203 THE HURRICANE RISK CALCULATOR: TRANSLATING POTENTIAL WIND IMPACTS FOR COASTAL AND INLAND RESIDENTS

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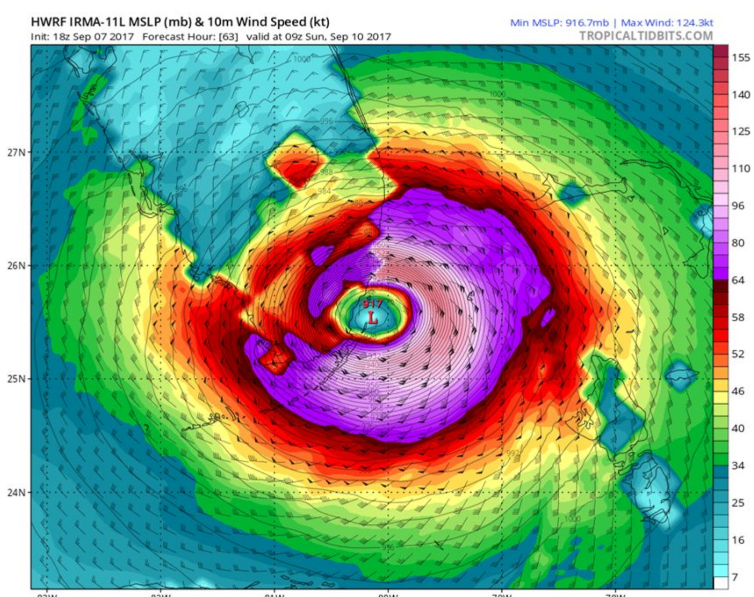

Figure 1: Simulated sustained winds (valid at 10-m height) and minimum sea level pressure from the Hurricane WRF (HWRF) model from 63-h before the simulated landfall time. Image from TropicalTidbits.com.

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[2] The National Center for Atmospheric Research is sponsored by the National Science Foundation.

1. INTRODUCTION

Coastal and inland residents in the U.S. often face a barrage of information when a hurricane landfall threatens. These include forecasts and products from official sources such as the National Hurricane Center (NHC), graphical and text products from local National Weather Service Forecast Offices, information from local and state governments (including evacuation orders/recommendations), and other kinds of information from a wide variety of unofficial channels such as TV/radio/internet media, blogs and other websites, and social media. Yet, members of the public still grapple with making timely decisions in the face of uncertainty, products they do not understand, and conflicting information. Worse yet, residents often get hung up on deterministic forecast scenarios which they view as either favorable or unfavorable to their particular situation, sometimes delaying action to see if a more favorable situation develops. Finally, residents struggle with understanding how various forecast scenarios will translate into impacts at their specific location. Even if trustworthy information is available, most stakeholders do not know how to optimize their own cost/loss situation. As a result, the decision-making process is often haphazard and leads to less-than-optimal personal and collective outcomes.

The recent experience of Hurricane Irma offers a sobering case study relative to some of these challenges. In the days leading up to U.S. landfall, Hurricane Irma wreaked a deadly path of destruction across multiple Caribbean isles. Predictions from some numerical models from four to five days before landfall suggested that this storm could be a “worst-case” scenario for Florida’s eastern coast with a potential Category 5 landfall near Miami, Florida. Meanwhile, by 60 hours before landfall, the projected track of Irma had shifted to focus an increasing threat to the southwestern coast of Florida and even the Tampa Bay area. By the time it was all over, more than 6.5 million people had been ordered to evacuate (Held 2017). Given the dire predictions and the fact that the peninsular geography and road network of Florida offers limited evacuation capacity and directional options, millions of people from across the state undertook long trips, evacuating to locations as far away as Tennessee, South Carolina, and Kentucky. It has been estimated that 6.8 million people actually evacuated, making this by far the largest peacetime evacuation in U.S. history. Interestingly, 3 million of the evacuees were not in areas where evacuations had been ordered. Considering this information, along with the fact that evacuations had been ordered for more than 6.5 million people, one can also infer that nearly 4 million people who had been ordered to evacuate did not do so. Even in the vulnerable Florida Keys, where Irma posed a clear threat to life and safety, approximately 10,000 residents stayed behind. This case study highlights the challenges to the Emergency Management community of getting the *right* people to evacuate and at the right time. Often, the people who do not need to evacuate end up doing so anyway, hampering the evacuation of those who are more directly in harm’s way. In certain regions of the U.S., this mis-evacuation effect could someday lead to a mass casualty event.

Due to the way in which hurricane forecasts and hazards have been conveyed in the past, people are tuned to the track forecast and the intensity forecast (or expected Saffir-Simpson Category); however these parameters say little about what the local impacts will be at a given location. Although of scientific importance, it is fairly irrelevant to the average person as to where the exact track will be, whether they will be inside or outside the cone of uncertainty, or what the maximum intensity of the storm will be. To be useful, such information needs to be convolved with the size of the storm and the distribution of the wind field.

In particular, people need probabilistic information about the potential wind, surge, and inland flooding hazards that are translated into forms that:

- can be easily understood,
- are relevant to their situation,
- are localized and adapted to their specific residence, and
- are made available within actionable timescales.

This study aims to develop a “hurricane risk calculator” that combines risk assessment methods with real-time wind data to provide actionable information for homeowners and other residents. The calculator tool will provide detailed and relevant information about potential hurricane wind impacts for a user’s specific location, and translate this risk information into forms that the user can understand, such as whether their home may be habitable after the storm. A primary goal of this tool is to inform decisions to evacuate vs. shelter-in-place and other potential mitigative actions, thereby encouraging decisions and actions that lead to more optimal outcomes.

This paper is organized as follows. Section 2 discusses the drawbacks and weaknesses of current source of real-time wind data. Section 3 explains why probabilistic wind modeling is the preferred method to express wind hazards and their associated uncertainties. Section 4 discusses how design wind speeds used in building codes can offer a simple method to bracket critical thresholds and how more sophisticated approaches such as fragility analysis could be used. Section 5 discusses how the output of the calculator will be translated into forms that are understandable by average residents. Section 6 details how the risk output of the calculator can be contextualized and used to inform evacuate vs. shelter-in-place decisions. Finally, section 7 describes future plans for the calculator.

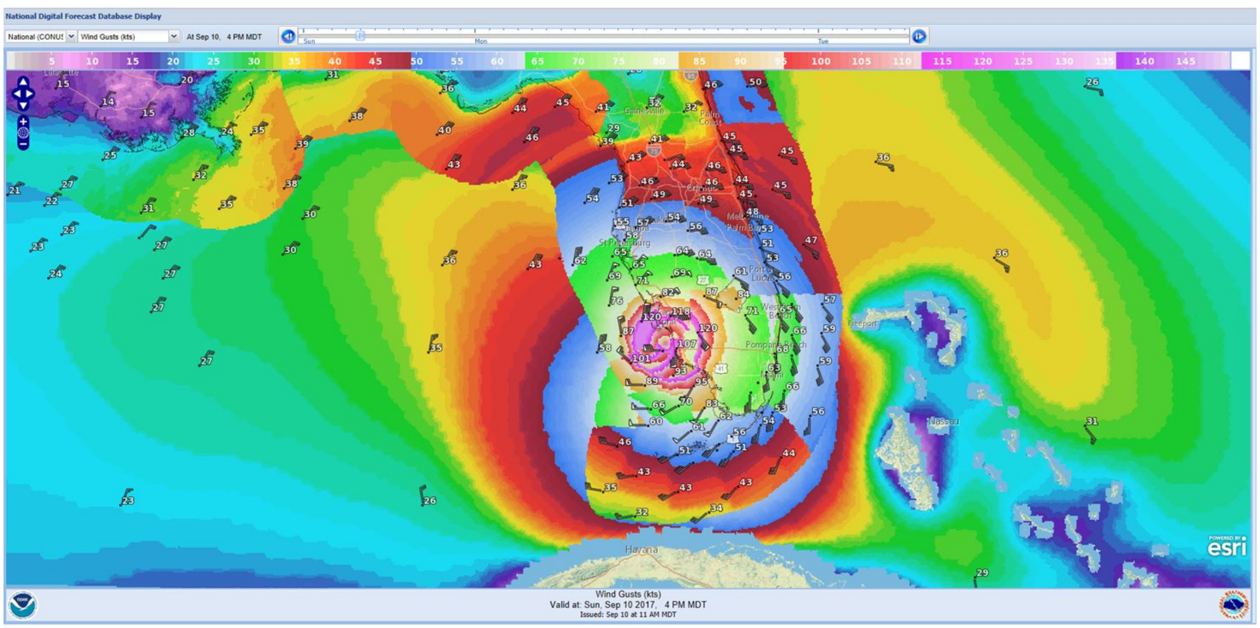

Figure 2: Wind gusts (in knots) from the gridded Tropical Cyclone Message Wind Tool (TCMWind) for Hurricane Irma valid for the approximate time of landfall. This product was issued at 11 AM EDT on 10 Sep 2017.

2. WEAKNESSES OF CURRENT DATA SOURCES

A number of operational real-time wind data sources are available during impending hurricane events, yet each of these existing publicly-available data sources have some drawbacks or are not sufficient to use for the probabilistic risk assessment as envisioned in this paper. These data sources range from simple wind swaths generated from parametric models to the output of more sophisticated numerical weather prediction (NWP) models. This section discusses some of the weaknesses and drawbacks of using these existing data sources for assessing the risk from hurricane wind hazard.

The first data source considered is from high resolution model output. Figure 1 shows an image generated from the post-processed output of the Hurricane WRF (HWRF) NWP model for a forecast lead-time of 63 hours (approximately two and a half days prior to landfall). HWRF is a state-of-the-art NWP model used by NOAA's National Centers for Environmental Prediction (NCEP) to provide guidance for hurricanes and tropical storms. The first striking feature evident in this image is the very rapid drop-off in wind speeds just a few miles inland from the coast. If taken at face value, this model projection seems to suggest that sustained winds corresponding to Category 4-5 strength (115 - 140+ kts) would quickly drop to Category 1 strength (65 - 80 kts) just a couple miles inland. Such a rapid drop-off is extremely unlikely, as Hurricane Andrew demonstrated in 1992 when towns and neighborhoods were heavily damaged or leveled 5-10 miles inland (Wakimoto and Black 1994). Part of the issue here is that nearly all model and forecast products use the metric of 1-min sustained winds, yet damage is more directly tied to shorter period fluctuations such as the 3-sec gust. It is well known that sustained winds drop as the hurricane winds come in over land, however the gustiness tends to increase so that gusts over land may still be similar to over-water values. This effect can accentuate or exaggerate marine vs. land differences, possibly misleading users. This situation can be particularly problematic if the model does not use a high resolution coastal-land mask for the post-processing of model winds from the lowest model level down to the standard 10-m height. Additionally, the model height, where the lowest level lies, does not always match the "real" terrain height, which can add another bias to wind speeds. In HWRF, the coastal land-mask from the parent domain is used to compute the 10-m winds rather than the high-resolution inner mesh. This leads to “blocky” wind speed variations that do not correspond to the actual coast. A user in an “on-land” block might falsely interpret that his or her wind hazard was significantly lower than a resident just up the coast in one of the coarse “offshore” blocks, even though both locations are a similar distance from the actual coast. Thus, use of the 1-min sustained wind to convey wind hazard over land can be misleading and could very well send the wrong message to users trying to interpret their own wind hazard.

Another data source for real-time wind information is provided by the gridded Tropical Cyclone Message (TCM) Wind Tool. Significantly, this tool is used to populate the wind fields of the National Digital Forecast Database (NDFD) with a representation of the hurricane. This wind field is in turn used to drive the National Weather Service’s (NWS) point-and-click forecast product, showing a localized time series of the wind and other forecast parameters. This tool uses a parametric model to represent the wind field of the hurricane, with the parameters taken so as to be consistent with the official track, intensity, and wind radii forecasts provided by NHC. The tool uses a standard gust factor of 1.15 to provide the output in gusts as well as sustained winds. Figure 2 shows an example of TCMWind output for Hurricane Irma, generated just five hours before landfall in SW Florida. A number of features can be seen in this image, such as striking differences between the winds over land and water, as well as some blending or interpolation artifacts that may have been caused by one or more local NWS forecast office incorrectly applying interpolation to the tool.

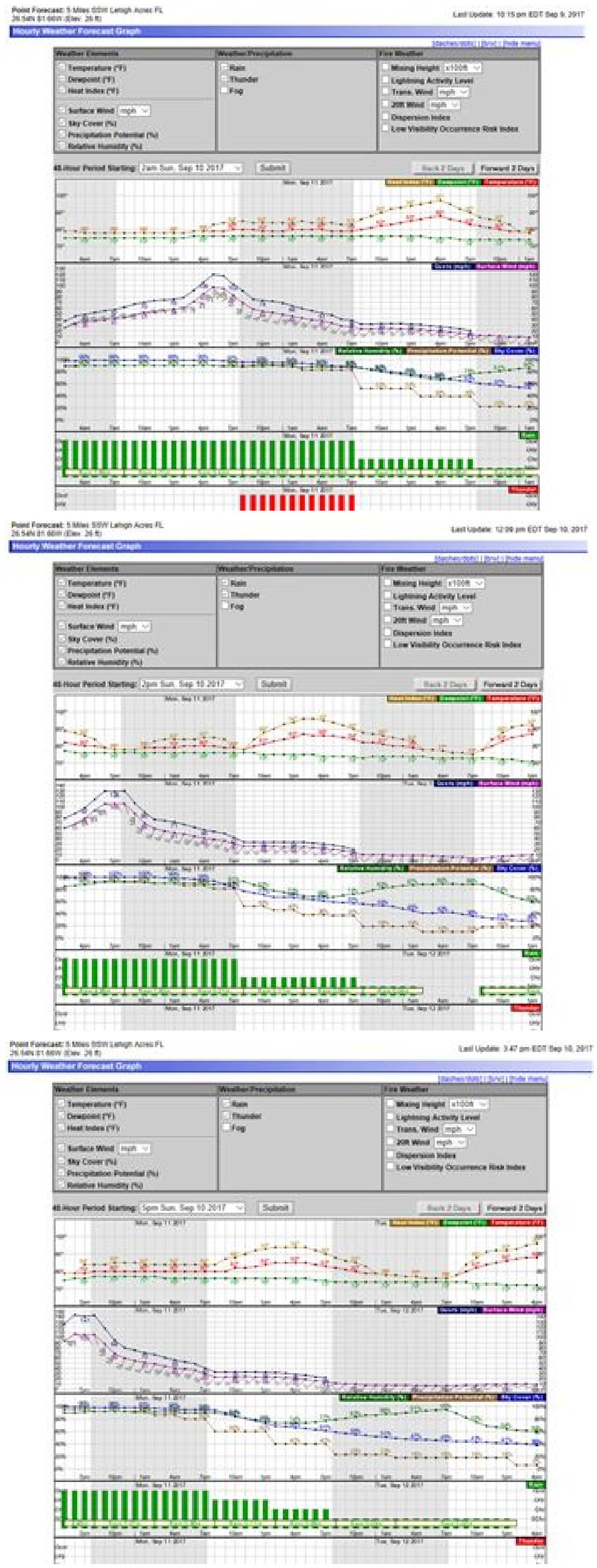

Figure 3: NWS grid point forecasts for Lehigh Acres, FL: a) 18 h before landfall; b) 5 h before landfall; and c) 2 h before landfall. Images obtained from weather.gov.

Having the wind information expressed in terms of gusts is helpful, but several other issues render these data problematic for use in risk assessment. An important issue is that the tool is deterministic rather than probabilistic. An illustration of why a deterministic framing can cause problems is shown in Fig 3. This figure presents screenshots of the point-and-click forecasts for Lehigh Acres, a suburb of Fort Myers, FL located approximately 17 miles inland. Eighteen hours prior to landfall, the product indicated that sustained winds of 98 mph were predicted, with gusts to 120 mph. As the storm approached the coast, the track curved further right than had been forecast. This change increased the projected wind threat. At five hours prior to landfall, the product predicted sustained winds of 105 mph with gusts to 128 mph. Finally, as the eye of the storm moved onshore and the predicted path of the storm now took the right semicircle of the eyewall over this location, the product at two hours before closest approach predicted that sustained winds would be 105 mph with gusts to 140 mph! This dramatic escalation of the projected wind hazard with decreasing lead-time is typical for hurricanes since the high wind region is typically confined to a small area in and near the eyewall, but may not be represented as passing over a location with any certainty until just a few hours before it happens. Well before landfall the exact track is not known, so a deterministic product may alternately show extreme winds or just modest winds.

Another issue with TCMWindTool is that the tool uses an empirically-determined rate of decay for the intensity of the storm as it moves inland, but this does not physically account for the fetch and upstream trajectory of the wind as it moves over land. To partially compensate for this lack of physical modeling, the tool offers either an empirical adjustment factor or a set reduction rate (e.g., a 15% drop in wind speed over land areas). Because the physical wind field at a given location depends less on whether the storm center is over water or inland and more on the actual trajectory the wind takes as it comes over land, the wind speeds provided by this tool can sometimes be considerably too high. All of these deficiencies are well-recognized and a new version of TCMWindTool has been developed (Mattocks et al 2018). The new version uses a more sophisticated parametric wind model, makes additional improvements to the sources used for the model's parameters, and incorporates a boundary layer to represent the effect of the upwind trajectory. Output from the new version of TCMWindTool will be available as an experimental product during the 2018 hurricane season.

3. THE NEED FOR FULLY PROBABILISTIC WIND MODELING

Probabilistic approaches offer a much better way to incorporate all of the various sources of uncertainty (track uncertainty, intensity uncertainty, size uncertainty, etc.) in hurricane wind predictions. The NHC Wind Probability Product (Demaria et al 2013) is one example of such a product. Figure 4 shows the output of this product for the hurricane-force wind threshold (64 kts) approximately 72 h prior to landfall. Even at this long lead time, the product showed that locations in SW Florida had a relatively high (60-70%) chance of experiencing hurricane force winds.

This product accounts for the track/intensity/size uncertainty using a Monte Carlo method (1000 realizations) coupled with a parametric wind model. Drawbacks to this product are that it still uses inland decay rather than explicit physical modeling of the changes in wind over land, it does not account for terrain (no topographic speed-up is included, which can be substantial in mountainous areas), and it does not provide any information regarding wind speeds greater than 64 kt. While the NHC wind speed probability product is a major step in the right direction, the risk calculator tool envisioned in this paper will require that the full probabilistic density function (PDF) be computed for the full range of all plausible wind speeds (e.g., 0 to 250 kt).

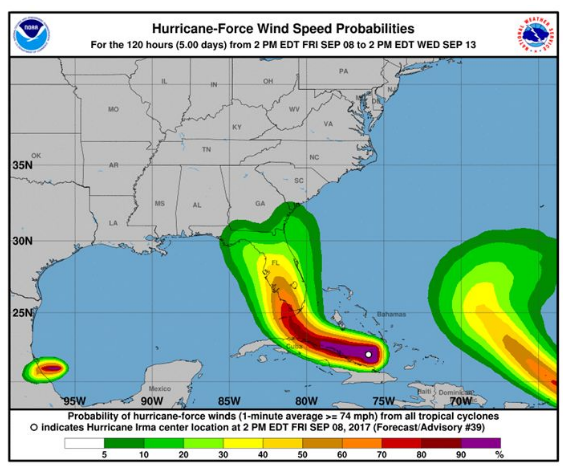

Figure 4: The accumulated probability of experiencing hurricane-force (sustained 64-kt) winds over the next 120 h, from 2 P M EDT 08 Sep 2017. Image from the NHC website.

4. USING DESIGN WIND SPEEDS TO BRACKET CRITICAL THRESHOLDS

Historically, the design wind speed used to set building codes, called the v_{basic} or v_{design} was the 3-sec gust wind speed that has a 50 year return period (2% probability of occurring in a given year), measured in an open exposure (Category C) at 10 m height. Various importance and wind loading factors were applied based on region and building category.

New standards, such as the ASCE 7-16, now use what is called the *ultimate design wind speed*, or $v_{ultimate}$, which is set by structure category. For residential construction (Risk Category II), $v_{ultimate}$ is determined approximately by the 700-year return level wind speed. In the 2012 International Building Code (2012 IBC), a building code used by many communities, the older design wind speed was based on the philosophy of *allowable stress design* (v_{asd}). This wind speed is related to the ultimate design wind speed by (approximately):

$$v_{asd} = v_{ultimate} \sqrt{0.6}$$

In the absence of any additional information, the two design wind speeds can be used to bracket the critical thresholds that may be relevant for a typical structure (explained in more detail in the next section). These thresholds can be obtained from websites such as the Applied Technology Council's (ATC) hazards portal (https://hazards.atcouncil.org/). Figure 5 shows a screenshot of an earlier version of this web interface, which provides a number of return level wind speeds for different return periods. The relevant return level wind speeds for this discussion, are the 50-year return level wind speed, which approximates v_{asd}, and the Risk Category II value, which corresponds to $v_{ultimate}$.

For design of specific structures (and the assessment of risk), the exposure category, terrain factor, building height, and other factors must all be taken into account. Figure 6 shows a satellite image of a house in a typical neighborhood in Lehigh Acres, FL. There is open exposure to the south (category C), with trees and urban exposure (category B) to the north. The house is 32 feet above sea level, meaning that it is quite safe from all but the most catastrophic storm surges. The local exposure (within a few miles) of a location is very important to the strength of the gusts that can be experienced for a given strength of winds in the boundary layer, so an accurate assessment of the local exposure and terrain influences is key. Recently, work has been undertaken along these lines by computing ground surface roughness and then examining resulting damage patterns through field assessments (Roueche et al 2018).

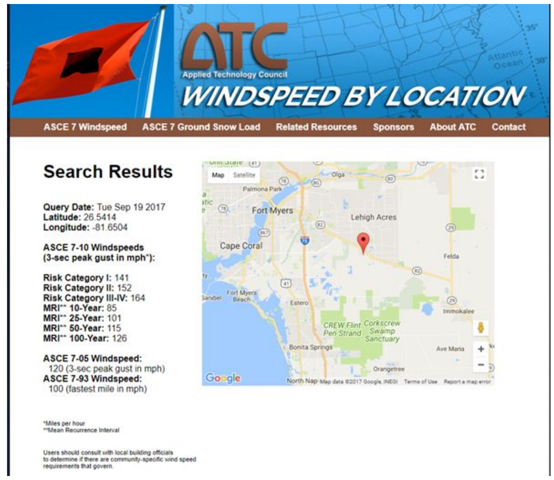

Figure 5: Various return level wind speeds from the ASCE 7-10 catalog for an example location in Lehigh Acres.

Figure 6: Satellite image of a typical neighborhood showing the importance of properly assessing exposure for a given site. The place marker shows location of an example house.

5. TRANSLATING WIND IMPACTS

In the absence of actual information about a given structure, the design wind speeds v_{asd} and $v_{ultimate}$ that the structure was built to can be used as a rough guide to formulate an expectation on how a residential structure may perform during a hurricane. For purposes of estimating damage to the structure itself, and losses of the contents therein, the relevant structural performance characteristic is the breach of the building envelope (Li and Ellingwood 2009). Building components are typically rated such that they will not experience inelastic deformation or other types of failure so long as $v < v_{asd}$. For wind speeds above v_{asd} but still below $v_{ultimate}$, inelastic deformations may occur (i.e., damage to the building envelope), sometimes leading to significant damage to the contents within (e.g., water damage) which could compromise the ability of occupants to remain in the home after the storm (e.g., mold). In general, however, the structure should still generally maintain significant ability to protect the life and safety of its occupants. As the wind speed approaches and exceeds $v_{ultimate}$, significant damage becomes likely with an increasing possibility of total structural collapse.

To keep things as simple as possible, the initial version of the Hurricane Risk Calculator will display potential damage in a 3-point color categorical scale that relates to the potential safety of the structure during the storm and the habitability after the storm:

- **Green tag condition likely** ($v \leq v_{asd}$): no significant structural damage is expected (non-structural damage possible, e.g. fences, out-buildings, etc.).
- **Yellow tag condition is likely** ($v_{asd} < v \leq v_{ultimate}$): some structural damage possible; some loss to contents is likely; structure may not be habitable following the storm due to water damage, mold, and/or loss of utility services.
- **Red tag condition is likely** ($v > v_{ultimate}$): significant damage is possible up to a total loss of the structure and its contents; the structure could lose its ability to protect the life and safety of its occupants.

Further refinements and translation aspects can be envisioned. For instance, the real-time predicted wind information can be convolved with vulnerability curves for the particular class of structures to estimate a dollar figure for the probable or maximal damage. An even more refined approach to estimating the wind impact would be to undertake a full fragility analysis calculation based on the individual building components (e.g., roofing system, method by which roof is attached to walls, large windows, patio doors, garage doors). Generally, the weakest component in the building envelope represents the most significant risk to experiencing a breach of the envelope, although this depends significantly on the wind direction. If such information is available, a more accurate picture of the potential damage could be provided. Gathering the requisite information, however, would likely require a structural inspection.

It is important to stress that additional factors such as the presence of large trees, wind-borne debris, and other factors must also be considered. The calculator will ask some basic questions of users to screen for these risks.

6. INFORMING EVACUATION VS. SHELTER-IN-PLACE DECISIONS

The risks of remaining in a home, including the possibility of structural collapse (Melchers and Beck 2018) and the risks of being in the area after the storm must be weighed against the very real, but often under-appreciated risks of evacuation. *Table 1* contextualizes the potential mortality risks of evacuation within the larger spectrum of per-event risks for a variety of activities. The risk levels range from “certain death” (1 in 1 risk) to decreasing levels of mortality risk all the way to “astonishingly small risk” (1 in a billion risk). The right column provides examples of activities with risk on par with the levels indicated on the left. Of particular note are the examples given for certain hurricane events. For example, in New Orleans during Hurricane Katrina (2005), 80-90% of the city’s 485,000 residents evacuated, but approximately 50,000 - 100,000 remained behind. Of those, nearly 1,000 died in the ensuring disaster (Bunkard et al 2008), giving an estimated mortality of 1 in 100 (mortality rates were much higher in certain sections of the city that were deeply inundated, such as the Lower Ninth Ward). Another relevant example on the risk spectrum is the risk observed in certain hurricane evacuations. During Hurricane Rita’s mass evacuation, which involved 2.5 million people, approximately 107 people died from the evacuation itself, mostly due to accidents. Thus, the mortality risk due to this evacuation was approximately 1 in 23,000. This is somewhat comparable to risk of climbing Longs Peak, a famous 14,000-foot peak in Colorado. While this may not seem unduly risky from a personal perspective, when applied across a million or more people, this shows that a disorderly evacuation may lead to a substantial number of deaths across the participant population. The potential risks of long-distance evacuation can be further estimated by simply applying the baseline mortality risk of driving in personal automobiles. For the U.S. during the period 2000 to 2005, this risk was 1.5 deaths per 100 million miles traveled (https://en.wikipedia.org/wiki/Transportation_safety_in_the_United_States and references therein). This means

1 in X chance	Probability	Probability	Categorical Risk Description	Example activity or event with comparable mortality risk
1	1.00	10^{-0}	Certain death	Sum total of all-cause mortality over a lifetime
2	0.50		Catastrophic risk	Participating in a duel
5	0.20			
10	0.10	10^{-1}	Profound risk	Climbing Mount Everest without oxygen (actual risk: 12.4%)
20	0.05			Summitting Mount Everest (actual risk: 4.0%)
50	0.02			Attempting to climb Mount Everest (actual risk: 1.6%)
100	0.01	10^{-2}	Grave risk	***Not evacuating New Orleans during Hurricane Katrina (~1100 deaths out of ~100,000 who remained)***
200	0.005			
500	0.002			*(e.g., some major surgeries)*
1,000	0.001	10^{-3}	Severe risk	
2,000	0.0005			Base jumping, 1 jump (1 death every 2317 jumps)
5,000	0.0002			
10,000	0.0001	10^{-4}	Significant risk	Summitting Longs Peak (1 death for every ~10,000 successfully summits each year)
20,000	0.00005			***Hurricane Rita evacuation (actual risk: 1 in 23,364, based on 107 deaths out of 2.5 million evacuees)***
50,000	0.00002			***Taking a round-trip trip by car to a destination 500 miles away (actual risk: 1 in 66,000*)***
100,000	0.00001	10^{-5}	Considerable risk	
200,000	0.000005			Sky diving, 1 jump in 2010 (1 death per 153,000 jumps; based on 21 deaths for 3 million jumps in 2010)
500,000	0.000002			
1,000,000	0.000001	10^{-6}	Low risk	Skiing at a Colorado ski resort (about 1 death per million skier visits)
2,000,000	0.0000005			***Commuting to work or evacuating to a local shelter (20 miles round-trip, actual risk: 1 in 3,300,000*)***
5,000,000	0.0000002			Taking a long-haul round-trip flight (10,000 total miles; actual risk: 1 in 7,142,857**)
10,000,000	0.0000001	10^{-7}	Very low risk	So-called *des minimis* risk
50,000,000	0.00000002			***Taking a short-haul round-trip flight (1000 total miles; actual risk: 1 in 50,000,000**)***
100,000,000	0.00000001	10^{-8}	Extremely low risk	
500,000,000	0.000000002			Lifetime odds of being killed by hail in the U.S. (actual risk: 1 in 734,000,000)
1,000,000,000	0.000000001	10^{-9}	Astonishingly small risk	

* From 2000-2005, the risk of car travel in the U.S. is 1.5 deaths per 100 million passenger miles travelled.
+ Between 2000 and 2010, the mortality risk of flying on commercial avaiation in the U.S. is 0.2 deaths per 10 billion passenger miles travelled.

Table 1: The spectrum of risks. First column expresses the risk as a "1 in X" chance. The next two columns express the risk in terms of probabilities. The fourth column assigns a categorical risk description. The final column provides example activities with comparable mortality risk. All risks are expressed on a *per event* basis, corresponding to the risk a participant would accrue by partaking in that activity.

that for a typical evacuation scenario which involves driving to a destination 500 miles away and then returning (1000 miles driven total), the per-person mortality risk is 1 in 66,000. If this rate applied during the Hurricane Irma evacuation, and all evacuees traveled 1000 miles on average, 103 deaths would have been expected just due to routine traffic accidents.

There is one other relevant risk threshold on this table: the risk of commuting to work. This risk is estimated using the same rate of traffic deaths per mile, but for just a 20-mile total commute distance. The per-day risk of commuting this distance is 1 in 3.3 million. This is important because it establishes a "routine daily acceptable risk" that normal people take every day without much thought. This risk level is relevant because 20 miles could be a typical distance that residents might travel if they need to drive to a local shelter. If shelter space had been adequate to house all of the 6.8 million people who evacuated during Hurricane Irma, 2 deaths would have been expected due to driving risk.

Ultimately, each resident must make his/her decision based on their unique situation, vulnerability, and risk tolerance. We propose that optimal outcomes will become more likely when decisions are made in a risk-informed probabilistic framework. Many lives might be saved simply by encouraging evacuees to evacuate locally rather than to distant locations.

7. SUMMARY AND FUTURE PLANS

This extended abstract has outlined a vision to develop a "hurricane risk calculator" which provides detailed and relevant information about potential hurricane wind impacts for a user's specific location. In the initial version, slated to be ready by the peak of the 2018 hurricane season, a user will be able to enter in their street address (or geographical coordinates) into a web page and then view a dashboard-like interface with graphical and textual products that detail the expected magnitude and timing of potential wind impacts for the user's location. Initially, the tool will be driven using wind information from official sources, such as the TCMWindTool (via the NDFD grids), the NHC Hurricane Wind Speed Probability product, and a parametric model that uses the Kepert-Wang boundary layer model that accounts for varying orography. This will be a first step toward accounting for the fetch of the wind as it travels over varying terrain and orography.

A key aspect of the calculator will be to translate the projected wind impacts into terms easily understood by layman. One way this can be done is to explain what the projected wind impact means in terms of the potential damage to their residence. This translation process will reference American Society for Civil Engineers (ASCE 7-16) hurricane hazard simulation data (which is typically used to set local design wind speeds for coastal building codes) and then contextualize the wind risk in terms of the basic and ultimate design wind speeds for the building category of the resident. The basic wind speed corresponds to the threshold at which damage may begin to occur to the structure. The ultimate wind speed corresponds to the threshold at which major structural failure starts to become likely. Additional future translation capabilities could include providing information about the potential likelihood and duration of power outages and the severity of tree damage.

An eventual goal is for the calculator to be driven by a fully probabilistic treatment of wind hazard potential that accounts for the trajectory and fetch of the wind over land, local site exposure, and topographical influences. Coupled with information about the resident's structure class, age, and local building codes, the calculator may then be able to offer information about the expected range of damage to the resident's structure as well as the probability that that structure may lose its life-protective ability. Importantly, this tool is not meant to supersede any evacuation orders made by local authorities. For residents outside of mandatory evacuation zones (e.g., in voluntary evacuation zones or residents who are well inland, but still facing considerable wind threat), this tool can better inform the key decision of whether to evacuate or shelter-in-place. It can also inform decisions such as if and when to put up protection (such as hurricane shutters, etc.).

Acknowledgments

This work was supported by a grant from the FY2017 RAL Opportunity Fund. NCAR is sponsored by the National Science Foundation.

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