forecast information was also analyzed using the TCG to compare the vulnerability index costs to potential (and less extreme) evacuation scenarios.

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Acknowledgements

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Literature Review

Introduction

In the past years, increases in the accuracy of forecasts have led to a decrease in the fatalities associated with hurricane landfalls. Because there are limits to what can be done to improve hurricane forecasts, it is important that information is provided to the public so that they can make quality decisions. Currently, the National Hurricane Center (NHC) provides watch and warning information, however, decisions to evacuate are typically made at the county or parish level. Programs such as Hurricane Evacuation (HURREVAC) and HURRTRAK are used by state and local emergency management agencies to determine whether to evacuate a region or what actions need to be taken. Evacuation is typically the best action to take. Problems occur when there is a small probability of a strike at 36 hours, which is the usual time that an evacuation order is issued (Lindell 2007). Releasing evacuation decisions too early in the forecast period can result in unnecessary evacuations due to incorrect forecasts. Also, evacuations incur multiple costs to a household for gas, food, and lodging; costs to a business include lost revenue; costs to a government for emergency workers. All of these costs need to be borne whether or not a hurricane strikes and causes damages (Lindell 2007). A population also can suffer evacuation fatigue. Residents can make false assumptions about the effects of hurricane landfall because of previous experiences with hurricanes (Sattler, et al 2000). If a population is not evacuated or not evacuated with a large enough time margin for evacuation, then fatalities will occur. However, these risks must be balanced with against the risk of not issuing a needed evacuation with sufficient lead time.

Official Reactions

Public officials usually receive forecast information in repackaged forms of the National Hurricane Center data. Included in the packages are the wind-speed probabilities, or the likelihood that the wind will exceed a certain critical threshold at any single geographic location, and strike probabilities (Regnier 2008). Officials use the information to minimize the total costs of a hurricane; the costs are a function of the hurricane path and the decisions undertaken. The probabilities can be used in a static decision-making framework, where a region is either evacuated or not for the hurricane. There is no option to wait and reevaluate the situation in six or twelve hours (Regnier 2006). A chosen strike probability threshold for evacuation is the trade-off between missed evacuations and false alarms. Officials must minimize false alarms because they are disruptive, expensive, and can increase public apathy towards preparation (Regnier 2008). By having a shorter evacuation leadtime, the probability of giving a false alarm is reduced. However, the costs of evacuation will rise due to the short notice (Regnier 2008). Evacuations also will be faster because a smaller population will be evacuating.

A second option is to use a dynamic decision process to issue evacuation orders. In a dynamic model, a decision maker can still complete preparations after the critical lead time τ has passed, a feature that is not available in static frameworks. These actions typically are more costly and less effective than preparations completed before time τ. Overall, the dynamic frameworks prevent false alarms when the preparations are delayed and updated forecasts confirm that preparations are not necessary. These preparations are then more costly, but savings from the reduced number of false alarms can offset these additional costs, making the expected total costs of the dynamic processes lower than those for the static decisions. However, there are decreased values when the dynamic processes show an increased strike probability and preparations have yet to start occurring. Dynamic frameworks cannot be implemented widely in real time because they deal with specific cost profiles (Regnier 2006).

A third option is the Emblem decision making tool, which incorporates hurricane data from the National Hurricane Center and evacuation time estimate data to create two sets of decisions based on location using hurricane speed. The program then determines when and how many people to evacuate. Before the tool is put into widespread use, assumptions about the behavior of evacuees must be confirmed with data about actual evacuee behavior (Lindell 2007).

People Reacting to Decisions

Although officials can issue as many evacuations as they want, in order for them to be effective, the population must hear and act upon the warnings. For the general public, warnings are most effective when given by agencies that the public deems to be credible. Warnings are received rapidly due to owing official, broadcast components and informal, social network components. The rates of evacuation increased when there is detailed, complete, credible information given with specific facts for the recipient about what to do and where to go in an evacuation, in addition to why they must evacuate (Solis 2009).

Surveys administered to Florida residents are used to determine factors that influence a person's decision to evacuate. These reasons can include the type of dwelling in which a household resides, the number of children, the past hurricane experience, and prior preparation, and their pets. Evacuation rates increase when households live in more risky environments, such as trailer parks versus a house; have a greater number of children and previous experience with hurricanes. Increased net worth, homeownership, and pet ownership all will decrease the rates of evacuation. As well, the more money a family spent in evacuation preparation, the less likely they are to evacuate. Location also affects how likely a group is to evacuate; southeastern Florida residents are less likely to leave than those in northwest Florida (Solis 2009). Additional surveys administered by Lazo (2010) identify perceived higher level of potential flood damage, higher perceived accuracy of hurricane forecasts, or more elderly respondents as factors that increase the probability of evacuating from a hurricane. Higher income, being less willing to leave their property unprotected, or living for a long amount of time in their residence are associated with a decreased likelihood of evacuating. One of the best predictors of future behavior for hurricane evacuation is still past behavior

The public's expectation of the time needed to perform evacuation preparations can vary; many people assume that they have multiple tasks to complete before leaving. When there is a predicted landfall, there are both early evacuation rates and spontaneous evacuation rates. Evacuations have an s-curve shape in time, with slow changes in evacuation rates early and late in a storm. The influence of evacuation orders and storm intensity can be seen by modeling the rates of evacuation. Fu's 2007 study of the curve demonstrated that mandatory policies led to a faster evacuation response than the voluntary policies. Even when a voluntary evacuation is followed with a mandatory evacuation, the rates of evacuation are still lower than when a mandatory evacuation is the first policy announced. The majority of people tend to evacuate on the last day of the time involved in the evacuation procedures. The earlier in the day a notice was released, however, the more people leave. If a notice is released prior to 2 PM, evacuations take about two days, with more evacuations occurring on day three the earlier in the day the order is released. If an evacuation is issued in the evening, then the main evacuation is postponed until the next morning. An increase in wind speed corresponds with an increased evacuation response. Evacuation rates increase when the storm track was close to the region being evacuated.

Conclusions

The total cost for an evacuation must account for both the evacuations costs and potential loss of life. This calculation will allow costs for a range of forecasts to be calculated and compared; lower costs will identify a better forecast. Both official forecasts issued by the NHC and operational model forecasts are evaluated using this index. Because NHC forecasts, watch and warning declarations are overwhelmingly are favored by public officials when making decisions (Regneir 2008), the veracity of the is of particular interest. Rates of evacuation can be modeled using influential factors that have been identified such as hurricane intensity, time at which the evacuation is issued, and past evacuations, the impact of delaying an evacuation issuance by six hours can be evaluated.

Methods

To complete the analysis of the costs of evacuation, a vulnerability index of costs, RC, is calculated. The RC index costs are then compared with the costs from simulated evacuation procedures from landfall events in the Tropical Cyclone Game (TCG) described below.

In this study, the seven storms that made landfall in Florida during the 2004 and 2005 hurricane seasons are analyzed (Table 2). For each storm, idealized estimates of the population that should have been evacuated based on the observed storm characteristics at landfall are compared with the population that would be evacuated using forecasts issued by the National Hurricane Center (NHC).

Index

The vulnerability metric advanced here determines the relative costs of evacuation (RC) via:

$$RC = c\, EP_i^F + \max\{q\,(EP^A - EP_i^F), 0\} \tag{1}$$

where c is the estimated order of magnitude cost to evacuate a person, EP_i^A is the population that would be evacuated given a perfect forecast, q is a value assigned to represent the cost of a life lost, and EP_i^F is the population evacuated based on the forecast storm landfall characteristics at lead time i. The value of c represents estimates of the evacuation costs for housing and travel and incidental expenses. The value of q, loss of life, is based on insured life estimates following Willoughby (2010). Importantly, q is greater than c by multiple orders of magnitude. Sensitivity analyses for reasonable ranges of the values assigned to these parameters did not qualitatively change the results presented here. Even so, the ranges of values chosen for both c and q are for demonstration and sensitivity analysis of the index and should not be construed as definitive.

For each storm, EP^A is a fixed value since it represents the societal vulnerability to the observed landfall conditions. EP_i^F is calculated at six-hour intervals, corresponding to the official forecast times from the NHC. The quantity $[EP^A - EP_i^F]$ is the evacuated population error compared with a perfect forecast. For example, assuming that the landfall location is correctly predicted, a positive $[EP^A - EP_i^F]$ value means too few people are evacuated, while a negative $[EP^A - EP_i^F]$ value means too many people are evacuated. If there is error in the landfall location, the quantity $[EP^A - EP_i^F]$ reflects the track and intensity forecast errors, as well as differing vulnerable population densities across counties.

The relative costs for four additional models (Table 3) are calculated (Fig 3) for comparison with forecasts from NHC.

Model

To simulate the evacuations that would take place for a forecast and the effect of decreasing time for evacuation on potential fatalities, this research used a revised version of "The Tropical Cyclone Game" code. The Tropical Cyclone Game determines the percent population that will evacuate and the number of casualties given forecasts and issued evacuations (Table 1). For the model, two sets of information are entered into the code (Fig 1, step 1). Forecast information includes the time of issuance, predicted landfall time, and predicted landfall wind intensity. County information contains the predicted region of landfall, county preparation status, county population, and current county awareness. Each county contains three zones (Fig 2) based on county evacuation plans. Based on the predicted landfall intensity of a hurricane, different zones are evacuated, with zone 1 (blue in Fig. 2) being evacuated starting with category 1 hurricanes and zone 2 (yellow in Fig 2) also being evacuated for category 2 or 3 hurricanes. For category 4 or 4 hurricanes, the populations in zone 3 (red in Fig 2) are included in the evacuation. County awareness is measured by awareness points; at the start of the hurricane season, each county has the same number of points. Points can be added by having a predicted landfall in the county or deducted if there is no hurricane activity in the region. Counties are also assigned the same evacuation rate (percent of eligible population who will evacuate) initially.

Likelihood of evacuation has been shown to depend on the timing (in the diurnal cycle) of the evacuation order. Thus, evacuation rates are linked to time of day classified into four categories: early morning (12 AM to 6 AM), morning (6 AM to 12 PM), afternoon (12 PM to 6 PM), and evening (6 PM to 12 AM). Each category is associated with four equally probable evacuation rates. A baseline evacuation rate for the 6-hour forecast time is chosen randomly from these four. Having a mobile county will increase the initial evacuation rate. Based on the time, storm intensity, and preparation status, the mobilization status of each county is determined by a random choice (Fig 1, step 3). Mobilization is determined separately for each zone in a county. Higher storm intensities, a daytime forecast, and an issued warning will increase the probability of having a mobile zone. If a zone is determined to be mobile, then an additional percentage of the population evacuating is added to the baseline evacuation rate.

The evacuation rates also are supplemented by the total awareness points (Fig 1, step 4). By increasing the number of awareness points for a county, an additional percentage of the population will evacuate. The number of awareness points is associated with four evacuation rates. One rate is chosen randomly and added to the current evacuation rate. The total fraction of a county population that is evacuated (Fig 1, step 5) at the time of a forecast is calculated via:

$$Fraction\ evacuated = PE + EF \tag{2}$$

in which PE is the fraction of the population already evacuated at the time of the forecast and EF is the total fraction of the population that will evacuate based on the issuance time of the forecast, mobilization, awareness level, and storm intensity. Evacuation fractions are given for each zone in the county. The casualties are calculated by the equation:

$$Casualties = (1 - fraction\ evacuated) * population * d \tag{3}$$

in which d is a randomly chosen fraction based on the awareness level. Each awareness level is associated with four different fractions with equally weighted likelihoods. Once the evacuation rates and casualties for a forecast are determined, the awareness points are recalculated (Fig 1, step 7). Counties in the predicted landfall region of a forecast are made more aware by increasing the number of awareness points. The game continues to calculate evacuation rates, predicted casualties, and increased awareness for all of the forecasts associated with a storm. After the storm has made landfall, a single discount rate, not dependent on the amount of time before the next storm, is used to discount the awareness points of all counties.

After the game has been run for all hurricanes, the associated costs (AC) of the simulated forecasts are determined with the formula:

$$AC = c\ EP_t + q\ F \tag{4}$$

in which c is the cost of evacuating one person, q is the cost of a life from the index calculation, F is the number of predicted fatalities and EP_t is the entire population that will leave in the duration of the storm. Figure 4 shows the final calculations from Charley for the five models. The game is run a total of 25 times for each forecast time within a storm. The final evacuation rates and predicted fatalities for a forecast are calculated from the average of the runs.

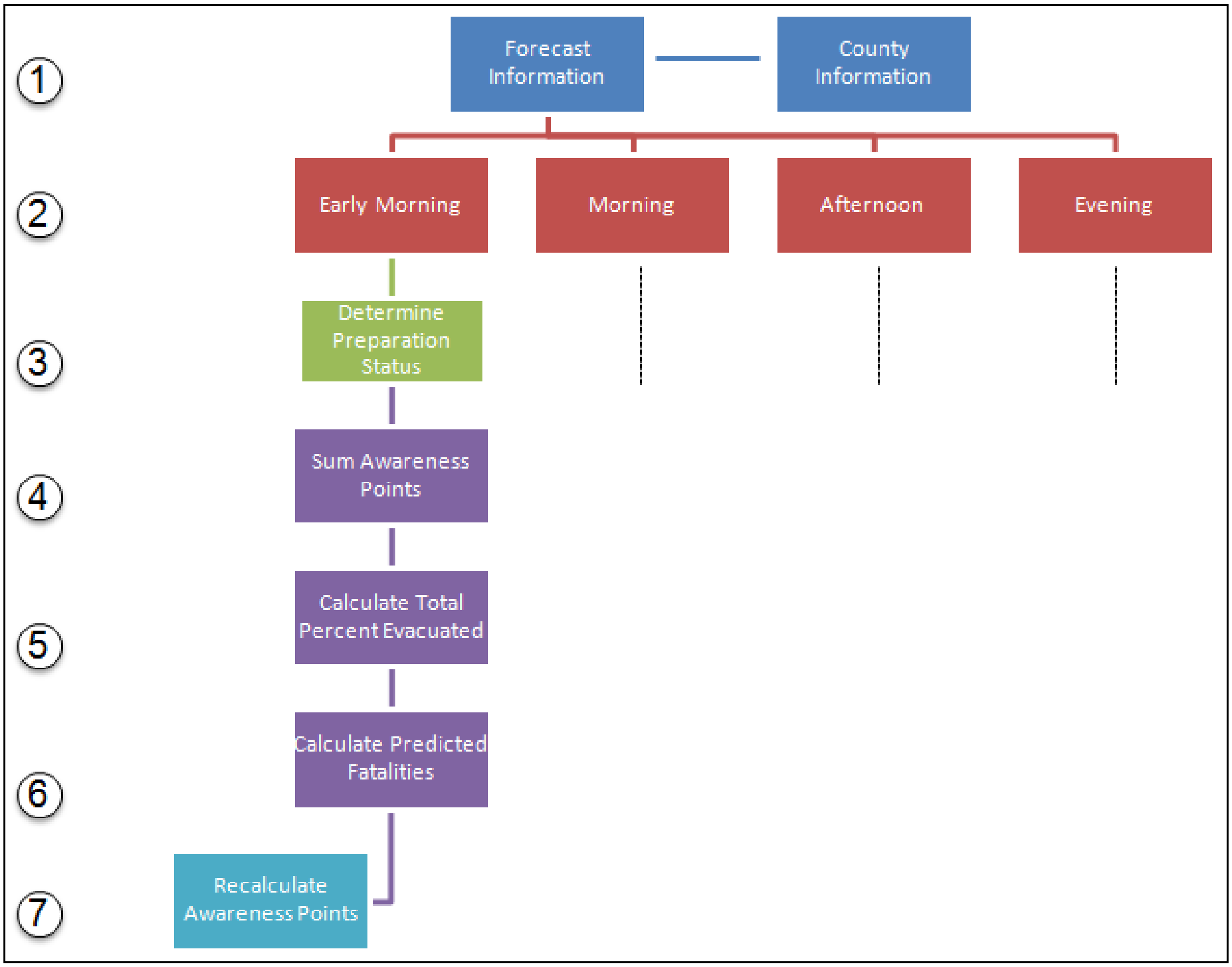

Figure 1: *Flowchart of the Tropical Cyclone Game code.*

Variable	Description
t	Time forecast was issued in GMT
w	Maximum wind speed in knots
l	Counties impacted on landfall
m(x)	Mobilization status of a county
CP(x)	Population information for a county
Z(y)	Evacuation zone populations
AP(x)	Awareness points for a county
q	The cost of a life
c	The cost of evacuating one person

Table 1a: *A list of input variables for the Tropical Cyclone Game, where x is the individual county and y is the zone number.*

Variable	Description
PE(y)	Fraction of a population evacuated from a zone
F(y)	Predicted number of fatalities in a zone

Table 1b: *A list of output variables for the Tropical Cyclone Game, where x is the individual county and y is the zone number.*

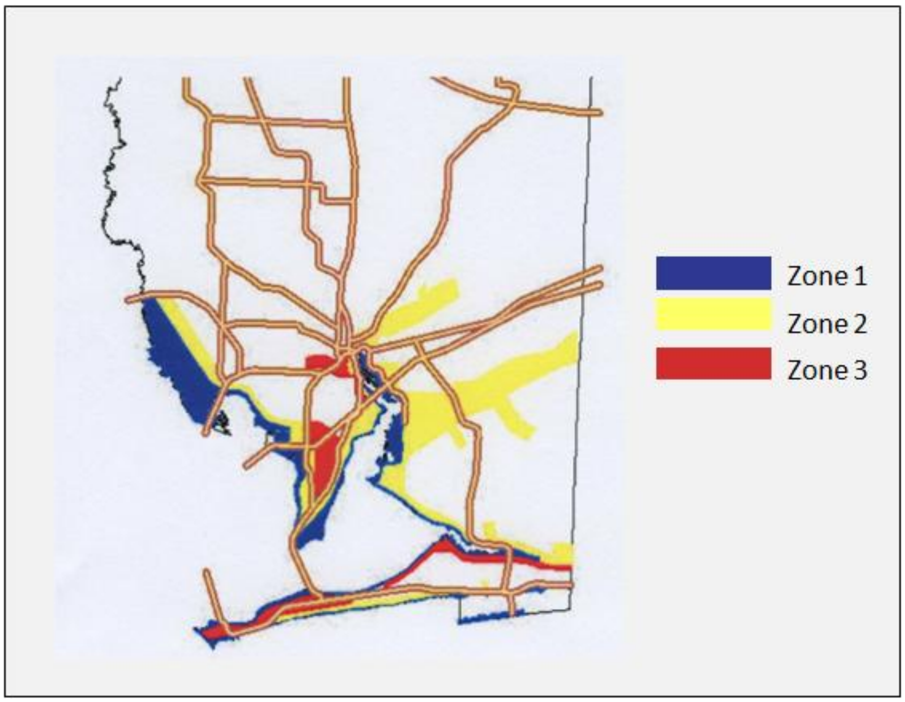

Figure 2: *Map of evacuation zones in Santa Rosa county as defined in the Tropical Cyclone Games. Map is courtesy of the state of Florida.*

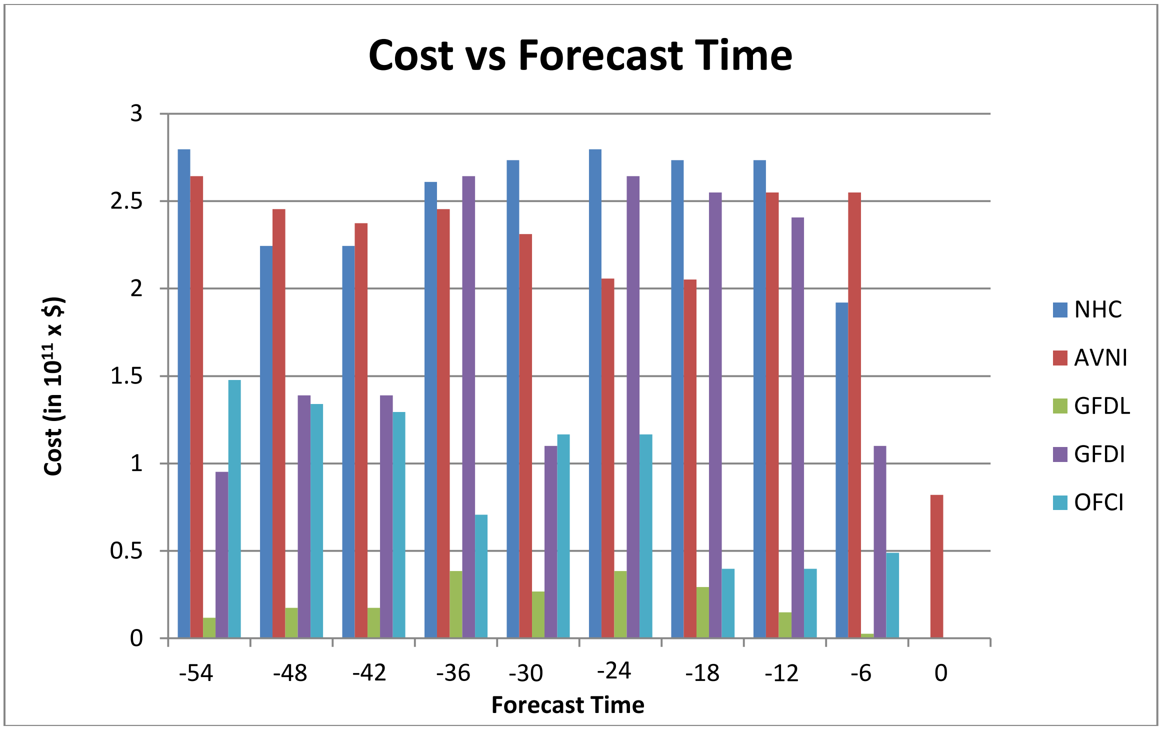

Figure 3: *Vulnerability index (units of 10^{11} $) calculated for Hurricane Charley at 6-hour intervals. Calculations are based on model and NHC forecasts and assume all residents in the evacuation zone* ***do*** *evacuate for each county predicted to be impacted at landfall and the casualty rate is 100% for landfall in an unevacuated county.*

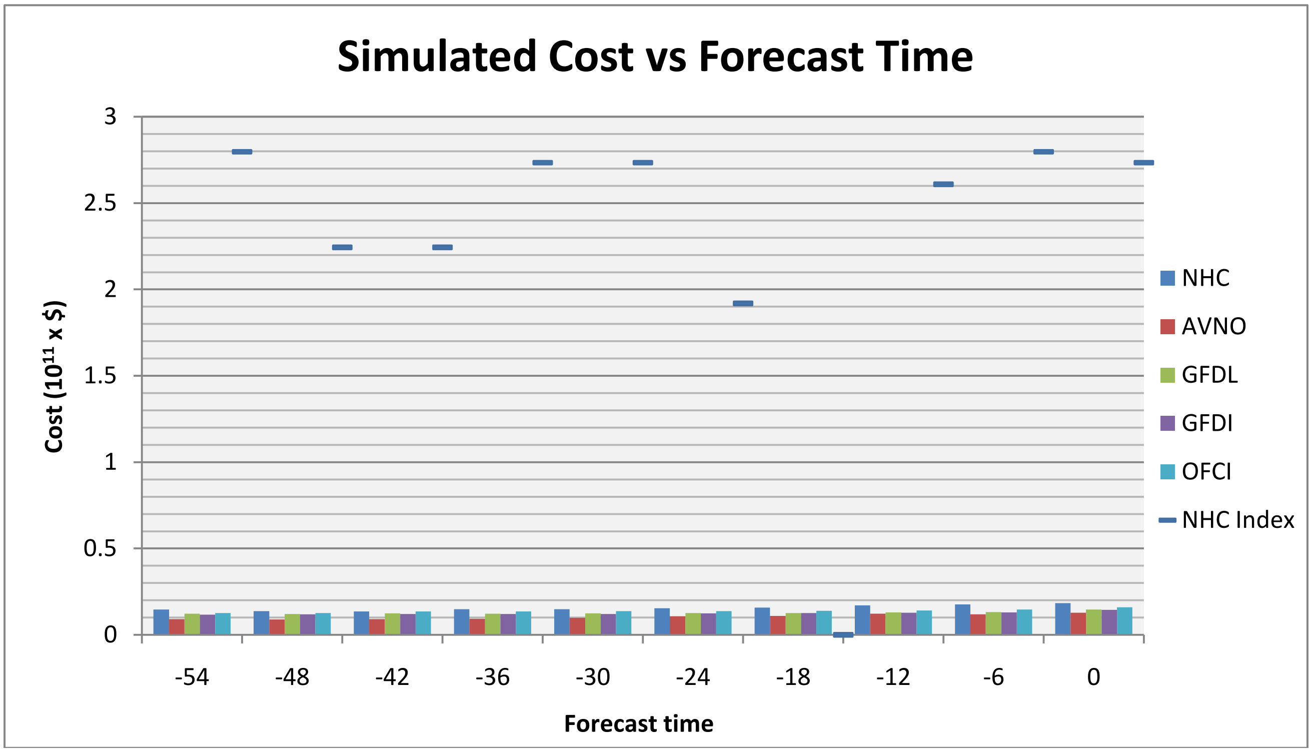

Figure 4: *The Tropical Cyclone Game-simulated costs (units of 10^{11} $) calculated for simulations of forecasts for Hurricane Charley. The vulnerability index for the NHC forecasts as shown for comparison. Unlike the vulnerability index, the Tropical Cyclone Game does not assume all residents in the evacuation zone evacuate for each county predicted to be impacted at landfall or that the casualty rate is 100% for landfall in an unevacuated county. Landfall occurs at forecast time=0*

Storm	Landfall Time	Landfall Date	Landfall Location	Wind Speed (kts)	Initial Forecast Time
Charley	1945Z	13-Aug-04	Lee	130	1800Z
Francis	0430Z	5-Sep-04	St. Lucie	95	0300Z
Ivan	0650Z	16-Sep-04	Escambia	105	0300Z
Jeanne	0400Z	26-Sep-04	St. Lucie	105	0300Z
Dennis	1930Z	10-Jul-05	Santa Rosa	105	1500Z
Katrina	2230Z	25-Aug-05	Miami-Dade	65	2100Z
Wilma	1030Z	24-Oct-05	Collier	105	0900Z

Table 2: *List of storms studied, their date and time of landfall, landfall location and intensity and the initial forecast times used in the analyses*

Forecast Model	Description
NHC	Official National Hurricane Center Forecast
OFCI	Adjusted previous cycle NHC
AVNO	NOAA/NWS Global Forecast System model
GFDL	National Weather Service/Geophysical Fluid Dynamics Laboratory model
GFDI	Adjusted previous cycle GFDL

Table 3: *Sources of the forecasts analyzed. For adjusted cycle models, data from the 06Z run are shifted to make the 6 hour forecast would match the hurricane's properties at 12Z. This creates an early run of the model. All sources available at 6 hour forecast intervals.*

Results

Overall, the NHC had vulnerability index values on the same order as the comparison models. The simulated costs for all forecasts are, on average, much less than the cost predicted by the index. The simulated costs varied between the forecasts. This result occurs because the vulnerability index considered a worst case scenario where all residents in a county under evacuation orders would evacuate and all residents in a landfall county that is not evacuated would be fatalities. In comparison, these assumptions are not made in the Tropical Cyclone Game and had much lower evacuation and fatality rates.

West Coast Landfall Hurricanes

Four hurricanes made landfall on the western coast of Florida during the 2004-2005 hurricane season. In 2004, Hurricanes Charley, Ivan, and Wilma made landfall on the western coast. Hurricane Dennis also made landfall on the western coast in 2005.

Hurricane Charley (2004)

Compared with the other west coast landfalls, Hurricane Charley had higher than normal costs (Fig 5a). Due to the inconsistency in consecutive landfall forecasts, large values of the index resulted from money being "spent" evacuating safe populations while endangered regions are not evacuated. This large variability in the forecasts is because there is no consensus on the location of landfall. Predicted evacuation costs for Hurricane Charley are an outlier in the data; no other storm had track error as large as seen in prediction from the NHC of landfall. Simulated costs from the TCG decreased 2000% of the vulnerability index costs. In contrast to the vulnerability index, the costs predicted by the TCG simulation are closer to the costs of other hurricanes analyzed in the study.

Hurricane Ivan (2004)

The vulnerability index calculations for Hurricane Ivan are average for the hurricanes that made landfall on the west coast. The predicted intensity at landfall remained close to the actual landfall scenario through the forecasting period for all of the forecasts. However, the predicted landfall location is typically further west than the actual location. Additional costs from not evacuating the entire endangered population are incurred in all forecasts. Overall, the five forecasts analyzed had similar output; there would not be a significant gain for choosing a model forecast over the NHC forecast (Fig 5b). This is because the predicted evacuation Costs from the TCG simulation are lower than the vulnerability index because each of the forecasts had at least one accurate landfall forecast. Because of this, part of the population from each county affected at landfall is evacuated, lowering the possible number of fatalities.

Hurricane Wilma (2004)

Wilma had a lower average evacuation cost compared with other landfalls in this region (Fig 5c). The predicted forecast track remained close to landfall during the forecast period so extra populations are not evacuated. During the forecast period, the NHC had the highest predicted costs overall, particularly in the 24 to 42 hour period. Model forecasts, such the AVNO, had more accurate forecasts of track and intensity. The actual populations affected at landfall are then able to be evacuated. This lowers the amount of costs incurred from fatalities. In TCG simulations, there are higher costs because unaffected populations are evacuated early in the forecasting period and continued to evacuate until landfall.

Hurricane Dennis (2005)

The evacuation costs for Dennis are low for the hurricanes making landfall on the west coast (Fig 5d). Throughout the forecast period, predicted intensity tended to be accurate or too high. The affected area at landfall is also typically included in the forecasted landfall region. Because the population is evacuated, fatalities are low. While all of the forecasts analyzed had similar track predictions for Dennis, the NHC forecasted a higher intensity landfall event within 24 hours of landfall. Because of this overestimation, the NHC's forecast had the greatest probability of evacuating the correct number of people from the correct locations. The costs simulated with the TCG are in agreement with the vulnerability index costs because the affected regions are evacuated, the number of fatalities is small.

East Coast Landfall Hurricanes

From the seven hurricanes studied, three made landfall on the east coast. Hurricanes Frances and Jeanne made landfall in 2004 and Hurricane Katrina in 2005.

Hurricane Frances (2004)

Calculated costs at landfall remained low for Hurricane Frances (Fig 5e). In the NHC forecast, the predicted intensity is typically higher than the actual intensity at landfall. The predicted NHC track tended to remain in the region of actual landfall. The AVNO and OFCI model forecasts tended to be more accurate, particularly with more than 24 hours lead time on evacuation, which gave a lower total cost at landfall. The landfall predictions for

Hurricane Frances stayed constant, resulting in minimal fatalities and high evacuation rates in the TCG simulations. The OFCI and AVNI forecasts remained closer to the landfall costs while the NHC and GFDI had higher ratios.

Hurricane Jeanne (2004)

There is relatively little variation between the forecasts in the vulnerability index costs (Fig 5f). The NHC forecasts did not stay constant in time. There is variability both in the predicted intensity at landfall and region of landfall. Because of this, the vulnerability index costs for the NHC forecast had more variability in time than the costs associated with the other models. Compared to other storms in this region, Jeanne's costs are average for the hurricanes making landfall on the eastern coast with an average of $1 x 10^6. Unlike most hurricanes, there is little variability between the costs found in the TCG simulations and the vulnerability index. Simulated costs from the AVNO model forecasts are the largest because more people tended to be evacuated with AVNO forecasts.

Hurricane Katrina (2005)

All of the forecasts analyzed for Hurricane Katrina with the exception of GFDI model, made the similar errors in undervaluing the strength of the hurricane at landfall. Track forecasts also are similar in all landfall predictions. Because of the agreements between forecasts, similar costs are incurred with each forecast. Compared to the other hurricanes that made landfall on the eastern coast, Katrina had higher predicted costs (Fig 5g) due to landfall in a populous region and failure to evacuate the entire endangered population. The costs predicted by the TCG simulations are lower than the vulnerability index costs. Katrina's costs from the simulations are, on average, 90% smaller than the vulnerability costs.

Cost Ratio

For further analysis, the ratio (CR) of the cost to evacuate a forecast ($c\ EP_i^F$) to the cost of the perfect evacuation (cEP_i^A) is calculated for the five forecasts with the formula:

$$CR = \frac{EP_i^F}{EP_i^A} \quad (5)$$

There is no correlation between the ratio and time before evacuation (Figs. 7, 8).The costs to evacuate each forecast are plotted in a time series of the seven storms (Fig. 6). On average, the costs from issuing evacuation orders based on a forecast prior to landfall would be 10^3 times greater than the costs associated from evacuating the actual counties impacted at landfall. For example, the ratio for the NHC forecasts for Hurricane Katrina 42 hours before landfall is 200,000. Thus, if evacuation orders are issued based on the 42-hour forecast, the total costs from evacuations and fatalities would be 200,000 times greater than the costs that would be incurred if perfect evacuation orders are implemented.

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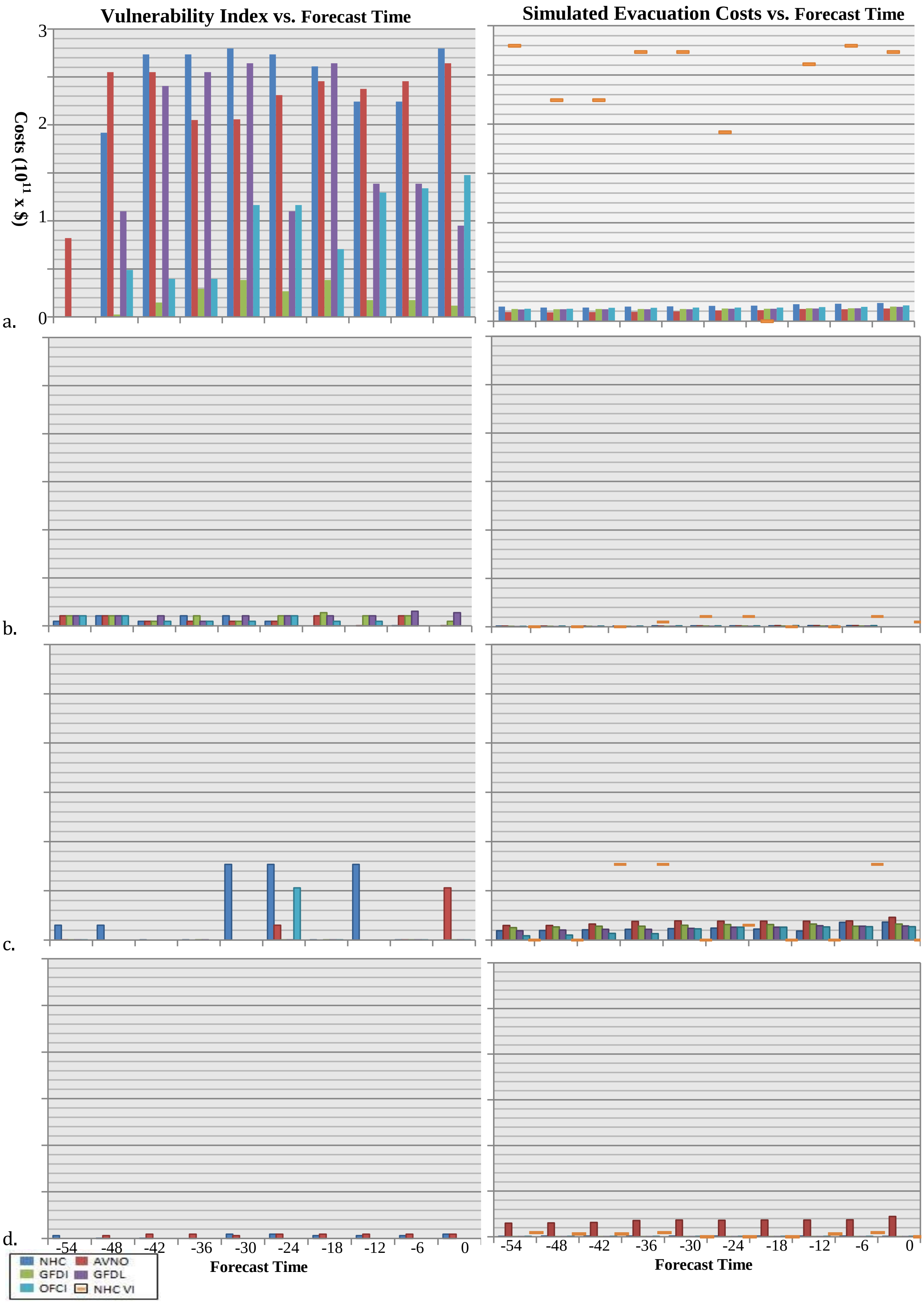

Vulnerability Index vs. Forecast Time
Simulated Evacuation Costs vs. Forecast Time
Costs (10^11 x $)
3
2
1
0
a.
b.
c.
d.
-54 -48 -42 -36 -30 -24 -18 -12 -6 0
Forecast Time
NHC AVNO
GFDI GFDL
OFCI NHC VI

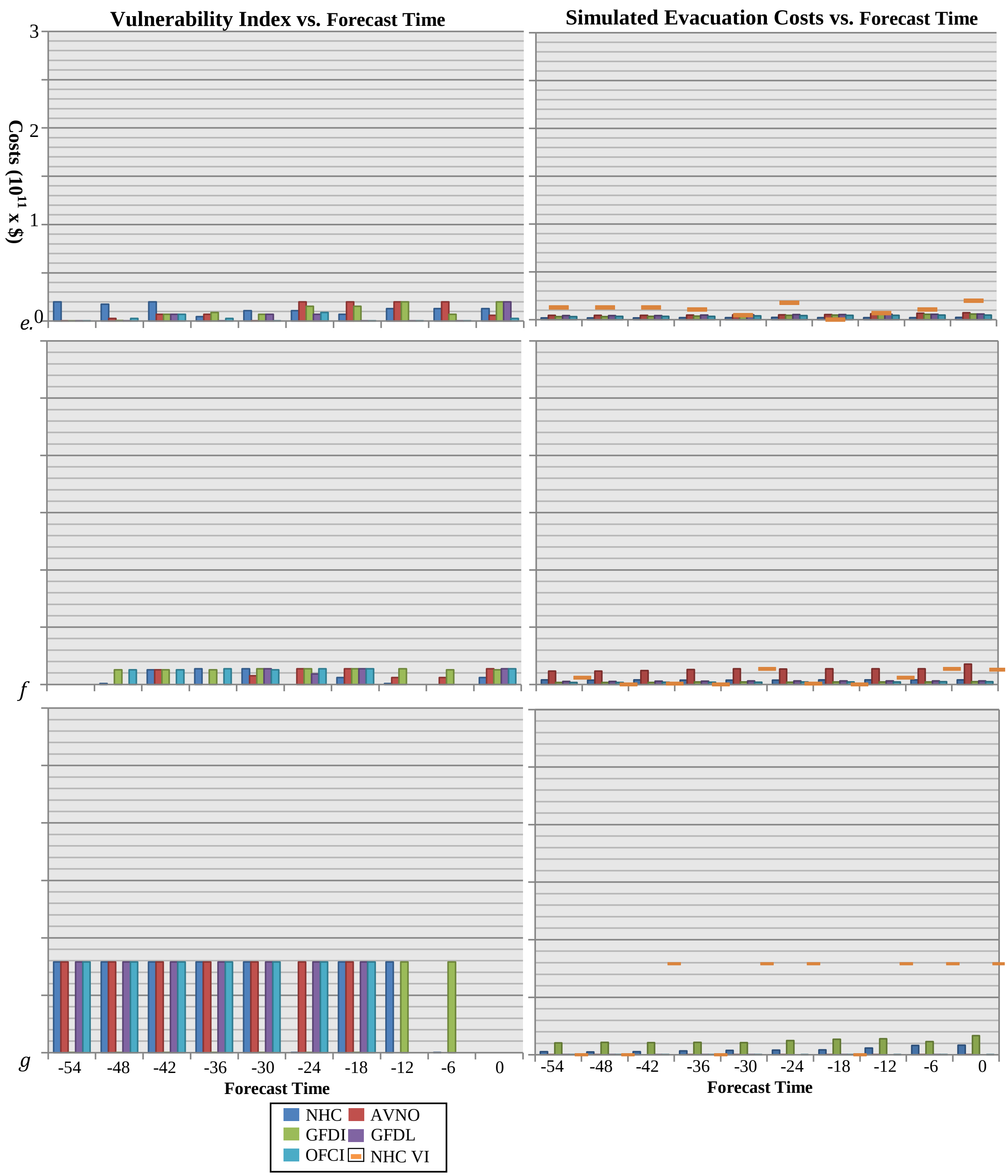

Fig 5*: The right column displays the vulnerability indices (units of 10^{11} $) calculated for the seven hurricanes at 6-hour intervals. Calculations are based on model and NHC forecasts and assume all residents in the evacuation zone* ***do*** *evacuate for each county predicted to be impacted at landfall and the casualty rate is 100% for landfall in an unevacuated county. The left column shows the Tropical Cyclone Game-simulated costs (units of 10^{11} $) calculated for simulations of forecasts for Hurricane Charley with vulnerability index for the NHC forecasts*

included for comparison. Unlike the vulnerability index, the Tropical Cyclone Game does not assume all residents in the evacuation zone evacuate for each county predicted to be impacted at landfall or that the casualty rate is 100% for landfall in an unevacuated county. Landfall occurs at forecast time=0. Charts a through d show westward approaching hurricanes and are, respectively, Charley, Ivan, Wilma, and Dennis. Charts e through g depict eastward approaching storms and are, respectively, Frances, Jeanne, and Katrina. The graphs for Hurricane Charley are duplicates of figures 3 and 4.

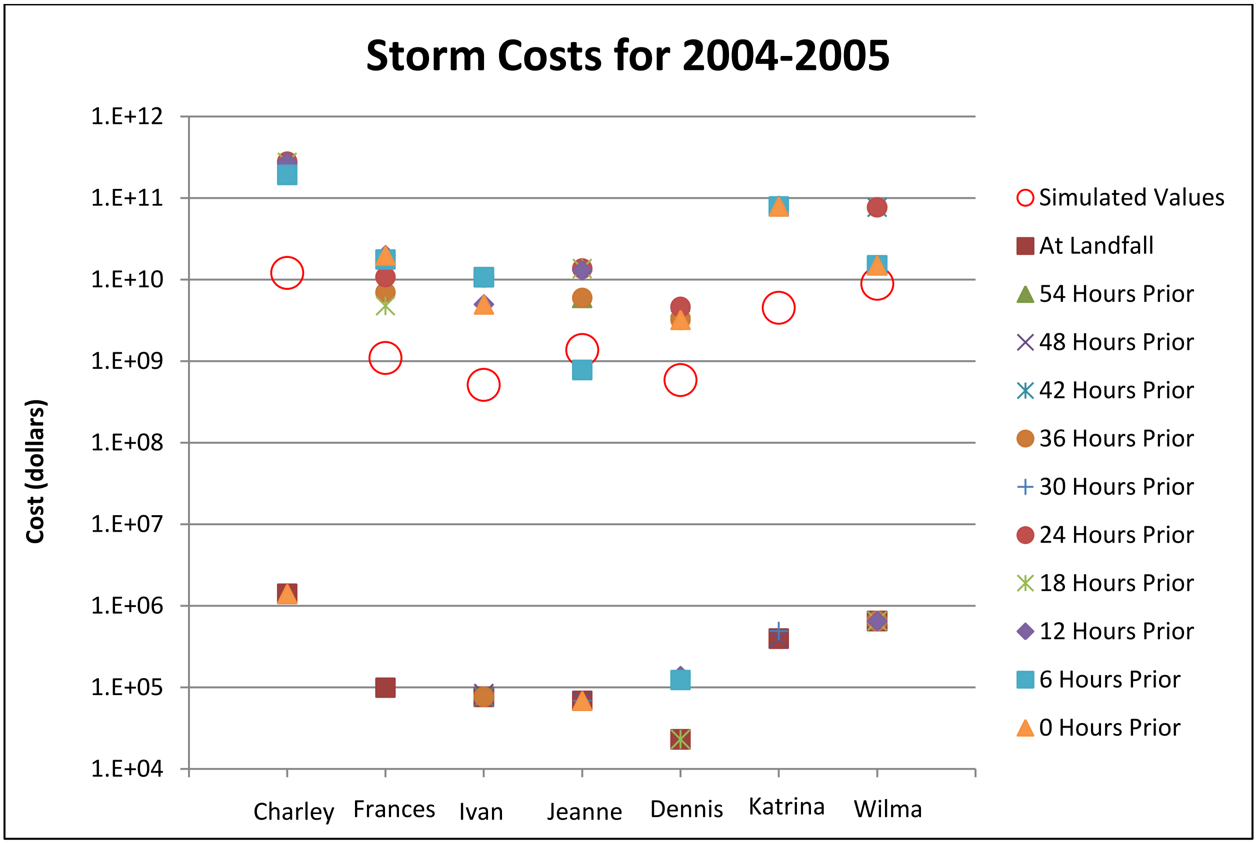

Fig 6: *Costs of evacuation at each forecast lead time, showing the increase in evacuation costs within 12 hours of predicted landfall. Cost estimates are plotted on a log scale.*

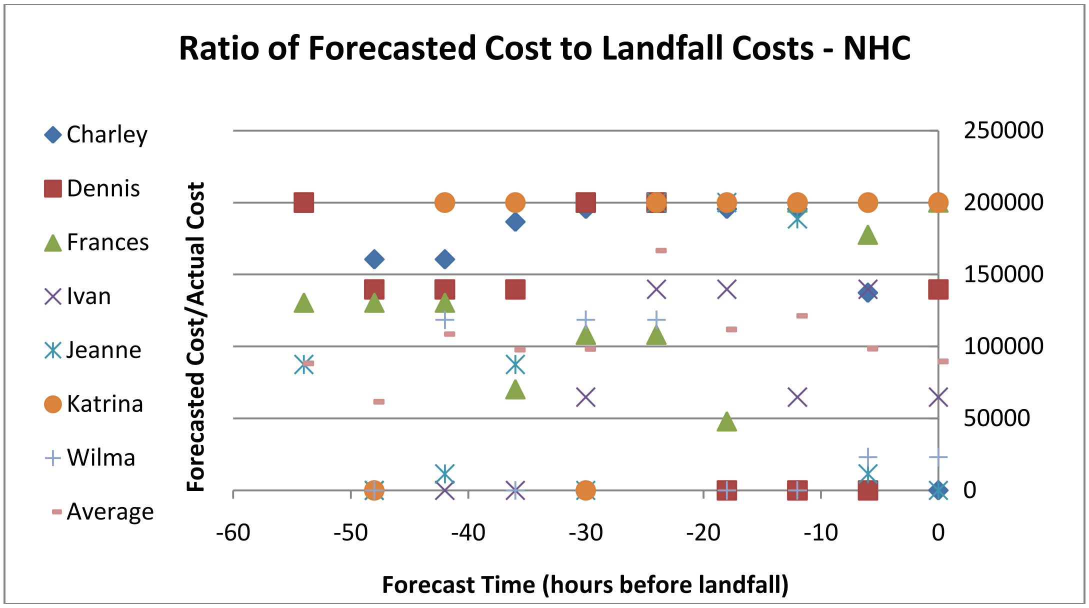

Fig 7: *Ratio of the costs of evacuating at a forecast to the costs incurred at landfall for the National Hurricane forecasts. There is little correlation between the ratio value and the time before landfall.*

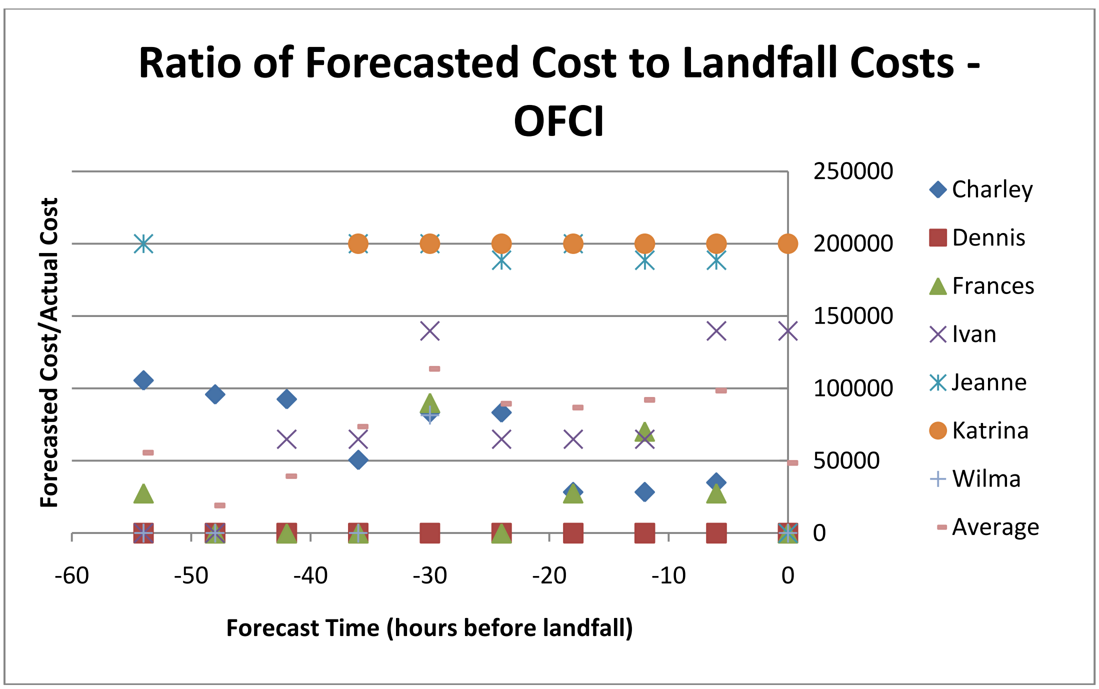

Fig 8: *Ratio of the costs of evacuating at a forecast to the costs incurred at landfall for the OFCI forecasts. There is little correlation between the ratio value and the time before landfall.*

Conclusions

On average, evacuations performed within 12 hours of predicted landfall are the most financially efficient. The costs at 12 hours prior to landfall are 10,000 times smaller compared with 18 hours prior. Additionally, the ensemble models AVNO, GFDL, GFDI, and OFCI do not have significantly lower vulnerability index costs than the NHC forecasts, implying that NHC are exploiting the full value of the objective model guidance. There is also no improvement with forecast lead times in the correlation between the ratio of costs of evacuation and time of evacuation from the NHC and operational model forecasts. Thus, using an ensemble model to make evacuation decisions in place of the NHC forecasts would not result in decreased costs. When simulated in the Tropical Cyclone Game, the total costs from the ensemble model forecasts varied compared to the NHC forecasts.

Future Work

To expand the analysis, the vulnerability index calculations should be completed for a larger range of hurricane landfall events, locations, and model runs. By expanding the current sample size, the trends determined in the current study can be expanded and verified. Additionally, the study can be moved to another region outside of Florida to compare the accuracy and costs of evacuations between the locations. As well, the Tropical Cyclone Game code can be refined continually. Currently, the psychology dictating the evacuation and fatality rates is original to the code. With increased studies on the effects of location, socioeconomic class, and population demographics, the updated evacuation rates will reflect more accurately a population's reaction to an event. The psychology could describe the reaction to an individual county's population to determine a more accurate evacuation rate. In addition, the equation governing the awareness points for a county can be updated or the probability distribution governing the awareness changes could be modified. Currently, the awareness of a county is based solely on when they are included in the predicted region of landfall. Having a more intense hurricane, such as a category 4 or 5, or being closer to landfall does not mean increased awareness compared with a category 1 hurricane or being further away from landfall. Although category is used in calculating the rate at which people evacuate, it should also be used to more accurately describe the state of awareness in a county. Finally, the prior landfall of an intense storm far from the location might also be expected to affect evacuation awareness. One example is the reaction in Texas to Rita (2005) after the devastation from the Katrina landfall earlier that year. This modification to the awareness should also be included to provide more accurate simulations of evacuations.

27.

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ACADEMIC VITA

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EDUCATION

Bachelor of Science, Meteorology
The Pennsylvania State University, University Park, PA
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RESEARCH EXPERIENCE

Research Assistant, Summer 2008 - present
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Analyze the NENA model output of the carbon cycle in the North Eastern Seaboard under the direction of Dr. Raymond Najjar.

Research Assistant, Summer 2009
MIT Haystack Observatory, Groton, MA
Studied effects from sudden stratospheric warming events in the mid and lower latitudes as modeled in TIME-GCM models under Larisa Goncharenko.

Research Assistant, January 2009 - present
Pennsylvania State University, University Park, PA
Analyze forecast tracks of hurricanes making landfall in Florida for forecast accuracy under the direction of Dr. Jenni Evans

PAPERS

"A Study of Cost of Hurricane Evacuations in Florida", presented at the 9th Annual American Meteorological Society Student Conference, January 2010.

OTHER EXPERIENCE

Undergraduate Grader, September 2008 – December 2009
Math 251 (Differential Equations)
Math 141 (Calculus II)
Pennsylvania State University, University Park, PA
On a semester-by-semester basis, I was responsible for the grading of problem sets and quizzes.

Teaching Assistant, January 2010 – May 2010
Ennec 473 (Risk Management in Energy Industries)
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Responsibilities included grading problem sets, quizzes, and exams and holding office hours to assist studies for the Risk Management in Energy Industries. (Enrollment: 110)

AWARDS AND HONORS

Schreyer Honors College Scholar, Penn State (2006 - present)
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