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Moving from Hazard to Risk: The Hurricane Risk Calculator

Dr. Jonathan L. Vigh

with thanks to Bruce Ellingwood, Cao Wang, Thomas Kloetzke

WWRP Typhoon Landfall Demonstration Project Workshop
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Direct Hazards from Tropical Cyclones in the U.S.

► Surge

► Inland flooding

► Landslides

► Wind hazard

► Building collapse

► Falling trees

► Waves

► Building collapse

► Rip currents

► Tornadoes

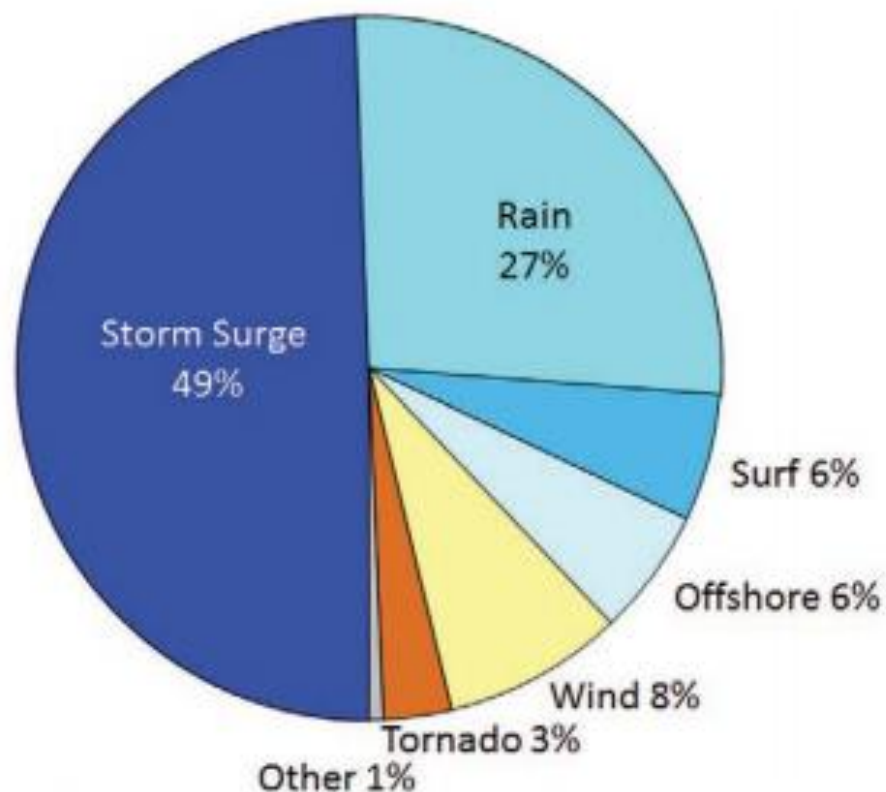


FIG. 1. Cause of death in the United States directly attributable to Atlantic tropical cyclones, 1963–2012.

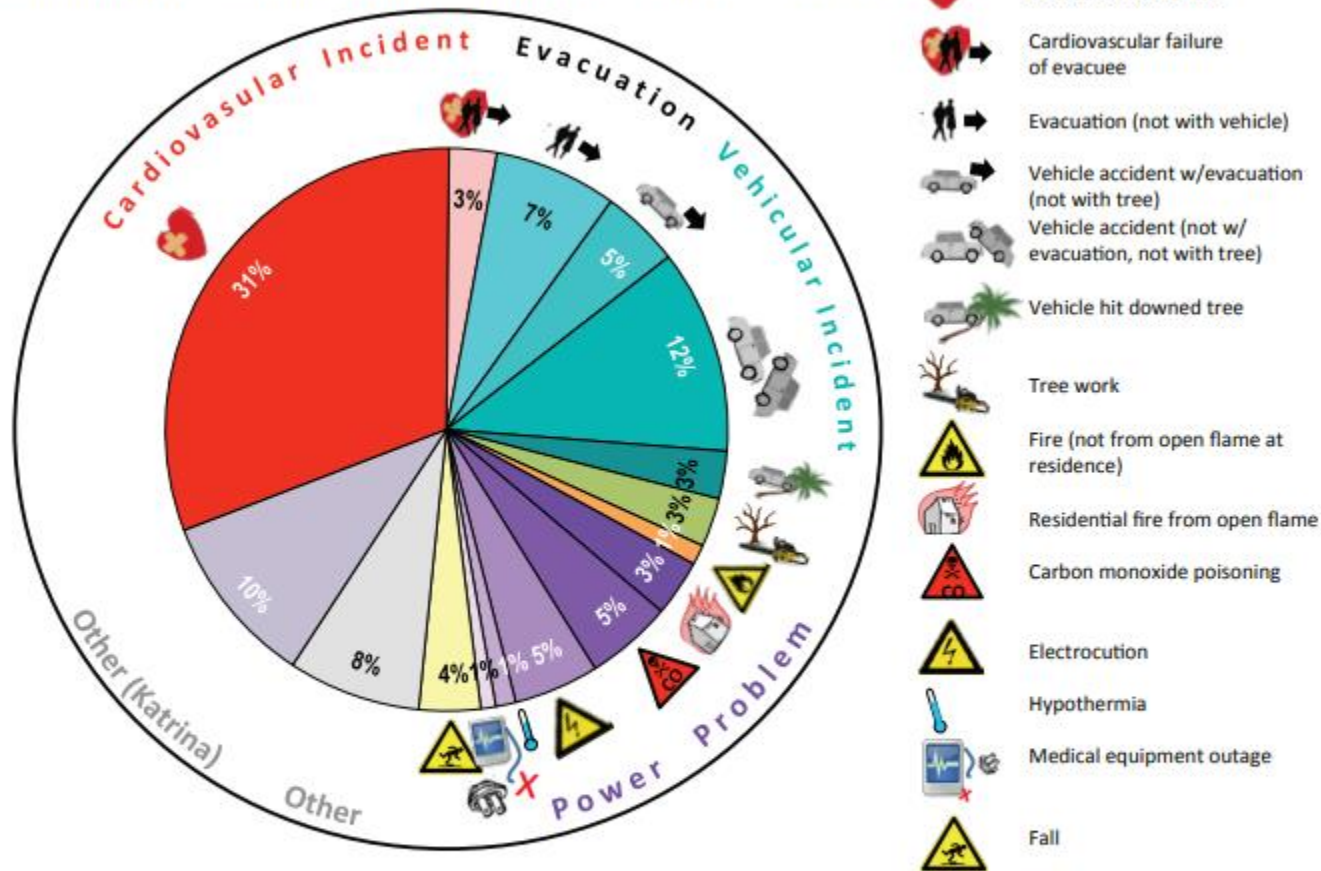
Rappaport (2014)

Indirect Hazards from Tropical Cyclones in the U.S.



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U.S. Atlantic Tropical Cyclone Indirect Deaths, 1963-2012



Additional hazards:

- Mold
- Lack of medical services
- Food insecurity
- Disease outbreaks

FIG. 1. 1963–2012 U.S. Atlantic tropical cyclone indirect deaths distributed by primary factor present. Note that power problems, beyond being the primary antecedent in the incidents having a purple shading, also occurred in another 2–3% of the other factors shown. Vehicle accidents where traffic lights had lost electricity are an example. To avoid double-counting these cases, they only contribute to the totals of those other factors. Table 1 provides additional information.

Rappaport and Blanchard (2016)



Evacuation also poses risks

The risks of remaining in a storm-affected area must be weighed against the very real, but often under-appreciated risks of evacuation

- ▶ Car accidents
- ▶ Storm affects in the evacuation area
 - Lack of medical services
 - Heat exhaustion
 - Falls
 - Fires
 - Carbon monoxide poisoning
- ▶ Stress on the elderly

In Hurricane Rita (2005), there were approximately 80 evacuation-related deaths

In Hurricane Irma, 6.8 million people are estimated to have evacuated, but 3 million of these were not from evacuation zones! Such people are known as “shadow evacuees”



Current emergency management practice

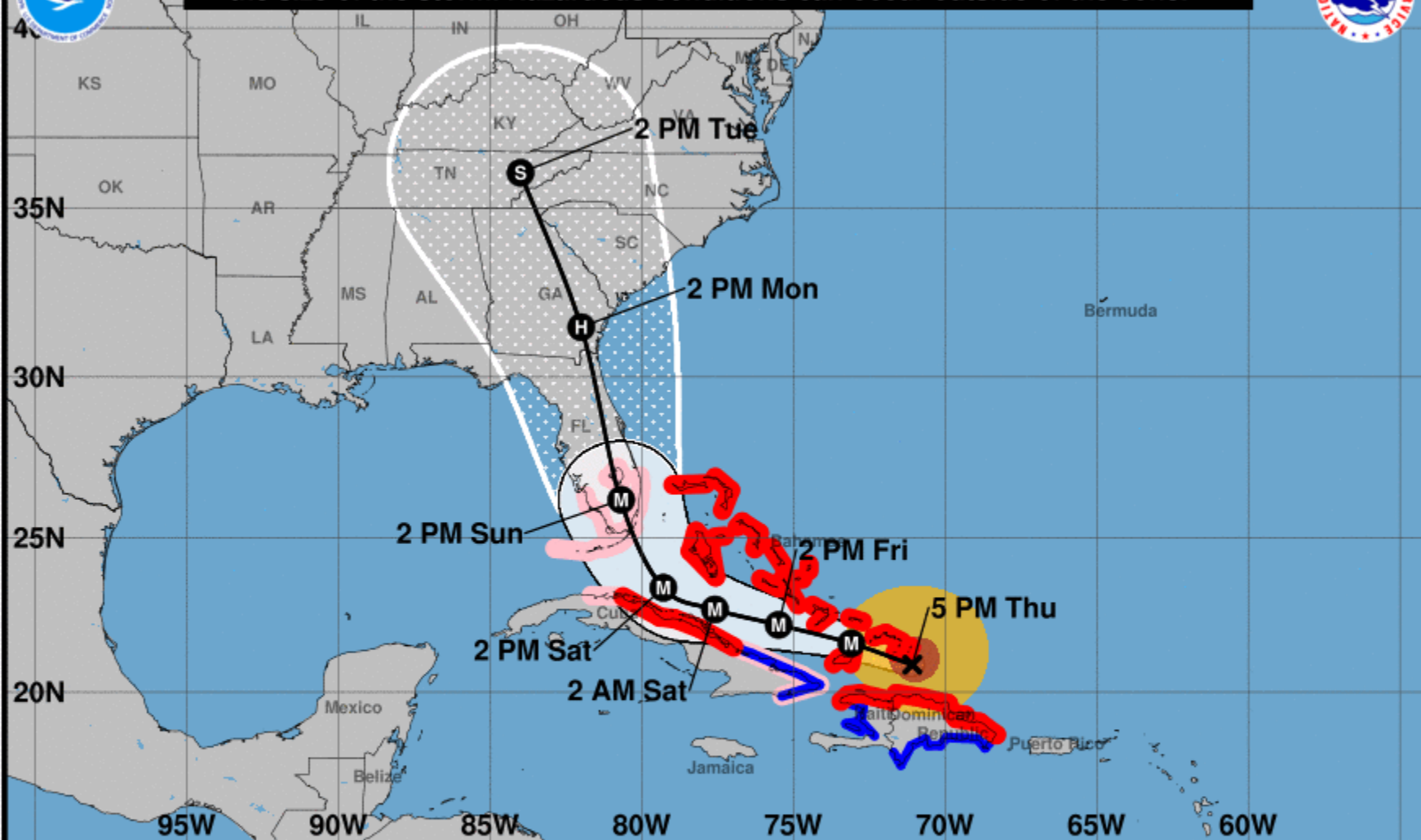
- Forecast enterprise
 - observations, modeling -> forecast, products
- Coordination meetings between forecasters, federal/state/local agencies, emergency managers (EMs)
- Emergency management make recommendations for each local jurisdiction
- Information disseminated through communication channels
- Local evacuations occur
 - sometimes staged optimally by surge risk zones, sometimes not

Response rates of 30 - 80%

FEMA estimated that 10,000 people stayed in Keys during Irma



Note: The cone contains the probable path of the storm center but does not show the size of the storm. Hazardous conditions can occur outside of the cone.



Hurricane Irma

Thursday September 07, 2017
5 PM EDT Advisory 35
NWS National Hurricane Center

Current information: x

Center location 20.9 N 71.1 W
Maximum sustained wind 175 mph
Movement WNW at 16 mph

Forecast positions:

● Tropical Cyclone ○ Post/Potential TC
Sustained winds: D < 39 mph
S 39-73 mph H 74-110 mph M > 110 mph

Potential track area:

Day 1-3 Day 4-5

Watches:

Hurricane Trop Stm

Warnings:

Hurricane Trop Stm

Current wind extent:

Hurricane Trop Stm



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Problems with the U.S. System

Too much emphasis on
deterministic scenarios

People receive info from
many different channels,
some of questionable quality

- e.g., web, social media

Contradicting
recommendations

- e.g., Hurricane Harvey: “Local leaders know best . . .”
- local officials contradicted state governor, did not recommend evacuations

Many people have trouble
interpreting complex
information under stress

- decision making is often haphazard

All-or-nothing evacuation
scenarios

- e.g., stay put vs. go out of state

Economic challenges

- Those with economic means are able to evacuate; most vulnerable are often still in harm’s way


Timing of evacuations is often
not optimal

- Massive traffic jams

Inadequate transportation
network

**Stakeholders find it difficult or impossible to get detailed and trustworthy
info needed to optimize their own cost/loss situation**

What do people need?



They need information specific to their location on the impacts from:

- storm surge
- wind impacts
- inland flooding

It's fairly irrelevant to them where the exact track is, what the size of the cone is, or what the maximum intensity of the storm will be

More specifically, they really need to know probabilistic information translated into forms that they can understand and which are relevant to their situation

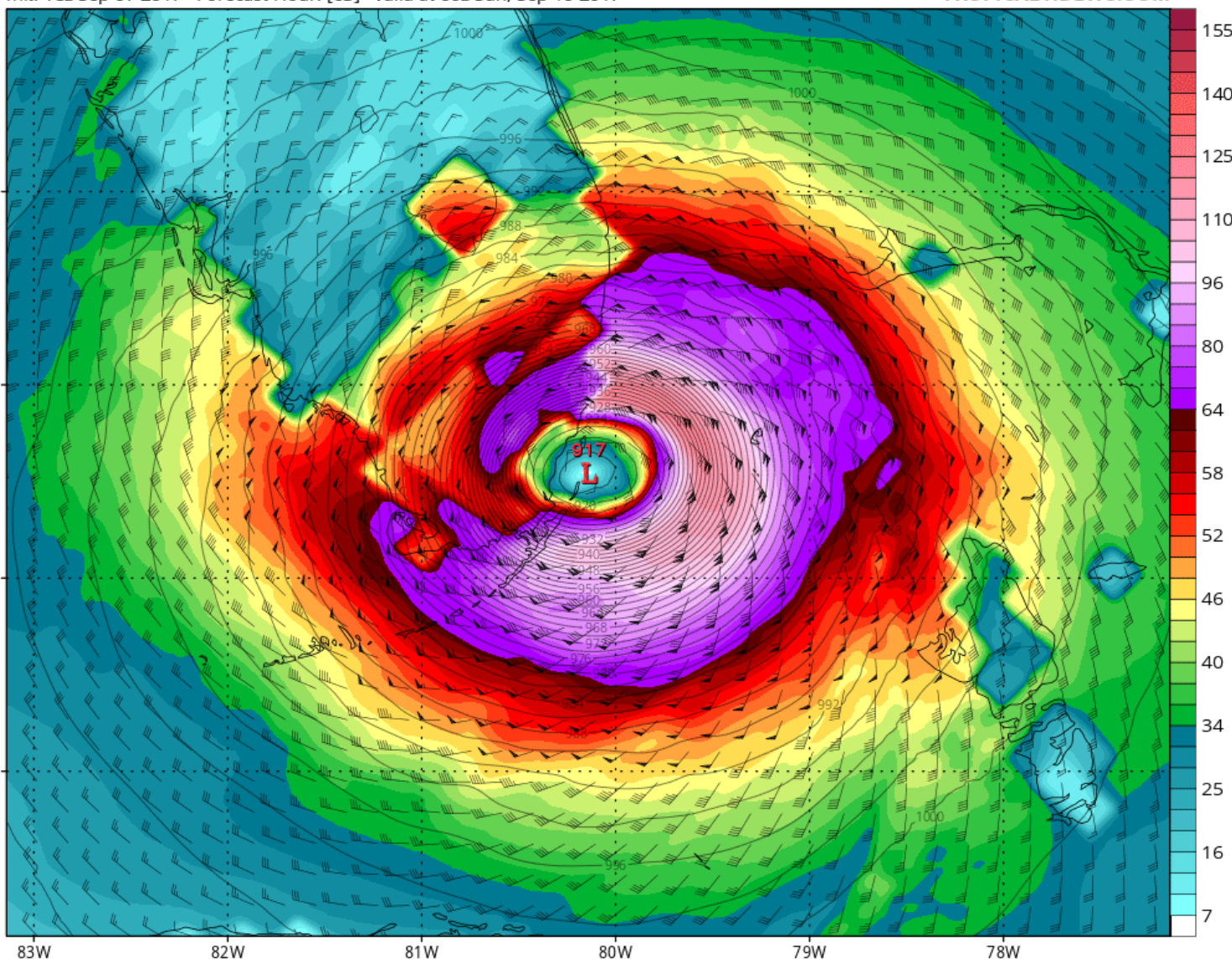
The next few slides will examine some of the state-of-the-art sources of hurricane wind hazard information and highlight some deficiencies

HWRF IRMA-11L MSLP (mb) & 10m Wind Speed (kt)

Init: 18z Sep 07 2017 Forecast Hour: [63] valid at 09z Sun, Sep 10 2017

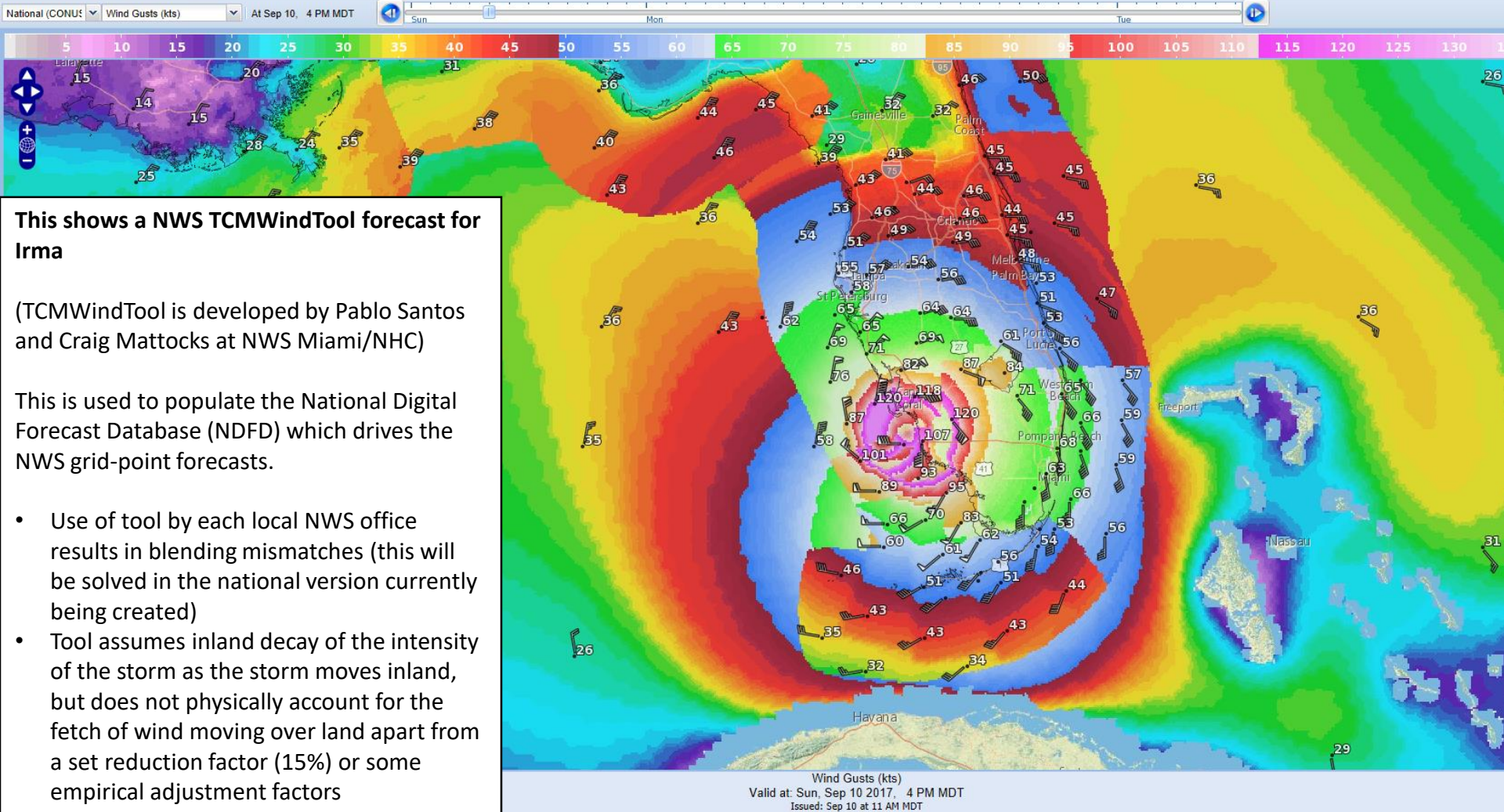
Min MSLP: 916.7mb | Max Wind: 124.3kt

TROPICALTIDBITS.COM



Example of current state-of-the-art NWP: the Hurricane WRF model (HWRF)

- Due to the use of the parent domain for the coastal-land mask and land surface, wind speeds over land are not well represented
- Furthermore, use of the metric of 1-min sustained winds also accentuates the marine vs. land differences in model products
- This 62-h forecast for Irma shows that Cat 3-4 winds would suddenly diminish to Category 1 winds within a couple miles of the coast – **unrealistic!**
- What really matters for damage are the gusts. These do not differ as much from sea to land as sustained winds.
- **Use of 1-min sustained wind in products sends the wrong message to users**



This shows a NWS TCMWindTool forecast for Irma

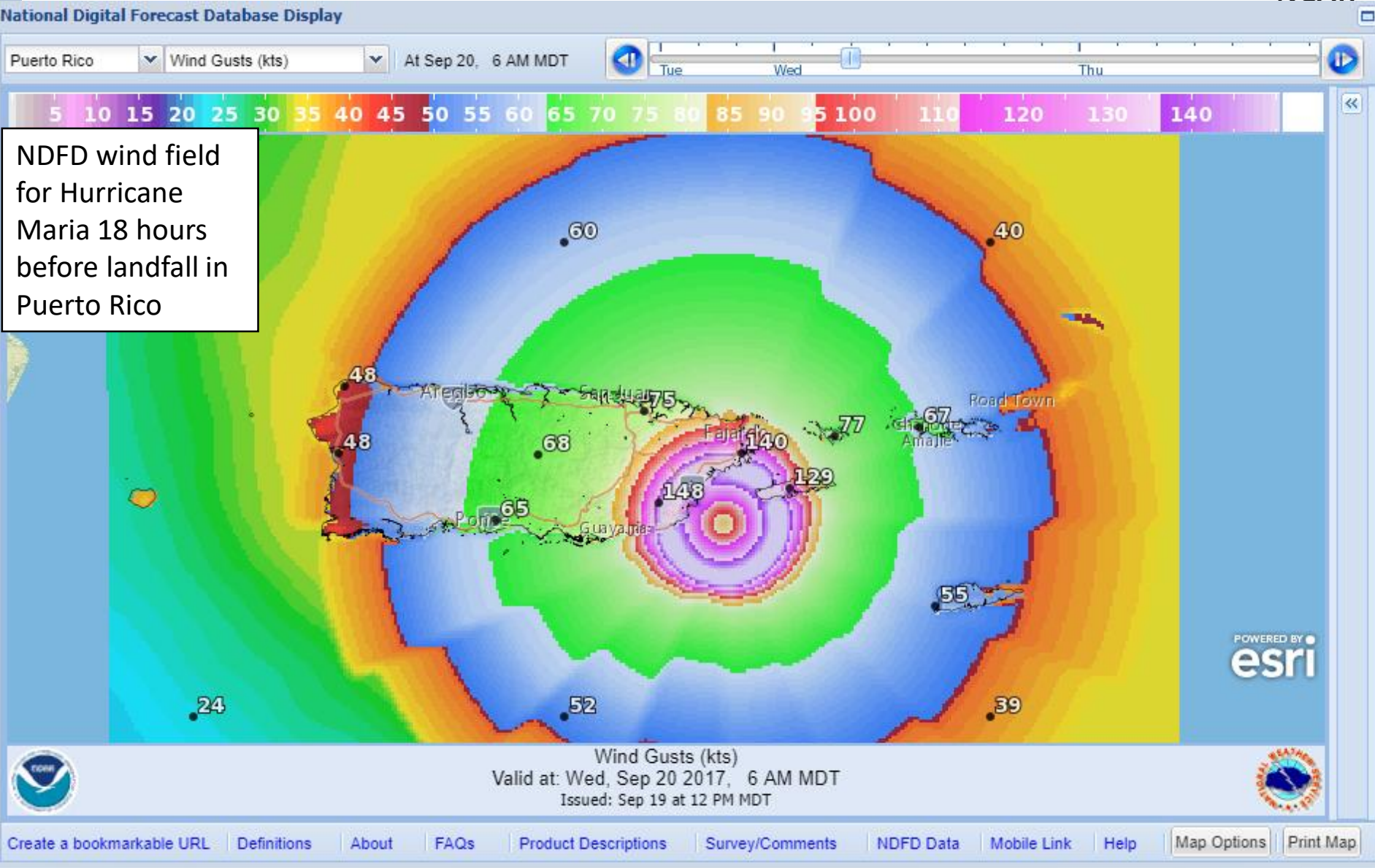
(TCMWindTool is developed by Pablo Santos and Craig Mattocks at NWS Miami/NHC)

This is used to populate the National Digital Forecast Database (NDFD) which drives the NWS grid-point forecasts.

- Use of tool by each local NWS office results in blending mismatches (this will be solved in the national version currently being created)
- Tool assumes inland decay of the intensity of the storm as the storm moves inland, but does not physically account for the fetch of wind moving over land apart from a set reduction factor (15%) or some empirical adjustment factors
- Usually the grid point forecasts over land are considerably too high
- There are plenty of other deficiencies, but **the main problem is that this tool is deterministic**



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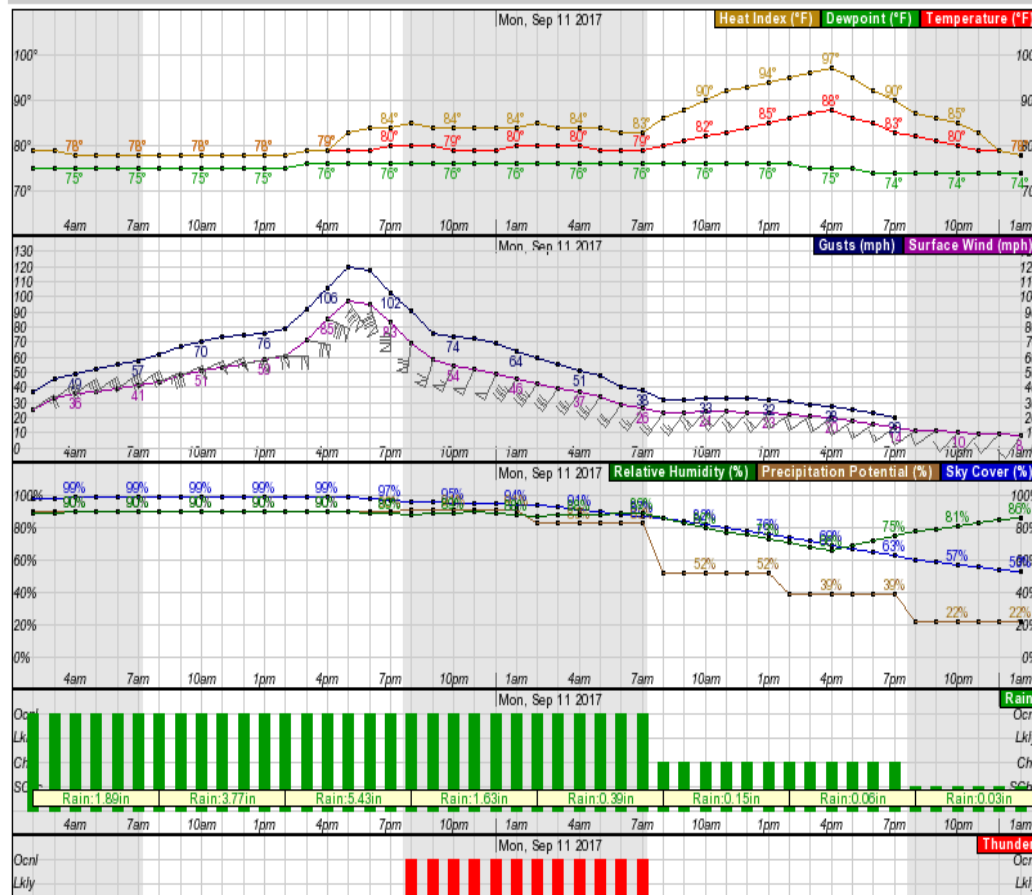
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Hourly Weather Forecast Graph

[\[dashes/dots\]](#) [\[b/w\]](#) [\[hide menu\]](#)

Weather Elements	Weather/Precipitation	Fire Weather
<input checked="" type="checkbox"/> Temperature (°F)	<input checked="" type="checkbox"/> Rain	<input type="checkbox"/> Mixing Height <input type="text" value="x100ft"/>
<input checked="" type="checkbox"/> Dewpoint (°F)	<input checked="" type="checkbox"/> Thunder	<input type="checkbox"/> Lightning Activity Level
<input checked="" type="checkbox"/> Heat Index (°F)	<input type="checkbox"/> Fog	<input type="checkbox"/> Trans. Wind <input type="text" value="mph"/>
<input checked="" type="checkbox"/> Surface Wind <input type="text" value="mph"/>		<input type="checkbox"/> 20ft Wind <input type="text" value="mph"/>
<input checked="" type="checkbox"/> Sky Cover (%)		<input type="checkbox"/> Dispersion Index
<input checked="" type="checkbox"/> Precipitation Potential (%)		<input type="checkbox"/> Low Visibility Occurrence Risk Index
<input checked="" type="checkbox"/> Relative Humidity (%)		

48-Hour Period Starting:



NWS grid-point forecast for Lehigh Acres, an eastern suburb of Fort Myers, FL

This forecast was made approximately 18 hours before the core of the storm moved through

Sustained winds: 98 mph
Gusts: 120 mph
Rating: low Category 2



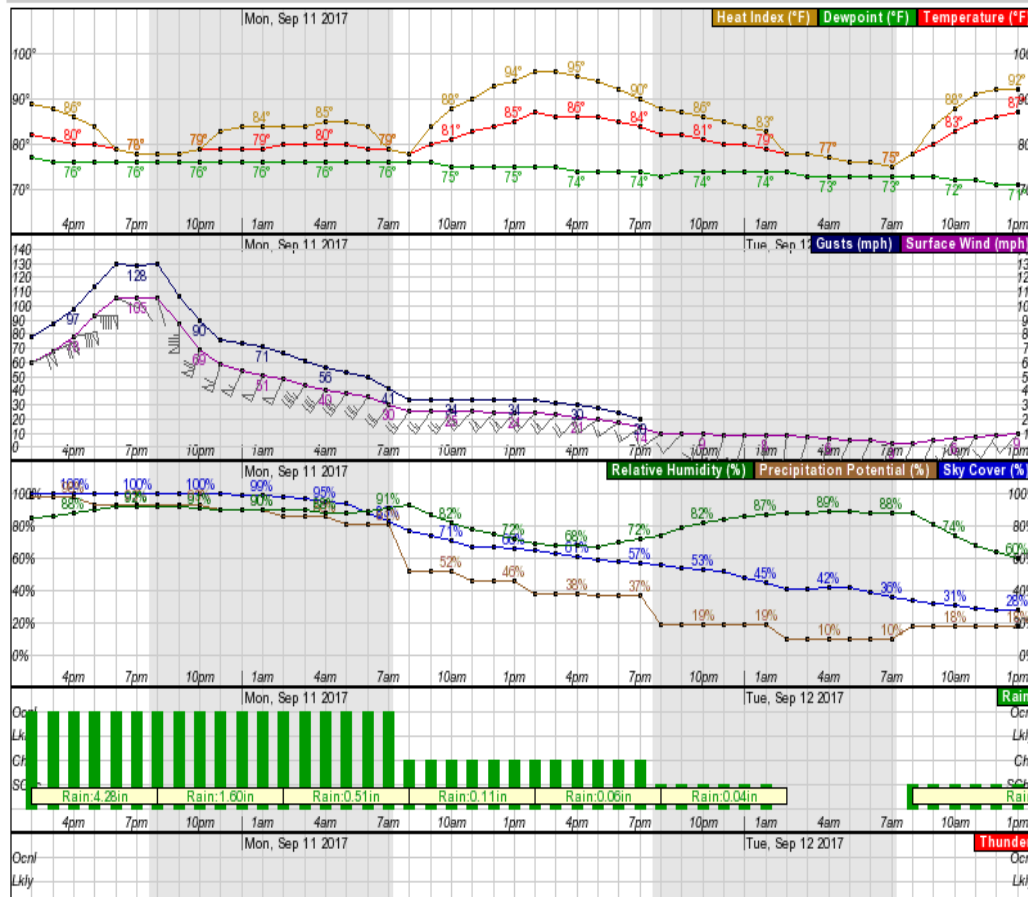
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Hourly Weather Forecast Graph

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<input checked="" type="checkbox"/> Relative Humidity (%)		

48-Hour Period Starting: ▾



Five hours prior to impact:

Sustained winds: 105 mph

Gusts:

128 mph

Rating:

mid Category 2



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Hourly Weather Forecast Graph

[\[dashes/dots\]](#) | [\[b/w\]](#) | [\[hide menu\]](#)

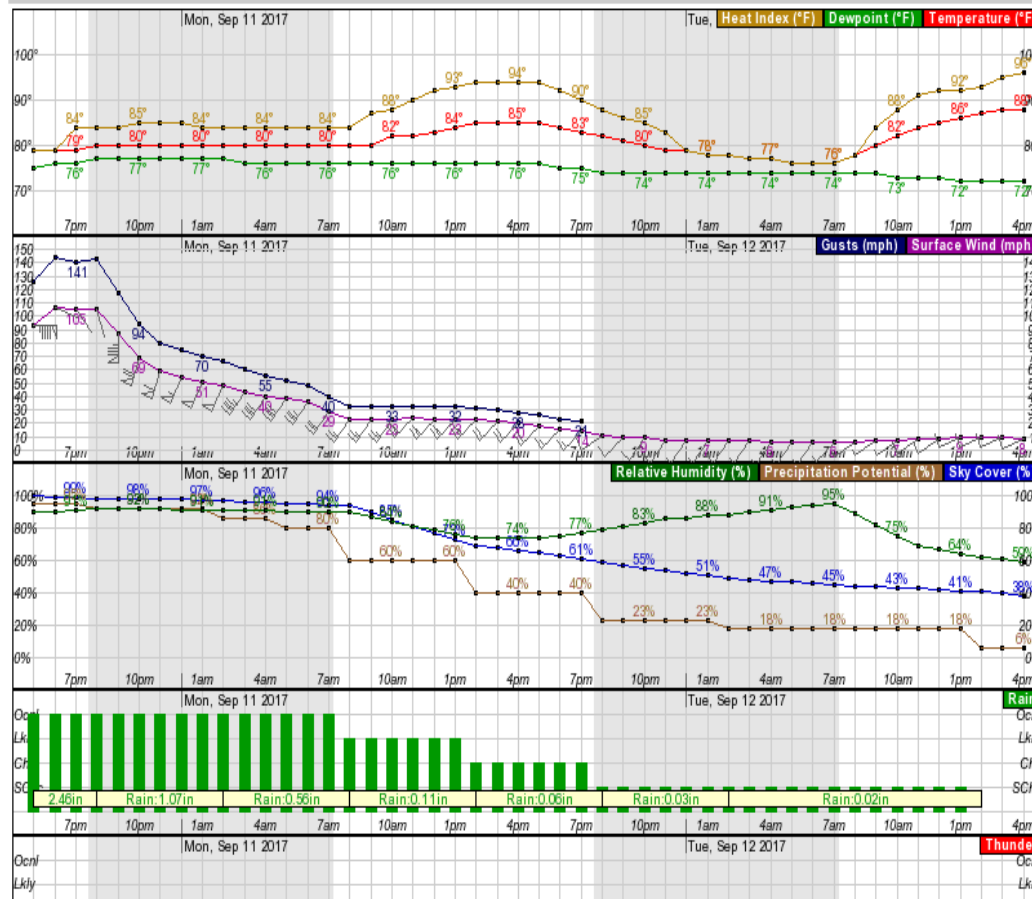
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<input checked="" type="checkbox"/> Temperature (°F) <input checked="" type="checkbox"/> Dewpoint (°F) <input checked="" type="checkbox"/> Heat Index (°F) <input checked="" type="checkbox"/> Surface Wind <input type="text" value="mph"/> <input checked="" type="checkbox"/> Sky Cover (%) <input checked="" type="checkbox"/> Precipitation Potential (%) <input checked="" type="checkbox"/> Relative Humidity (%)	<input checked="" type="checkbox"/> Rain <input checked="" type="checkbox"/> Thunder <input type="checkbox"/> Fog	<input type="checkbox"/> Mixing Height <input type="text" value="x100ft"/> <input type="checkbox"/> Lightning Activity Level <input type="checkbox"/> Trans. Wind <input type="text" value="mph"/> <input type="checkbox"/> 20ft Wind <input type="text" value="mph"/> <input type="checkbox"/> Dispersion Index <input type="checkbox"/> Low Visibility Occurrence Risk Index

48-Hour Period Starting: 5pm Sun, Sep 10 2017

Submit

Back 2 Days

Forward 2 Days



Two hours prior to closest approach:

Sustained winds: 105 mph

Gusts:

141 mph

Rating:

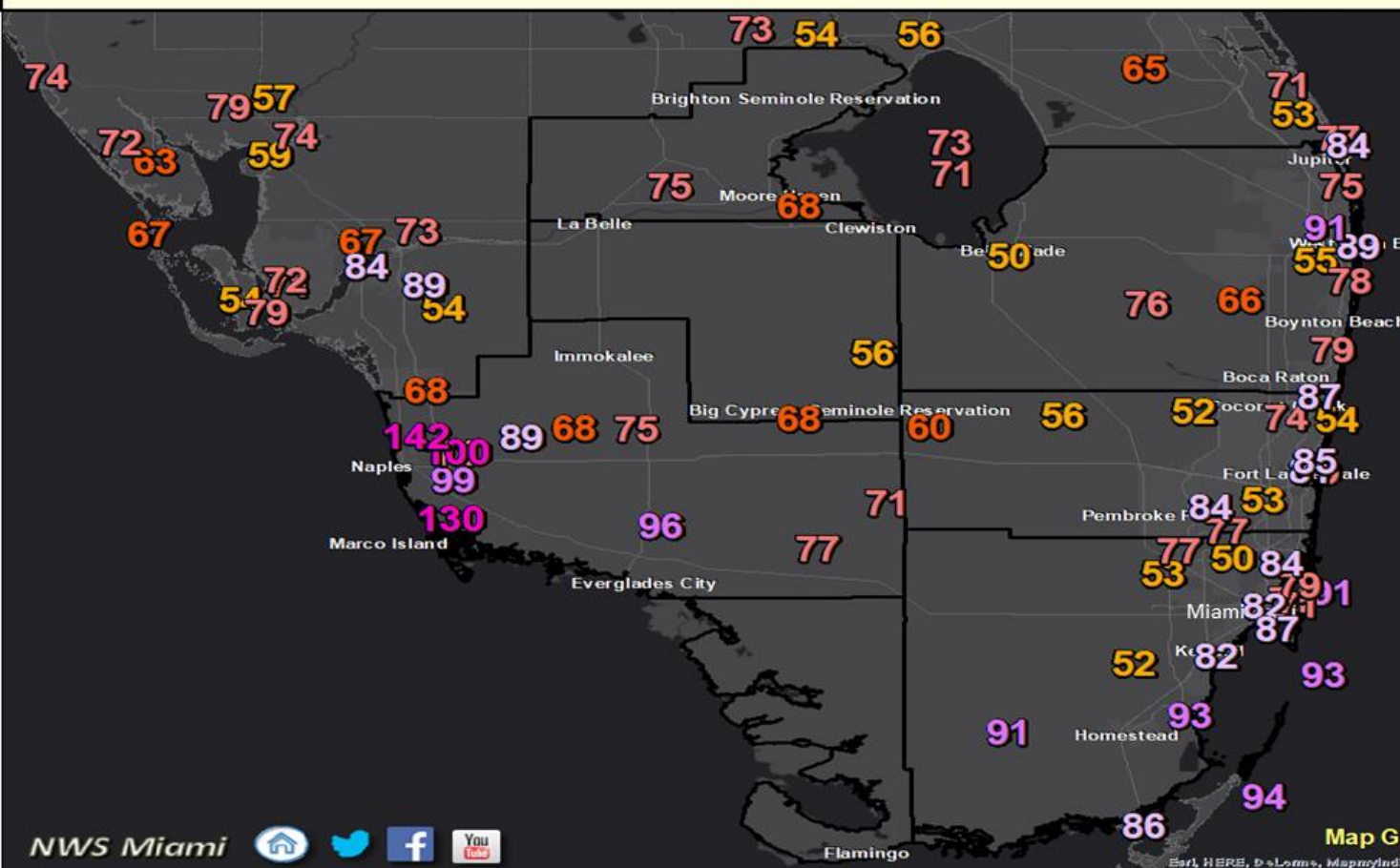
upper Category 2

What actually happened (sort of . . .)



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HURRICANE IRMA'S OBSERVED TOP WIND GUSTS (50+ MPH)



Verification:

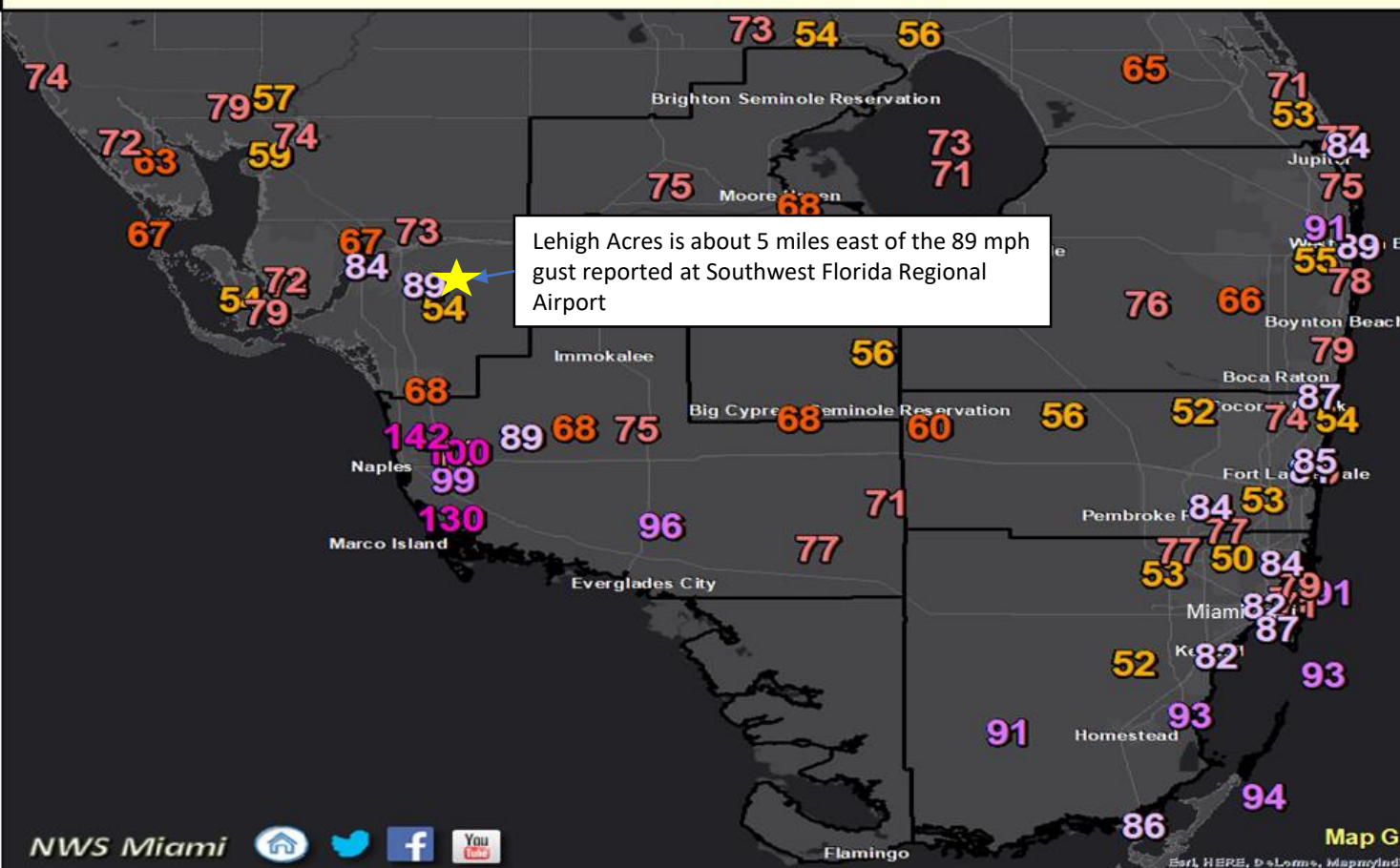
- Irma was already experiencing vertical wind shear and dry air
- By landfall on Marco Island, it had weakened to a Category 3 hurricane (100 kt)
- Structure was asymmetric and eyewall rapidly decayed

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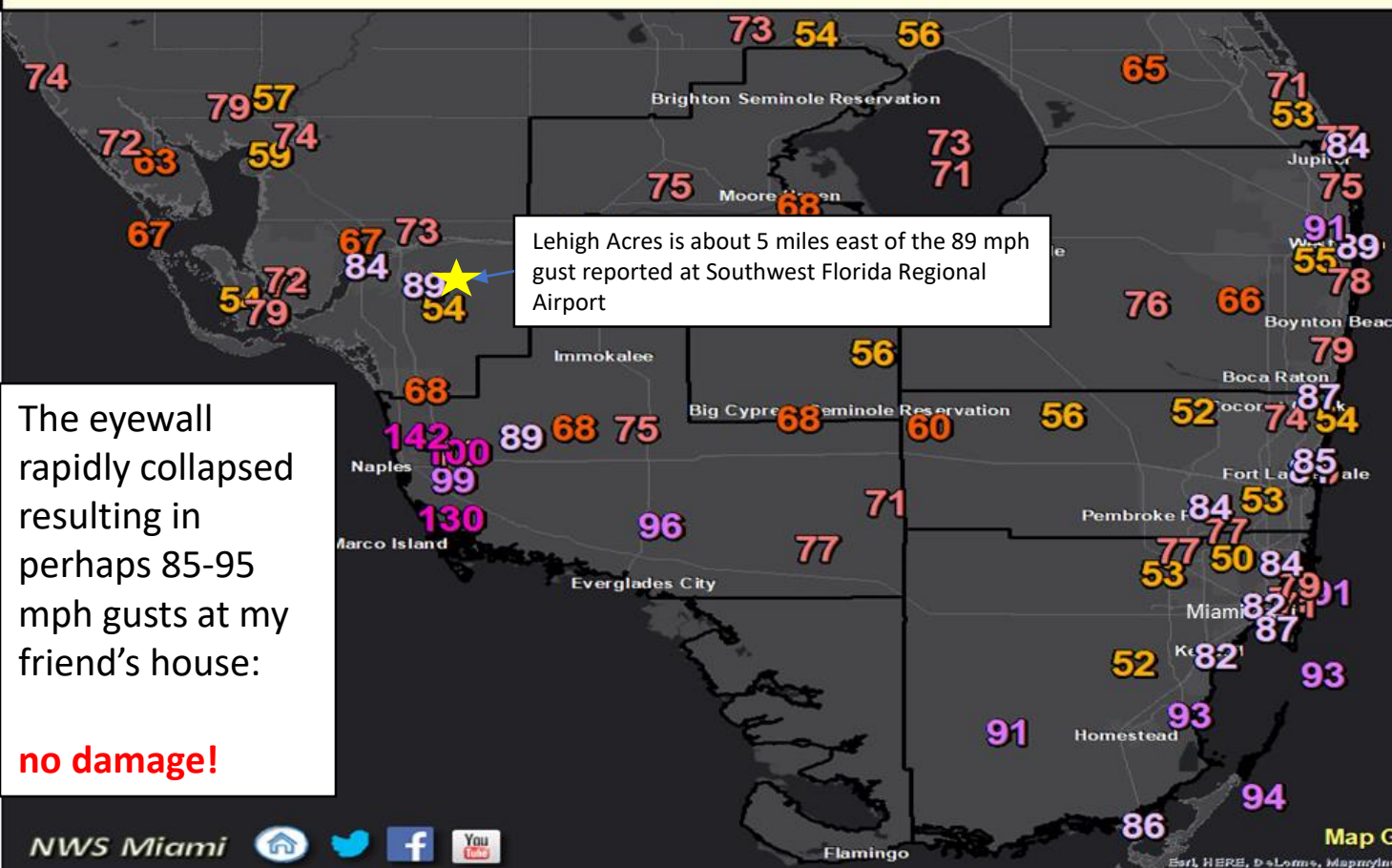
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The eyewall rapidly collapsed resulting in perhaps 85-95 mph gusts at my friend's house:

no damage!

NWS Miami

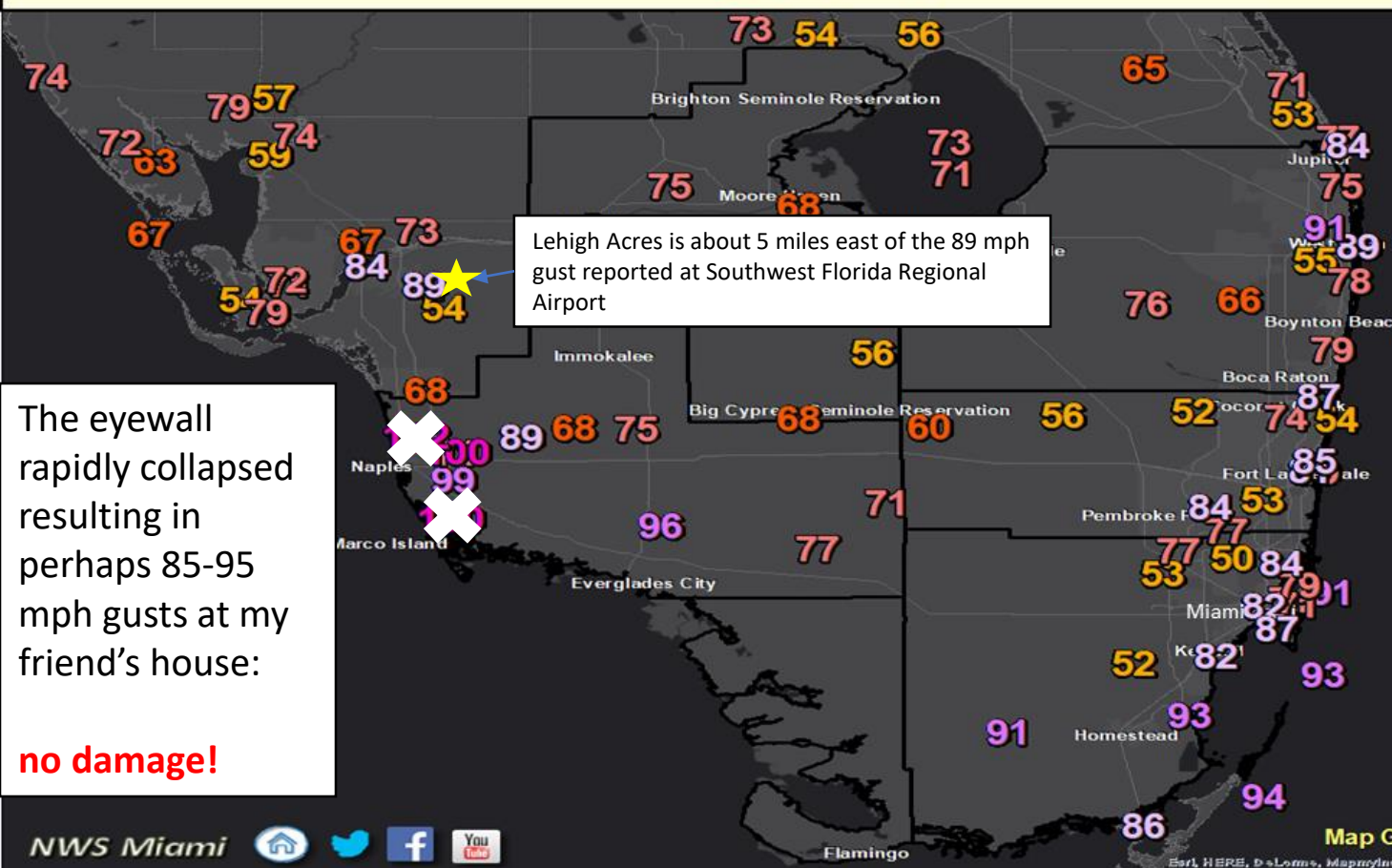


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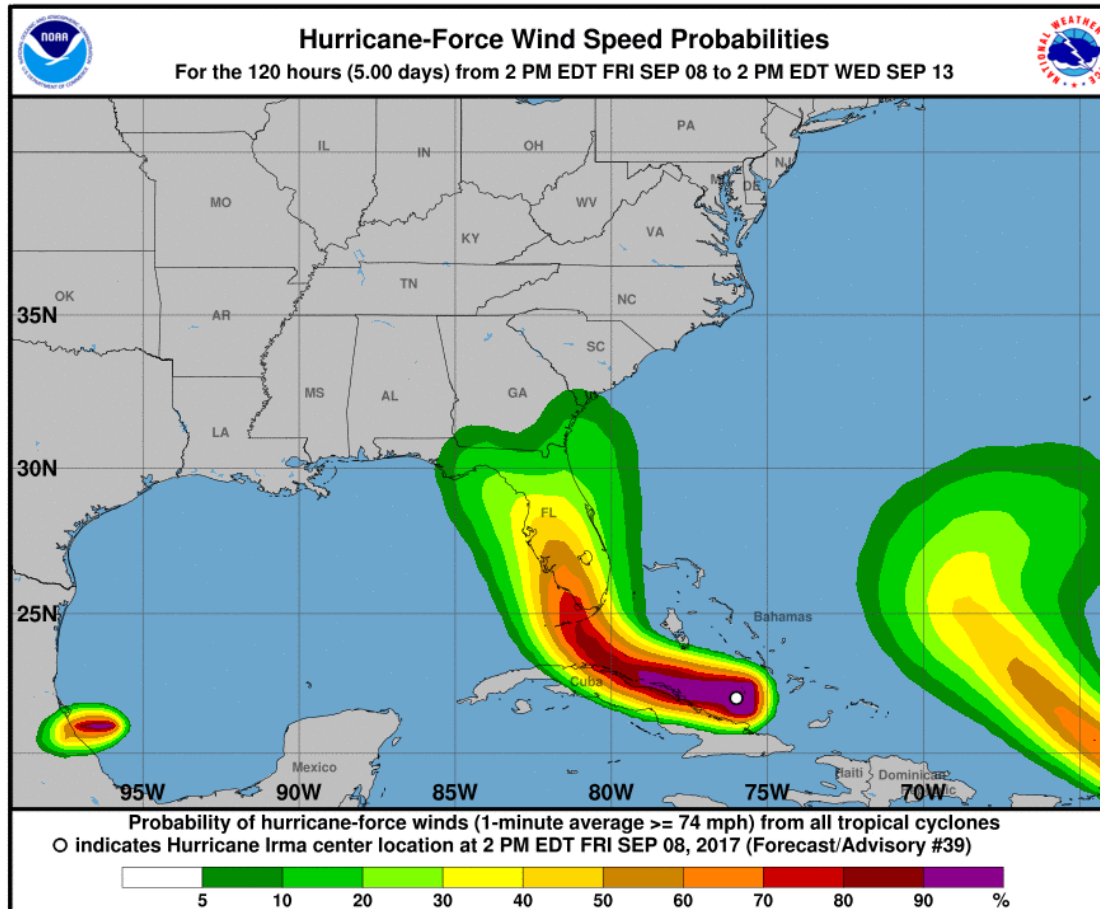
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Probabilistic Information



Probabilistic approaches offer a much better way to incorporate all of the various sources of uncertainty

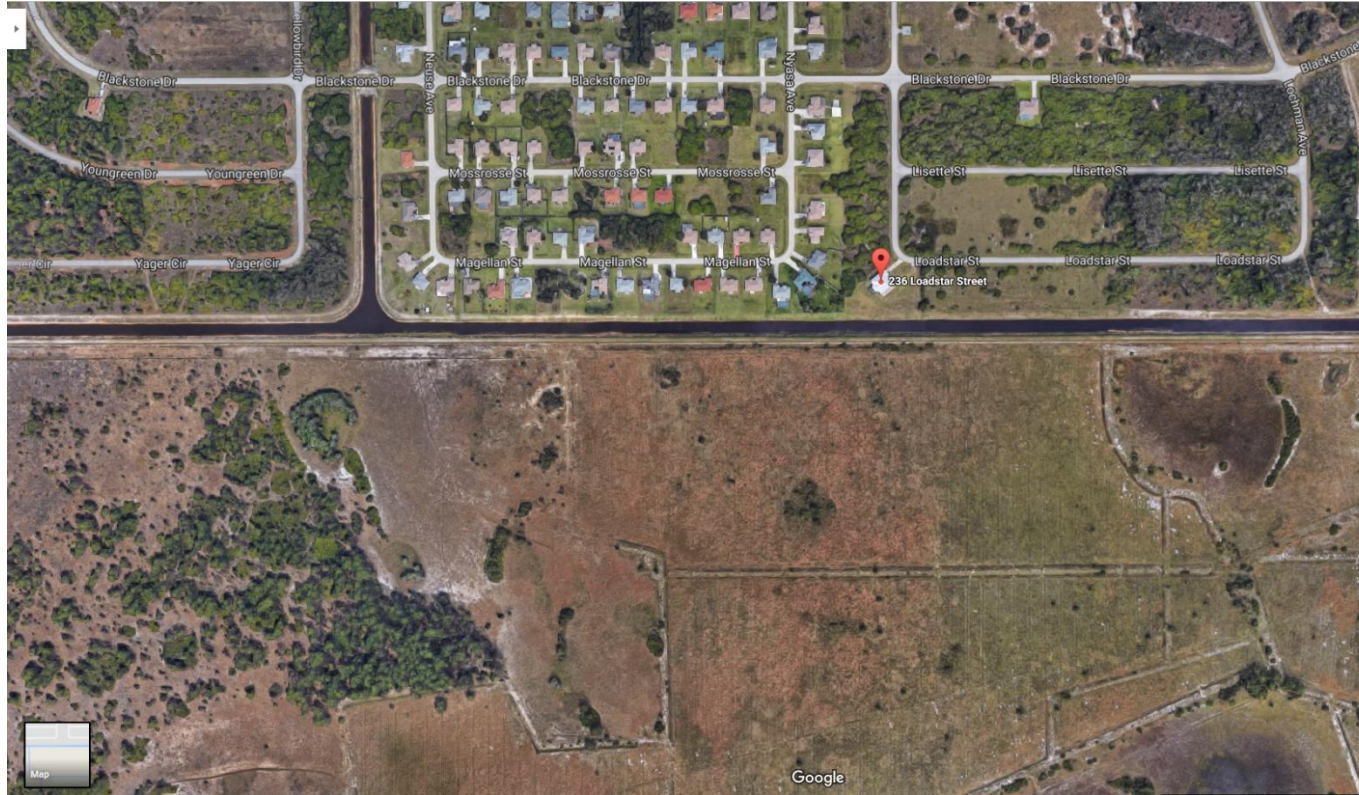
- track uncertainty
- intensity uncertainty
- size uncertainty

The NHC Windspeed Probability Product showed that his location had a high (60-70%) chance of hurricane force winds three days before landfall

Problems:

- uses inland decay rather than an explicitly physical modeling of the changes in wind over land
- does not account for terrain
- does not provide info for > 64 kt

Importance of adjustment for local terrain, fetch, and drag characteristics



Place marker shows the location of my friend's house

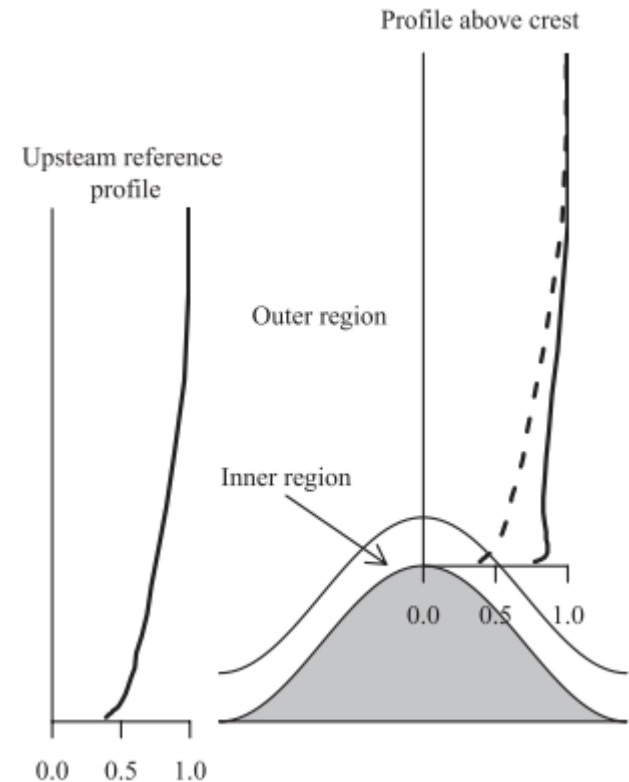
He has an open exposure to the south (category C), with trees and urban exposure (category B) to the north

His house is 32 feet above sea level -- safe from all but the most catastrophic storm surge scenario

The local exposure of a site is very important to the strength of the gusts that can be experienced for a given strength of winds in the boundary layer

The problem of topographic speedup

- Hurricane winds experience a significant speedup due to the Bernoulli effect even for low hills
 - A modeling study found that topographic speedup on ridgetops in Bermuda resulted in more than a Category increase in winds (from upper Cat 2 to Cat 4 winds)
 - Damage surveys and observations have borne this out
- Topographic speedup is especially dangerous in mountainous islands such as St. Thomas (USVI)
 - Residents described “horizontal tornadoes” causing severe damage in past hurricane events
- The enhanced wind risk posed by topographic speedup depends critically on the exact storm track
 - Tracks which result in a hillside locations getting exposed to the upslope wind may experience a 30-50% speedup in the winds
 - Tracks which result in the same location being sheltered can cause a 20-30% decrease instead
- A fully probabilistic framework is needed to account for the many possible track scenarios and upwind vs. downwind fetches



Miller et al (2013)



Importance of translation

- Even if the wind information is accurate, users will not know how to interpret this without context
 - “120 mph sounds bad, but will my house hold up?”
- Translation includes assessing the forecasted wind hazard in relation to the thresholds at which damage is expected to occur for their structure
- Needs to account for additional risks such as falling trees, wind-borne debris from neighboring structures, etc.
- Can also include estimates of how long it will take for power and other services to be restored
- Needs to stress uncertainty and get users to incorporate low probability but high-end scenarios rather than just the most-likely scenario



Translating Wind Hazard to Impacts in the United States

1. In the absence of detailed information about a structure, the design wind speed the structure was built to can be used as a rough guide to formulate an expectation on how the structure may perform during a hurricane

2. The **acceptable stress design wind speed** (v_{asd}) is the 3-sec gust wind speed that has a 50 year return period, measured in an open exposure (Category C) at 10 m height

- Building components are typically rated such that they will not experience inelastic deformation or other types of failure so long as $v < v_{asd}$

3. New standards, such as the ASCE 7-16, now use an **ultimate design wind speed** ($v_{ultimate}$) which is set by structure category

- For residential construction, $v_{ultimate}$ is determined by the 700-year return level wind speed

4. 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)

5. 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)

- The structure should still generally maintain significant ability to protect life and safety of its occupants

6. As the wind speed approaches and exceeds $v_{ultimate}$, significant damage becomes likely with an increasing possibility of total structural collapse



ASCE 7 Windspeed ASCE 7 Ground Snow Load Related Resources Sponsors About ATC Contact

Search Results

Query Date: Tue Sep 19 2017
Latitude: 26.5414
Longitude: -81.6504

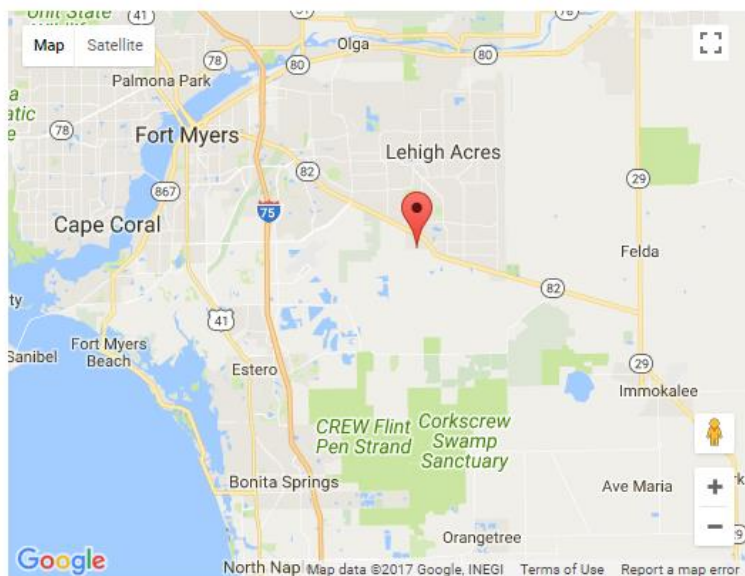
**ASCE 7-10 Windspeeds
 (3-sec peak gust in mph*):**

Risk Category I: 141
Risk Category II: 152
Risk Category III-IV: 164
MRI 10-Year:** 85
MRI 25-Year:** 101
MRI 50-Year:** 115
MRI 100-Year:** 126

ASCE 7-05 Windspeed:
 120 (3-sec peak gust in mph)
ASCE 7-93 Windspeed:
 100 (fastest mile in mph)

*Miles per hour
 **Mean Recurrence Interval

Users should consult with local building officials
 to determine if there are community-specific wind speed
 requirements that govern.



The 2012 International Building Code (2012 IBC) and many older building codes used the older design wind speed, v_{asd} . This wind speed is related to $v_{ultimate}$ by:

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

For design of specific structures, the exposure category, terrain factor, building height, and other factors must all be taken into account.

Residential buildings use Risk Category II, in which $v_{ultimate}$ corresponds to the 700-year return level wind speed. For his location according to the American Society for Civil Engineers (ASCE 7-16 wind standard), that is a wind gust to 152 mph.

Therefore, the v_{asd} for his location is likely to be around $152 \text{ mph} \times 0.7746 = 118 \text{ mph}$.

Translation: **IF** his house is built to the current code, it should be fine in wind gusts up to ~118 mph. Damage of increasing severity is expected as winds approach 152 mph. Complete building failure becomes likely much above that wind speed.

Graphic from the Applied Technology Council's Hazards-by-Location website

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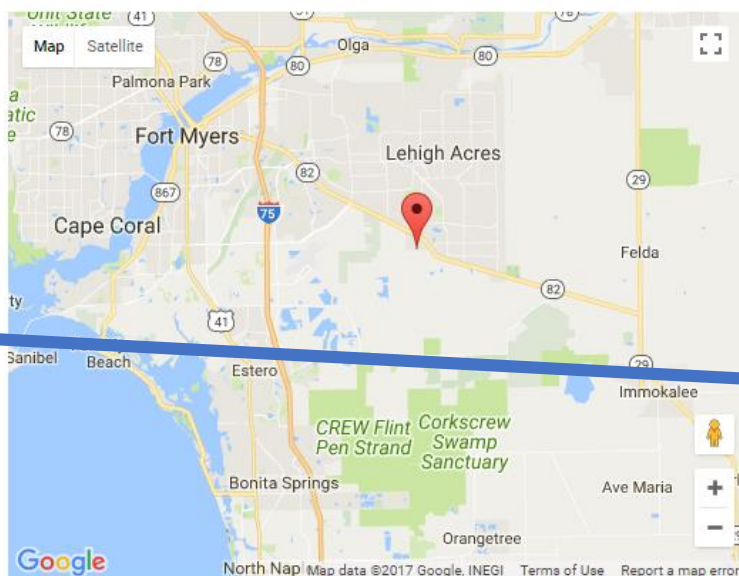
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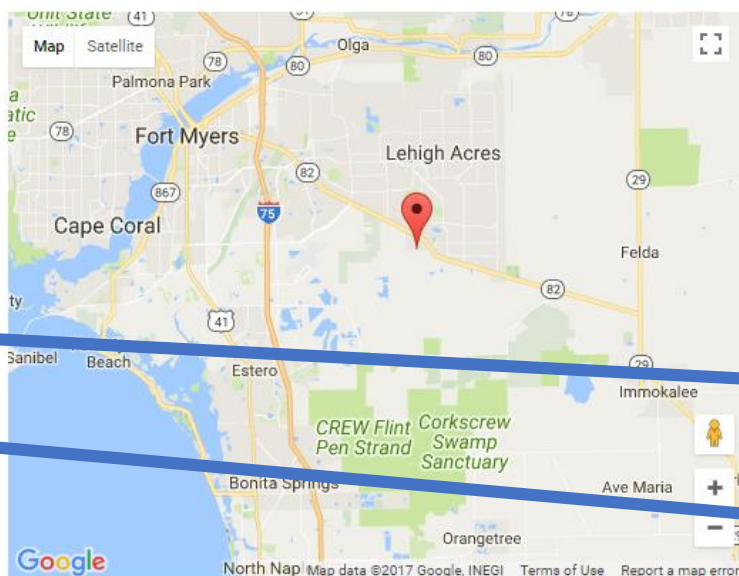
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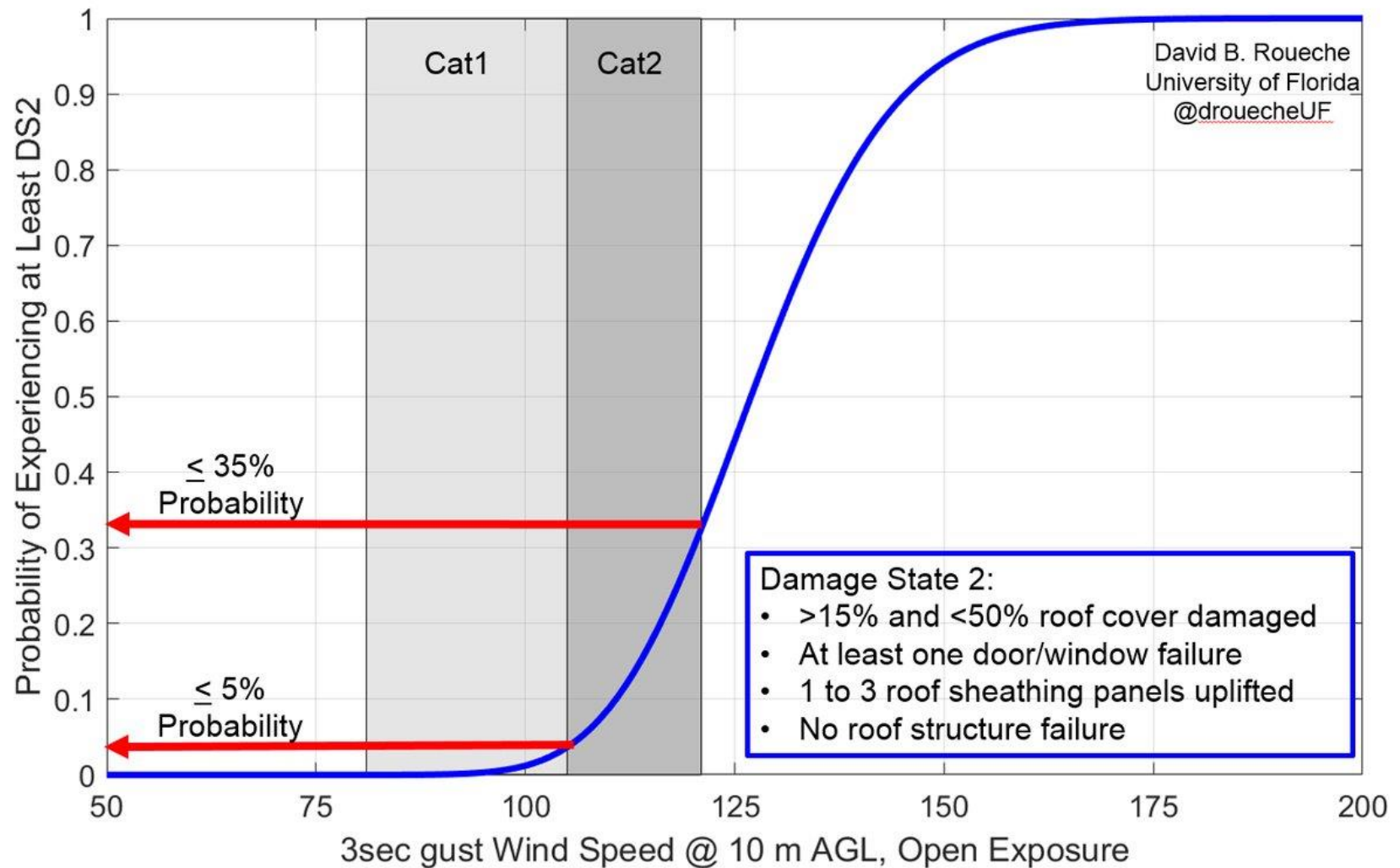


More sophisticated approaches

- ▶ Another approach to estimating the wind impact is a **fragility analysis** on the individual building components:
 - 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 can be provided
 - Gathering the requisite information however, would likely require a structural inspection
- ▶ When coupled with probabilistic wind information, fragility analysis can provide an estimated range of damage that may occur
- ▶ The likelihood that the structure may lose its ability to provide life and safety protection can also be estimated



Fragility Curves



*Data sourced from HAZUS-MH Hurricane



Keeping the message simple

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 is 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; structure could lose its ability to protect life and safety of occupants

The real-time predicted wind information can be convolved with loss curves for that particular class of structures to estimate a dollar figure for the probable damage

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

The Risk Spectrum



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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	<i>Not evacuating New Orleans during Hurricane Katrina (~1100 deaths out of ~100,000 who remained)</i>
200	0.005			
500	0.002			<i>(e.g., some major surgeries)</i>
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			<i>Hurricane Rita evacuation (actual risk: 1 in 23,364, based on 107 deaths out of 2.5 million evacuees)</i>
50,000	0.00002			<i>Taking a round-trip trip by car to a destination 500 miles away (actual risk: 1 in 66,000*)</i>
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			<i>Commuting to work or evacuating to a local shelter (20 miles round-trip, actual risk: 1 in 3,300,000*)</i>
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 <i>des minimis</i> risk
50,000,000	0.00000002			<i>Taking a short-haul round-trip flight (1000 total miles; actual risk: 1 in 50,000,000**)</i>
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 aviation in the U.S. is 0.2 deaths per 10 billion passenger miles travelled.



Goals of the Hurricane Risk Calculator (v1)

Provide wind risk information localized by a user's address

Users will enter their address, then get back wind hazard and risk information customized for their specific location, including:

- Their elevation
 - if <40 feet, flag the potential storm surge risk which would take precedence over wind risk
- NDFD grid-point-forecasted winds
- Official NHC hurricane wind probabilities for 34-, 50-, and 64-kt winds at their location
- Additionally, the tool will use the terrain-adjusted Kepert-Wang boundary layer model to provide an estimate of the local wind over land that accounts for terrain
- Timing of the onset of tropical storm-force and hurricane-force winds
- A “swath” or storm “footprint” showing the maximum expected winds
- The ASCE 7-16 wind hazard information for their location to provide context

Information will then be translated into understandable forms in a dashboard-like interface with graphs and text, with a goal of informing evacuation vs. shelter-in-place decisions

Initial project is being funded by the RAL Opportunity Fund

Will be incorporated into the Tropical Cyclone Guidance Project by ~Sep 2018



Alerting for enhanced personal safety

One potential solution to the multi-channel dilemma is to push judicious alerts through mobile apps

- Alerts should be risk-based and location-based
 - Based on the intersection of the projected hazard at the user's location and the user's specific vulnerability
- Thresholds for alerting should be actuarial, taking into account the cost/loss benefit to the individual
 - Avoid over-alerting
 - Avoid under-alerting



Alerting to recommend protective actions when a storm threatens

Goal is to mitigate losses and increase safety

- *Secure lawn furniture and other loose items*
 - >10% chance of 45 mph winds
- *Install protection (e.g., shutters) for windows/doors*
 - >20% chance of 58 mph winds
 - >10% chance of 75 mph winds
- *Move vehicles to higher ground / secure location*
 - >10% chance of 75 mph winds OR
 - >1% chance of >1 foot flood inundation
- *Secure valuables, move furniture to higher floor, consider evacuation*
 - >2% chance of exceeding structures acceptable stress design wind speed
 - >1% chance of minor (>3 feet) flood inundation
 - >0.1% chance of significant (>6 feet) flood inundation
- *Evacuate to local shelter*
 - >2% chance of exceeding structure's ultimate design wind speed
 - >0.01% chance of severe (>9 feet) flood inundation (1 story house)
 - >0.01% chance of extreme (>15 feet) flood inundation (2 story house)

Adapting the risk calculator

- This risk-based, individualized approach can be adapted for a wide range of regions and societies
 - Construction style and practices
 - Livelihoods and economic sectors
 - E.g. subsistence fishing
- The built-up urban environment presents an interesting challenge as more and more skyscrapers are being built in areas affected by tropical cyclones
 - Franklin et al (2003) showed that mean winds at the height of a modest high-rise (75 m) can be 17% higher than 10 m winds
 - Residents in high buildings need to consider the catastrophic scenario in which window thresholds may be exceeded
 - E.g., Miami high-rise windows are now rated to ~200 mph however this may not be sufficient in a high-end Category 5 at 300 m
 - Sheltering effects of building “wind shadows” can extend far downstream, so taking wind direction into account and upstream fetch is important

Summary

Intersecting hazard with vulnerability is the next frontier of hazard communication and risk mitigation

Value is added when:

- Hazard information is fully probabilistic
- Vulnerability information is fully probabilistic
- Both are specific to the individual's location
- Actuarial risk analysis is used to optimize the individual's cost/loss benefit and/or risk tolerance
- Information is translated to the individual in a simple and understandable manner
- Information/recommendations are provided within actionable time frames



What is
needed
to
achieve
this
vision?

- **Develop a fully probabilistic hurricane wind model that accounts for terrain and land-use variations in the fetch over land**
 - Build real-time probabilistic forecast capability into the open-source Tropical Cyclone Risk Model (Australia Geoscience)
 - Incorporate the Kepert-Wang boundary layer model
 - Incorporate latest research on wind in urban environments

- **Validate the wind model and fragility curves**
 - In-neighborhood wind measurements
 - Damage surveys
 - Loss data
 - Additional research to obtain fragility curves for all building classes (Structural Engineering)

- **Develop alerting protocols**
 - Determine optimum risk-informed/actuarial thresholds
 - Develop most effective formats of alerts (Social Science)

- **Develop data infrastructure to drive content delivery for apps**
 - Develop cloud-based infrastructure for maximum reliability
 - Alerts through mobile apps or e-mail, phone, web



NCAR