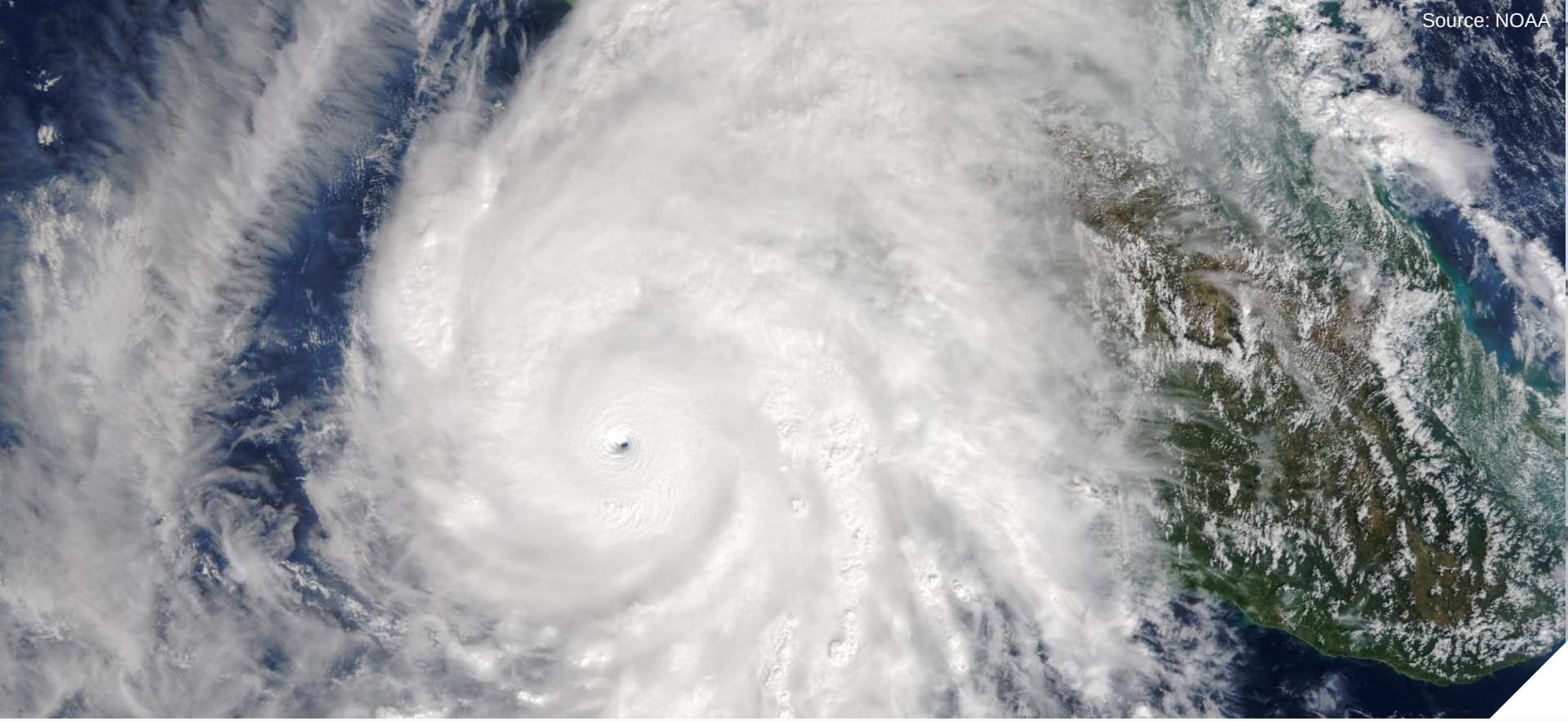
Source: NOAA

ASSESSING “GRAY SWAN” TROPICAL CYCLONE EVENTS IN CATASTROPHE MODELS

Mark Bove, CPCU, ARe
Senior Research Meteorologist
Munich Reinsurance America, Inc.

CARe
6 June 2016

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Agenda

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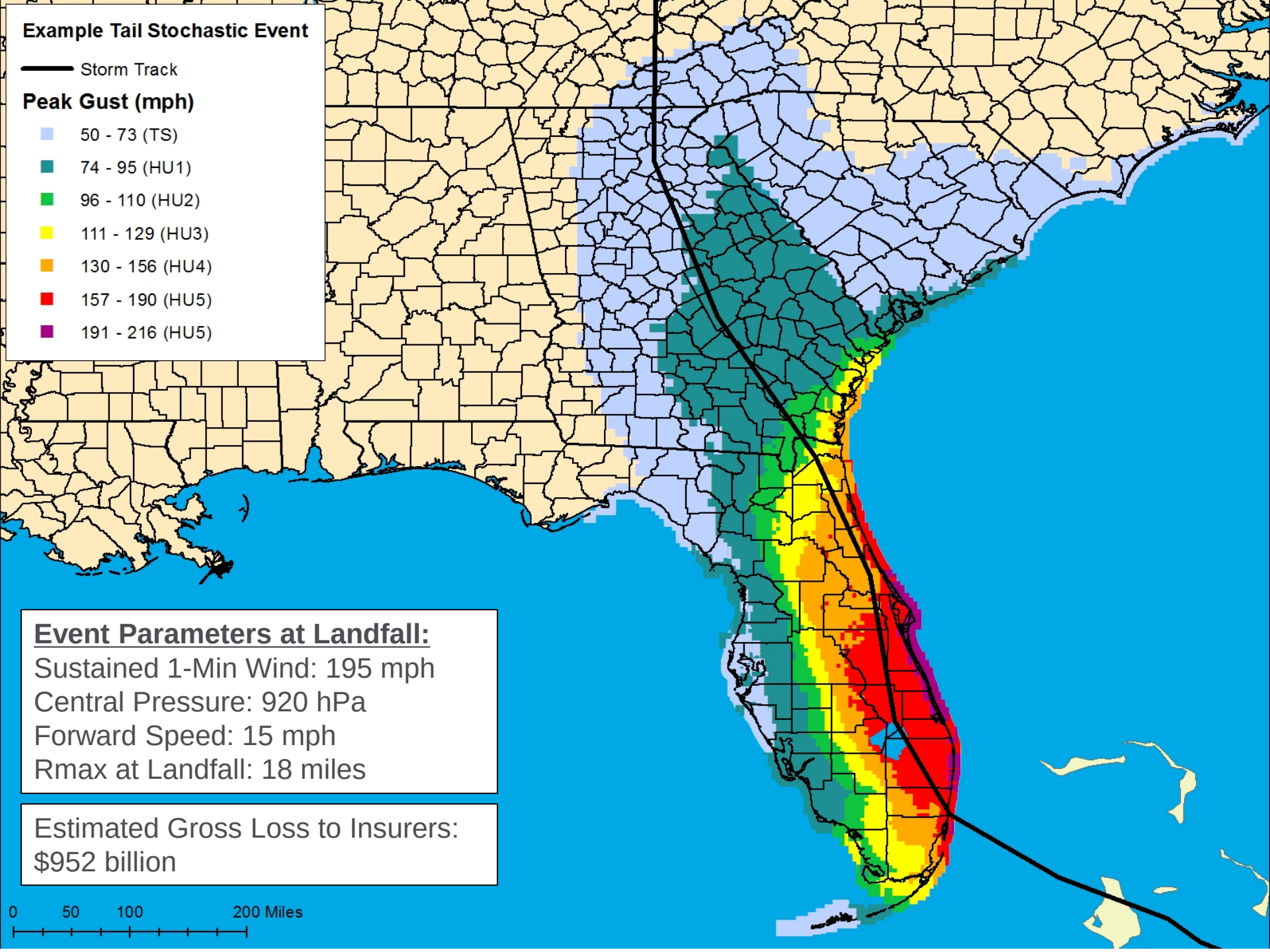
- Motivation
- Background
- The Meteorology of Extreme Tropical Cyclones
- Gray Swan Tropical Cyclone Events in South Florida
- Evaluating Gray Swan Events in Statistical Peril Models
- Summary


Example Tail Stochastic Event
Storm Track
Peak Gust (mph)
50 - 73 (TS)
74 - 95 (HU1)
96 - 110 (HU2)
111 - 129 (HU3)
130 - 156 (HU4)
157 - 190 (HU5)
191 - 216 (HU5)
Event Parameters at Landfall:
Sustained 1-Min Wind: 195 mph
Central Pressure: 920 hPa
Forward Speed: 15 mph
Rmax at Landfall: 18 miles
Estimated Gross Loss to Insurers:
$952 billion
0
50
100
200 Miles

Background

Photo: Kiril Kraslev; CC3.0

Background
What are “Black Swan” Events?

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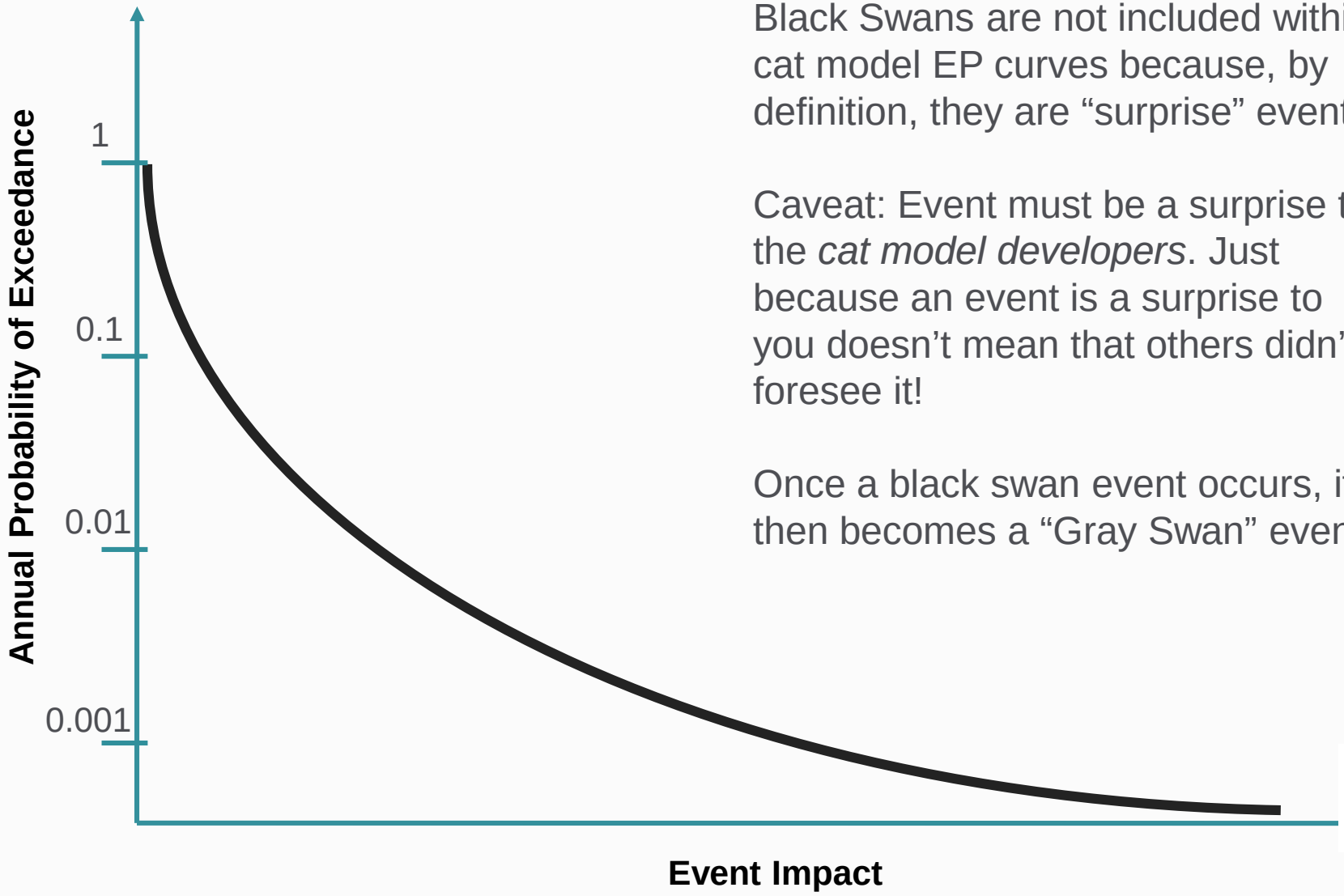
- The term “black swan” is a metaphor that describes an event that comes as a surprise, has major impacts, and is often inappropriately rationalized after the fact with the benefit of hindsight.
- The theory was developed by Nassim Nicholas Taleb in his 2007 book, which describes:
  - The disproportionate role of high-profile, hard-to-predict, and rare events that are beyond the realm of normal expectations in history, science, finance, and technology.
  - The non-computability of the probability of the consequential rare events using scientific methods (owing to the very nature of small probabilities).
  - The psychological biases that blind people, both individually and collectively, to uncertainty and to a rare event's massive role in historical affairs.


A Black Swan Event:
Tōhoku Earthquake & Tsunami
11 March 2011
Photo: U.S. Navy

Background
Black Swan Events & the EP Curve

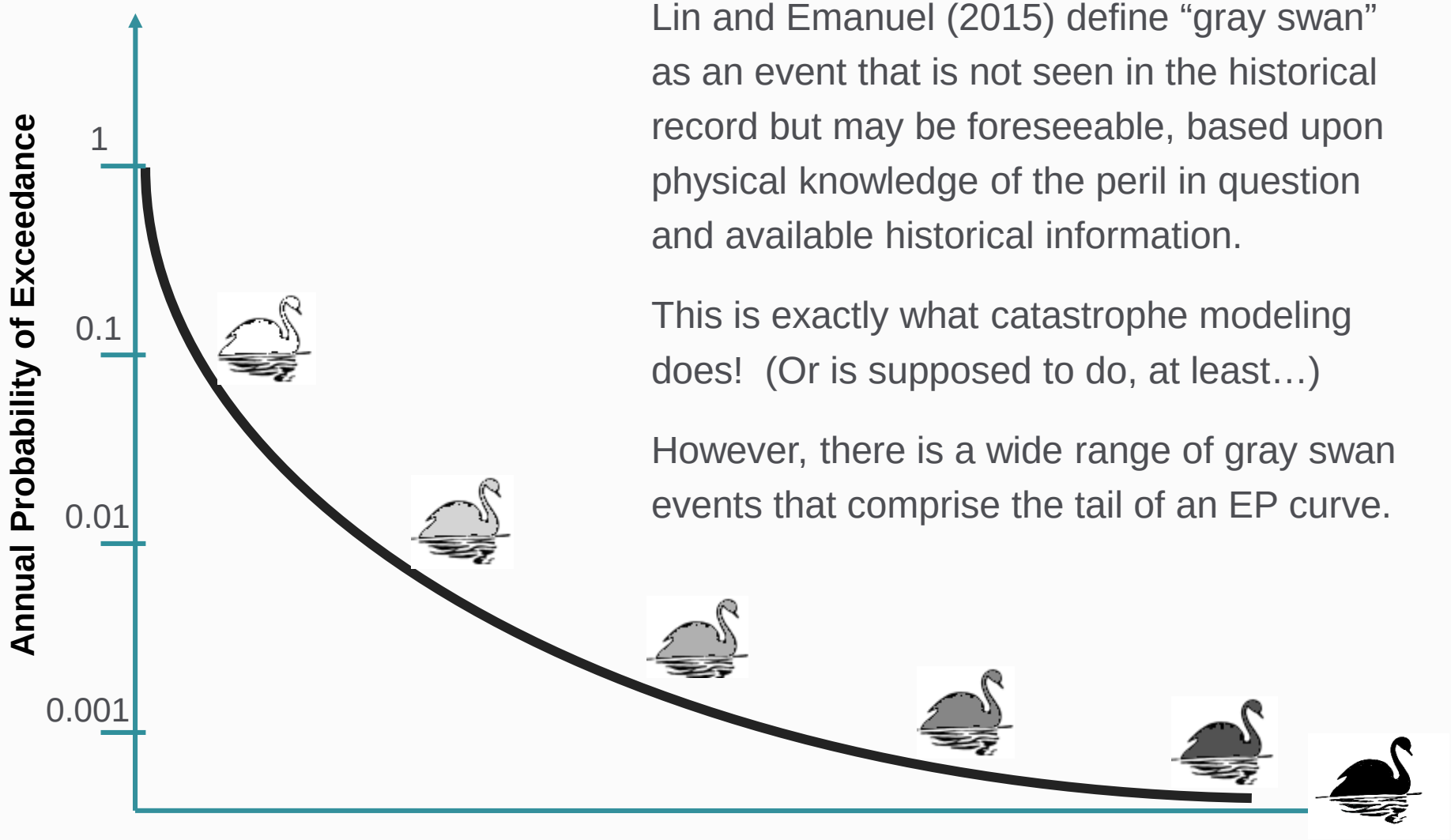


Black Swans are not included within cat model EP curves because, by definition, they are “surprise” events.

Caveat: Event must be a surprise to the *cat model developers*. Just because an event is a surprise to you doesn’t mean that others didn’t foresee it!

Once a black swan event occurs, it then becomes a “Gray Swan” event.

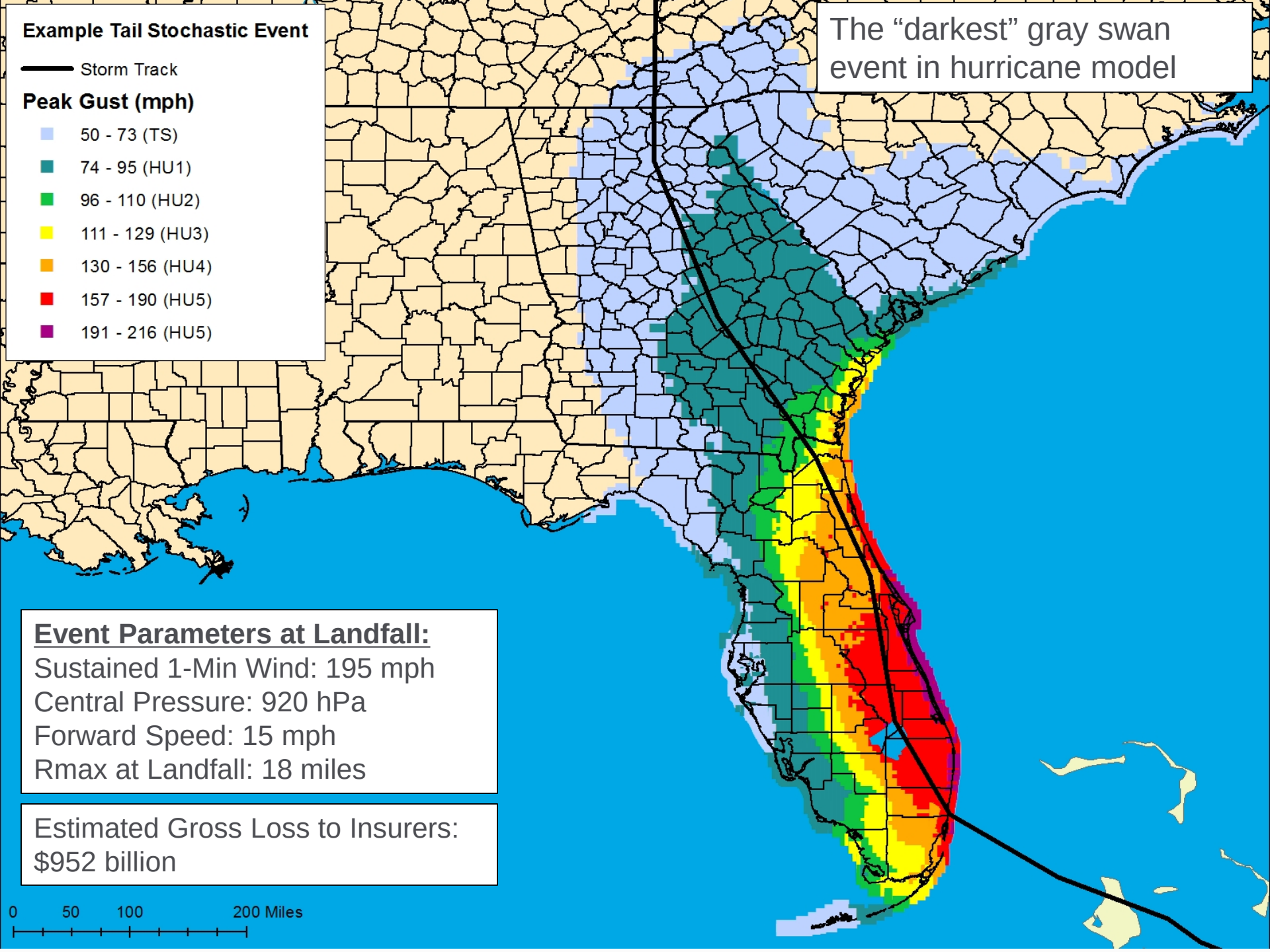
Background
What are “Gray Swan” Events?



Lin and Emanuel (2015) define “gray swan” as an event that is not seen in the historical record but may be foreseeable, based upon physical knowledge of the peril in question and available historical information.

This is exactly what catastrophe modeling does! (Or is supposed to do, at least…)

However, there is a wide range of gray swan events that comprise the tail of an EP curve.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The “darkest” gray swan event in hurricane model
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Estimated Gross Loss to Insurers: $952 billion
0
50
100
200 Miles

Background
Narrowing Today's Discussion

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- The (re)insurance industry manages their natural catastrophe exposures to some point in the tail of the EP curve, usually well within the realm of "gray swan" events.
- **Question: How realistic are gray swan events within catastrophe models, based upon our understanding of our physical knowledge of the peril in question and available historical information?**
- This presentation will focus on answering this question, from a meteorological perspective, for the peril of tropical cyclone, with a focus on south Florida.
    - What should a 100-year tropical cyclone look like in south Florida?
    - A 250-year TC? 500-year? 1,000-year? The darkest gray swan event?
- Note: Return periods / exceedance probabilities in this presentation refer to the meteorological return period. This presentation will not focus on the exceedance probabilities / return periods of (re)insurance losses, which are dependent on dozens of socio-economic variables.

The Meteorology of Extreme Tropical Cyclones

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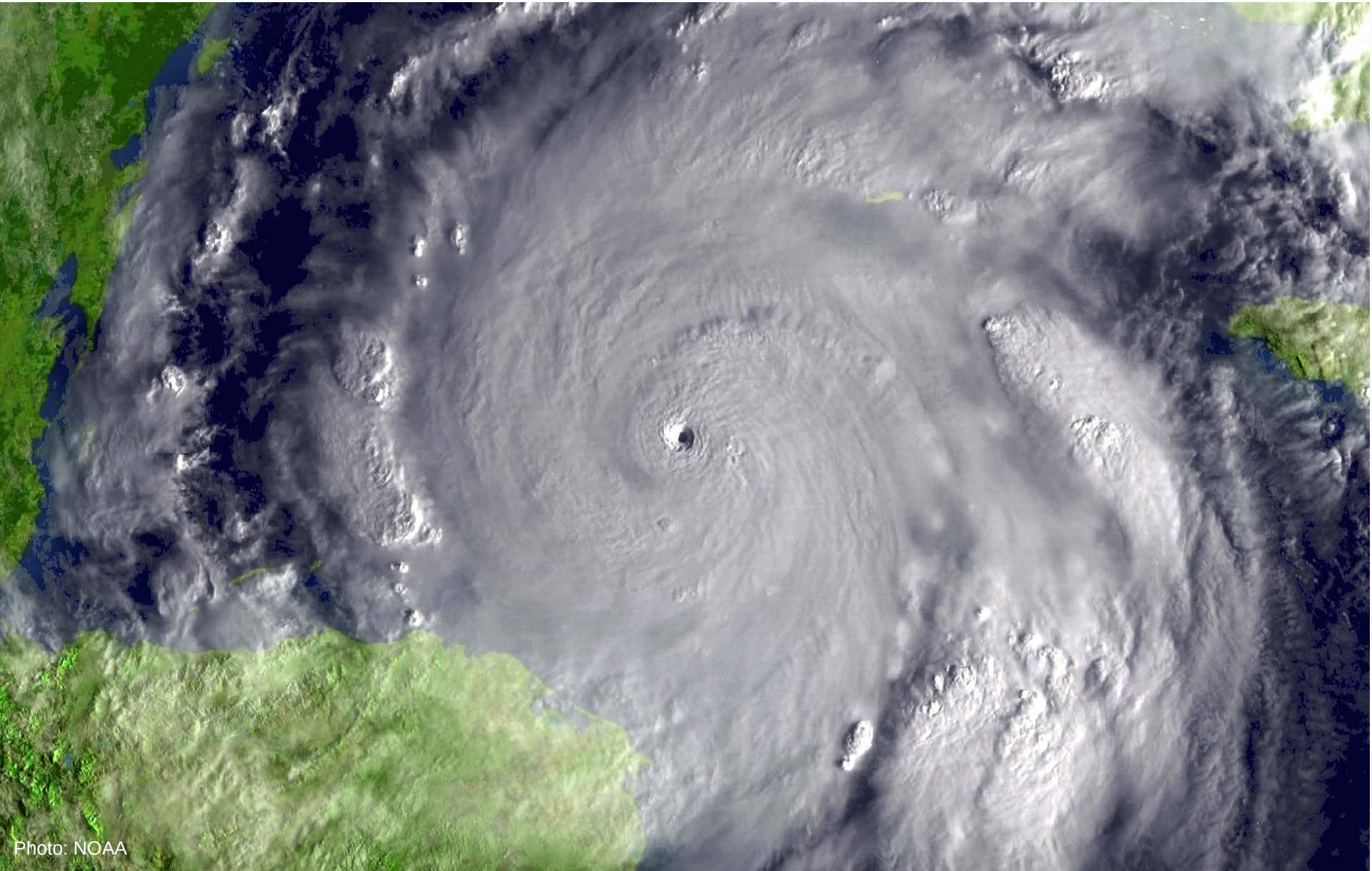

Photo: NOAA

The Meteorology of Extreme Tropical Cyclones
The Elusive Category 5 Hurricane

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- This first Saffir-Simpson Category 5 hurricane in the Atlantic Basin historical record is the “Cuba” Hurricane of October 1924.
- Including the “Cuba” Hurricane of 1924, there have been only 33 Category 5 hurricanes observed in the Atlantic.
- Over the period 1924 – 2015 (92 years):
    - Implied basinwide annual frequency of one per ~3.7 years
    - Implied basinwide annual rate of one per ~2.8 years
    - 806,472 hours elapsed over this period. Cat 5 hurricanes existed in the Atlantic for only 760 of those hours, less than 0.1% of the total.
- Longest gap between Cat 5 hurricanes: 15 Years (1939-1953)*, 2 at 8 years (1980-1988; 2007 – Present).

* - Wartime; Pre-Reconnaissance & Satellite Era

The Meteorology of Extreme Tropical Cyclones
Hurricane Structure

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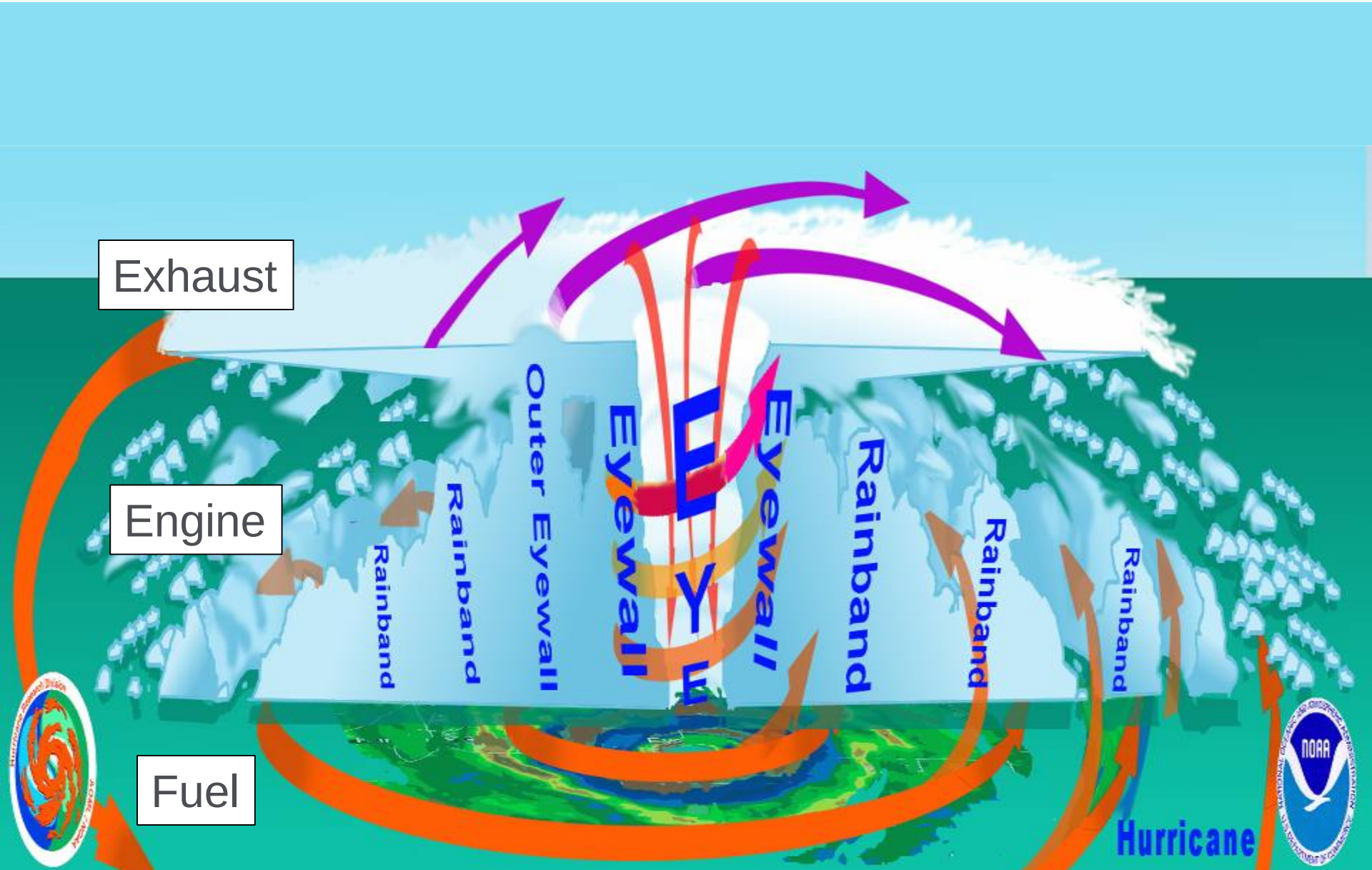
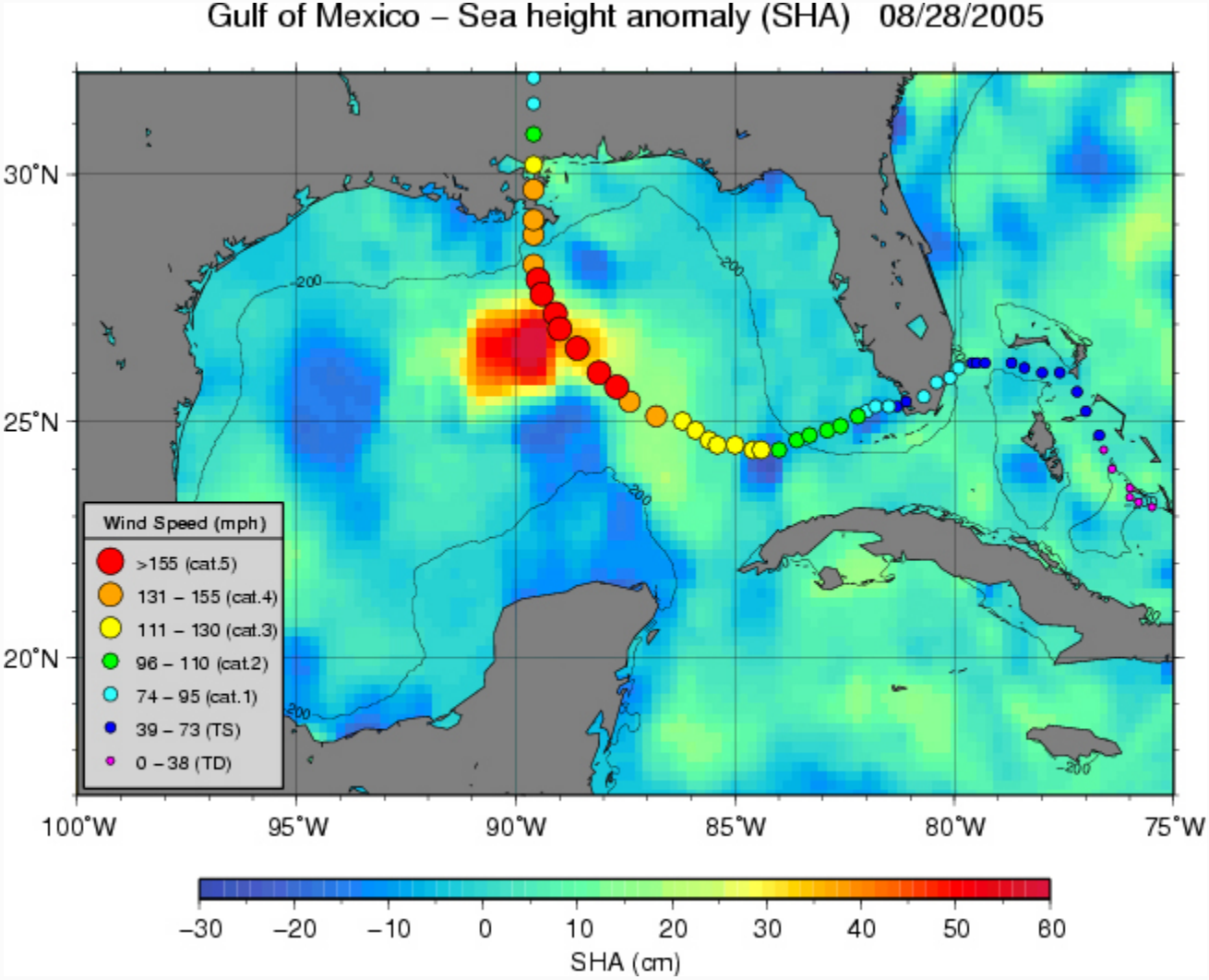
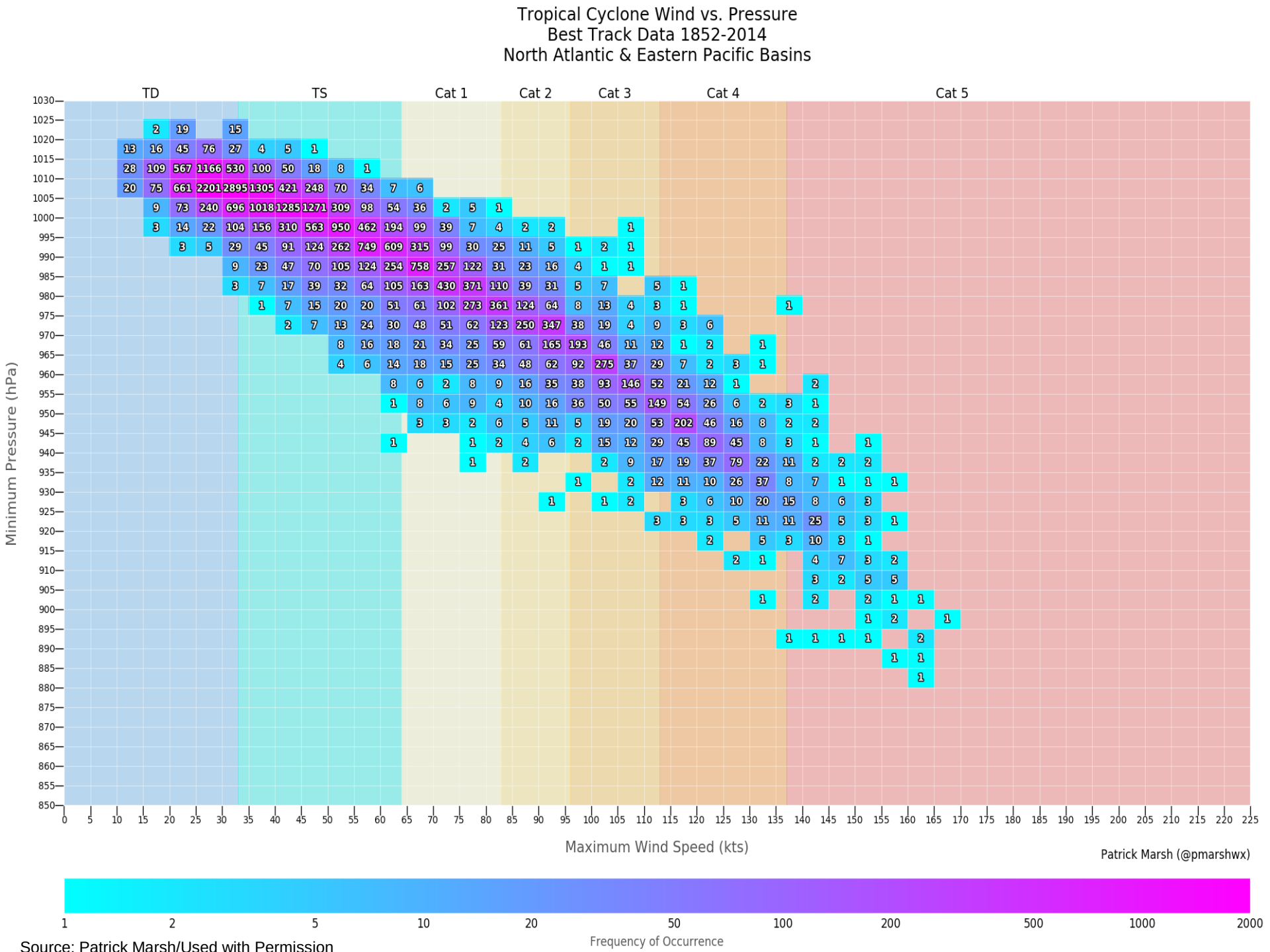




Sea Height Anomalies in Gulf of Mexico on 28 August 2005, day of Katrina Peak Intensity.



Source: Patrick Marsh/Used with Permission

The Meteorology of Extreme Tropical Cyclones
Theoretical Maximum Potential Intensity (MPI)

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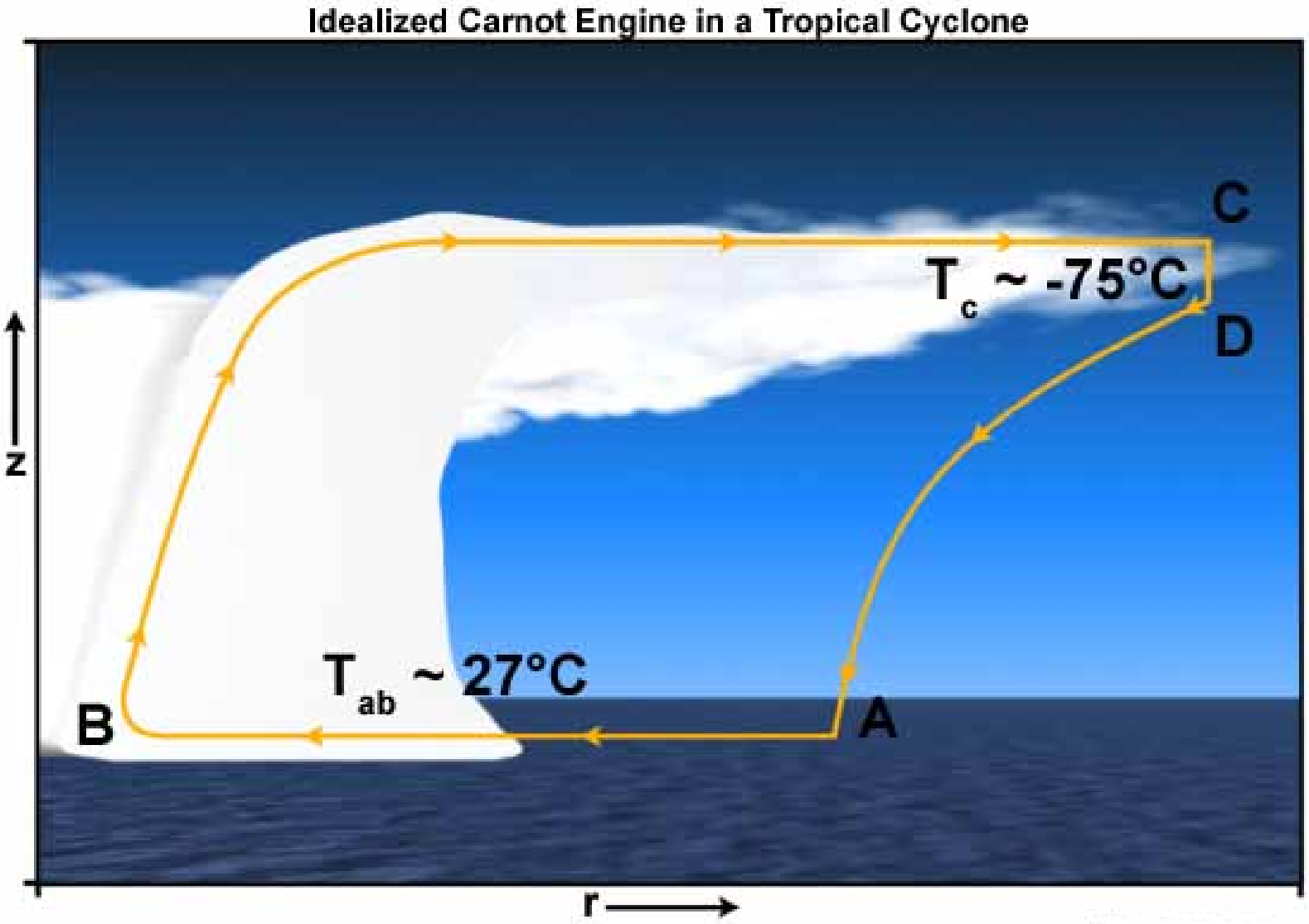
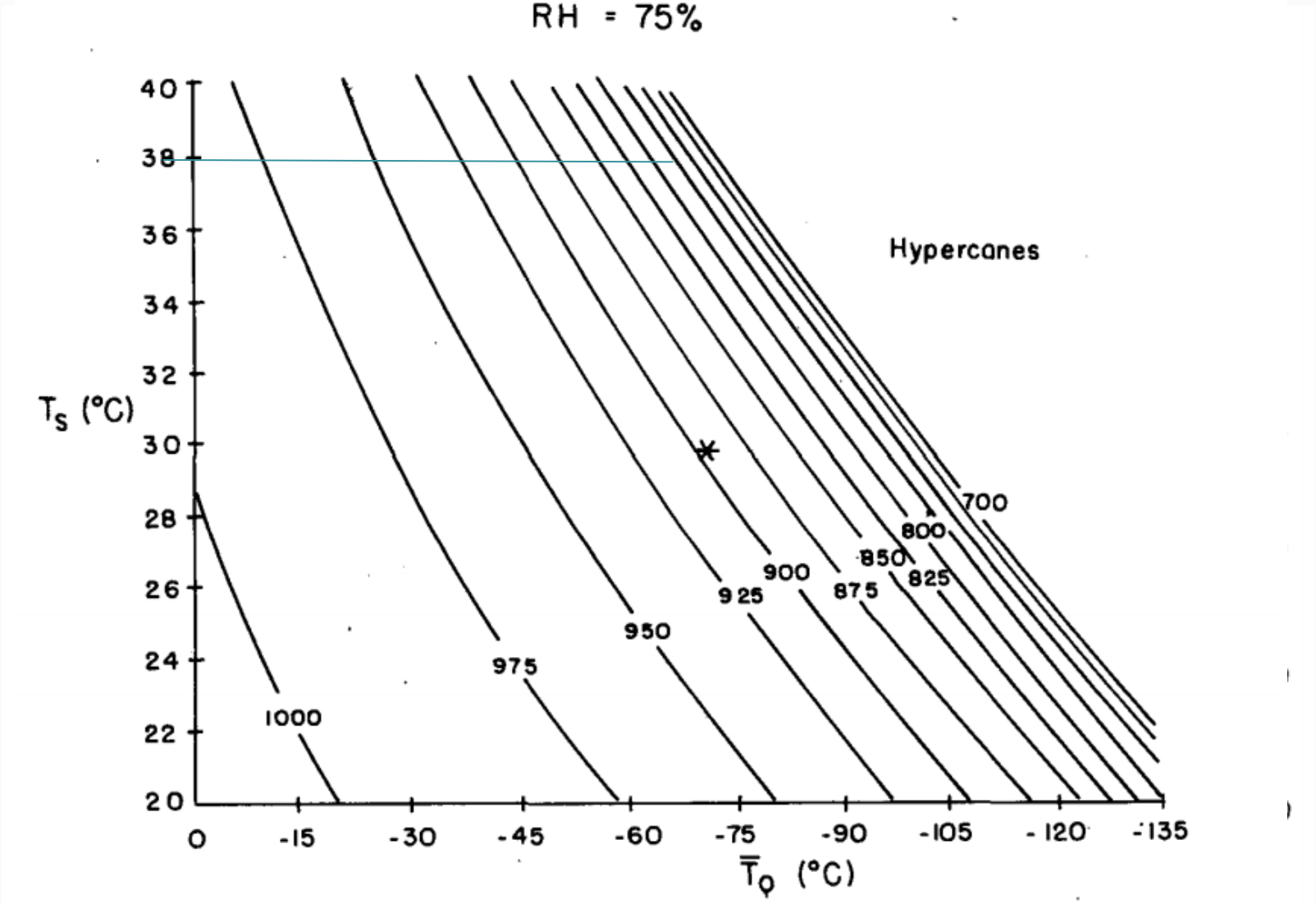


Source: NOAA.

The Meteorology of Extreme Tropical Cyclones
Theoretical MPI



Sources: Emanuel, K.A., 1988: The maximum intensity of hurricanes. *J. Atmos. Sci.*, **45**, 1143-1155.
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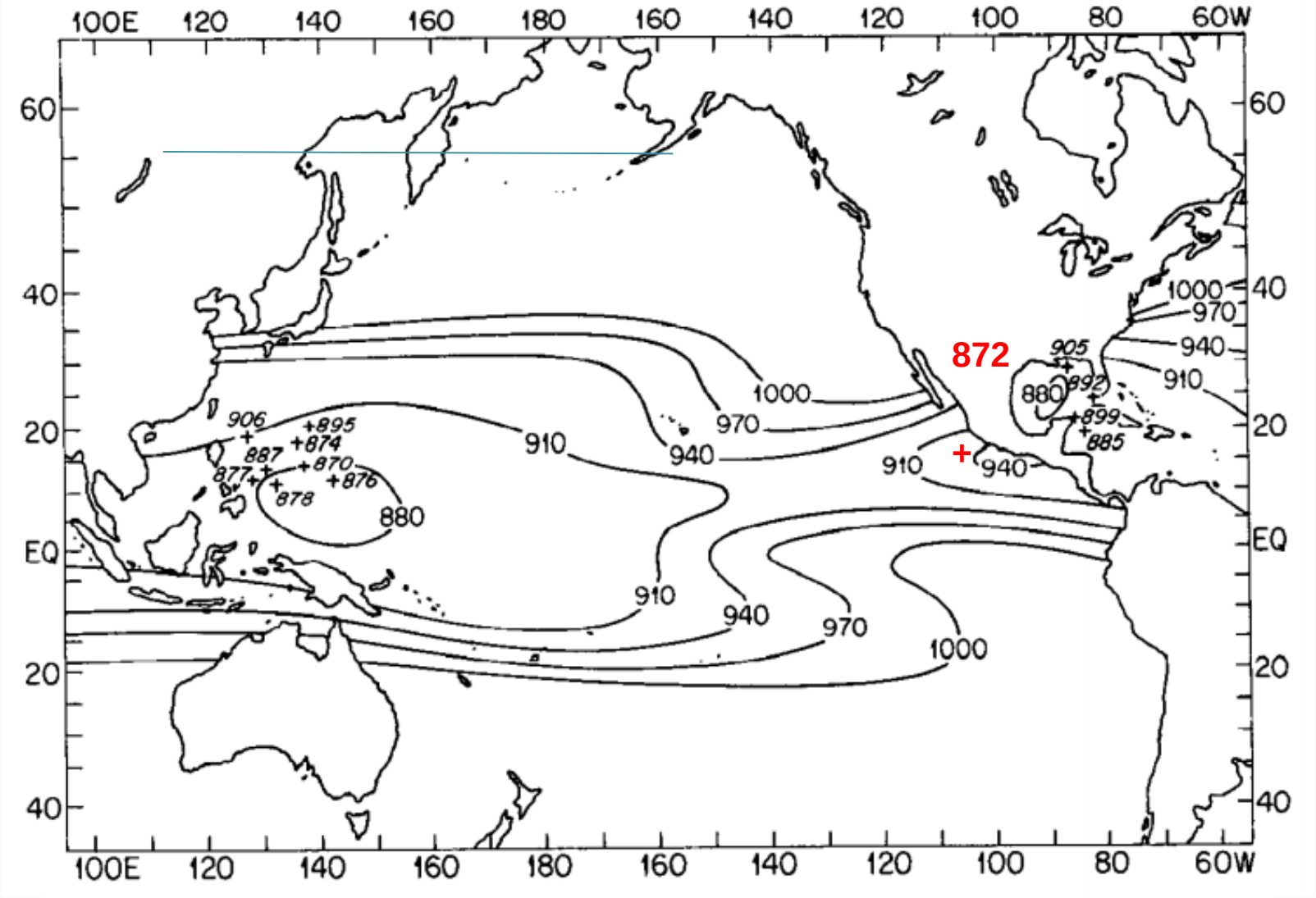
The Meteorology of Extreme Tropical Cyclones
Theoretical MPI



Sources: Emanuel, K.A., 1988: The maximum intensity of hurricanes. *J. Atmos. Sci.*, **45**, 1143-1155.
Emanuel, K.A., 1991: The theory of hurricanes. *Annual Rev. Fluid Mech.,* **23**, 179-196.

The Meteorology of Extreme Tropical Cyclones
Limitations of Theoretical MPI

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- The earliest MPI studies assumed a steady-state, axisymmetric tropical cyclone acting as a closed system, an idealized state that will never occur in nature.
- Other factors that likely impact MPI are:
  - Surface Heat and Momentum Exchange
  - Frictional Dissipative Heating
  - Eyewall & Boundary Layer Turbulent Mixing
  - Eyewall Thermodynamics
  - Outflow Boundary Conditions
- We shouldn’t consider theoretical MPI as an absolute limit, but it serves as a decent guide as to the limits of storm intensification.

The Meteorology of Extreme Tropical Cyclones
Cat 5 TCs & Other Storm Characteristics

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Parameter	Global	Atlantic Basin
Gale Diameter	1,380 miles (Tip, NW PAC, 1979)	945 Miles (Sandy, 2012)
Largest Radius of Maximum Winds	115 miles (Carmen, NW PAC, 1974)	40 Miles (Frances, 2004)
Smallest Radius of Maximum Winds	2.3 miles (Wilma, NATL, 2005)	2.3 miles (Wilma, 2005)
Forward Speed	~70 mph (NATL, Multiple)	~70 mph (Multiple)

The Meteorology of Extreme Tropical Cyclones
Eyewall Diameter at Peak Intensity

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The average eyewall diameter in a tropical cyclone is about 20-40 miles.

The eyewalls of extreme tropical cyclones at peak intensity tend to be much smaller, especially in the cases of rapid intensification.

There are a few exceptions, however…

Storm	Eyewall Diameter
Gilbert	15 miles
Hugo	8 miles
Andrew	22 miles
Mitch	24 miles
Isabel	30-40 miles
Ivan	20 miles
Emily	13 miles
Katrina	50-60 miles
Rita	16 miles
Wilma	5 miles
Dean	25 miles
Felix	12 miles

The Meteorology of Extreme Tropical Cyclones
Gale Diameter / Hurricane Force Diameter

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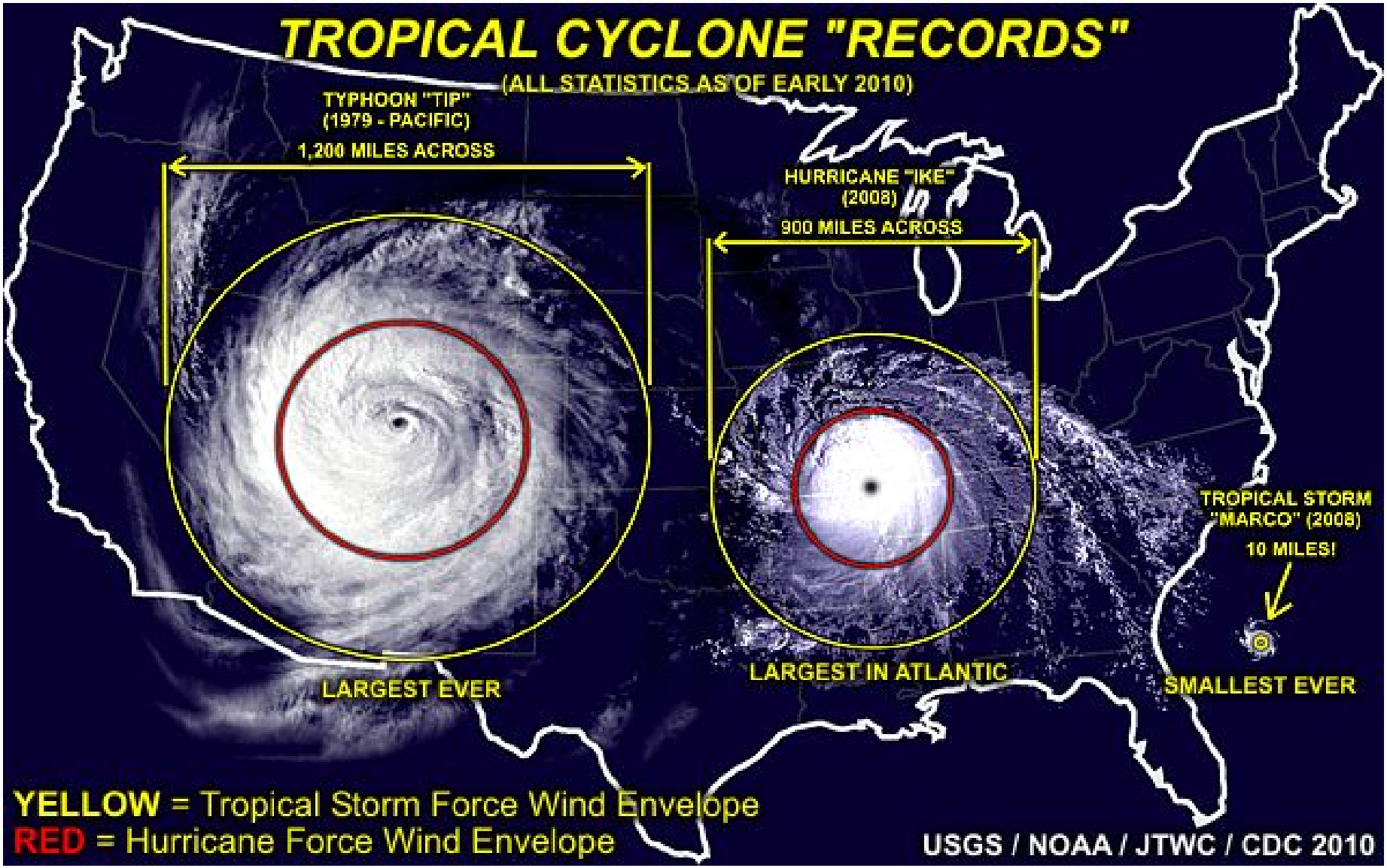
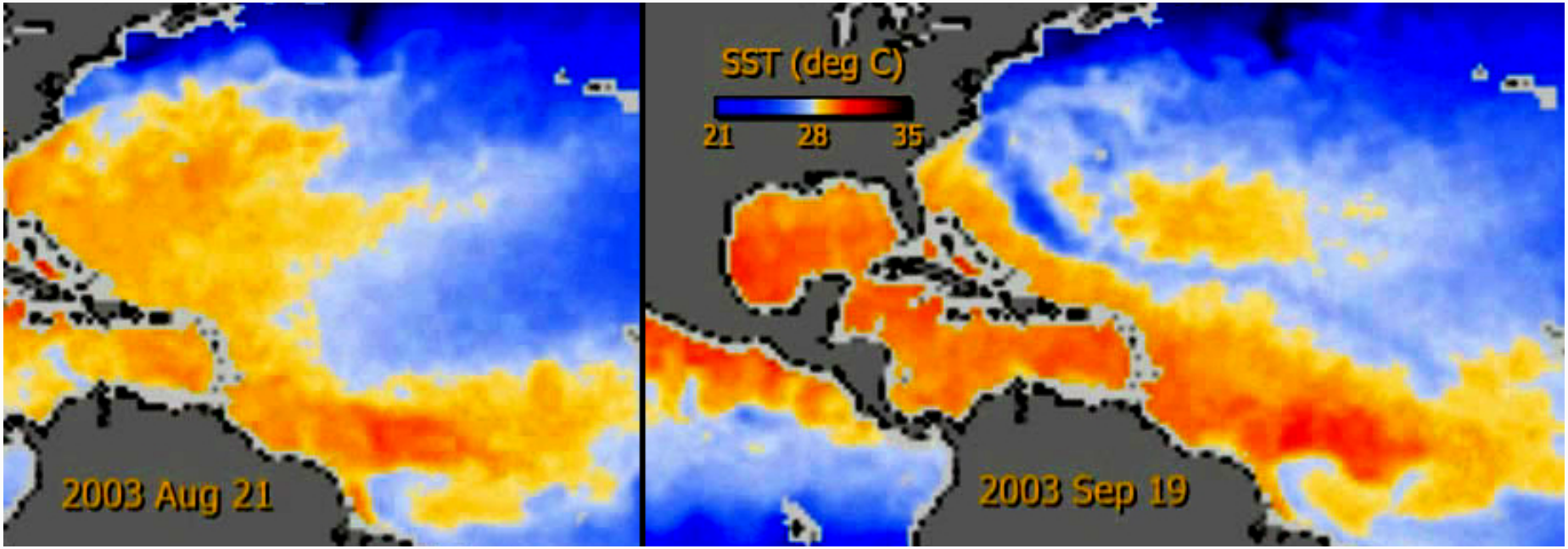


The Meteorology of Extreme Tropical Cyclones
Forward Motion



The amount of energy an intense tropical cyclone needs to develop and maintain itself is enormous.

If it moves too slowly, heat fluxes and upwelling will cool the down the ocean underneath it, reducing the energy available.

If it moves too quickly, shear impacts on the vertical structure of the hurricane will likely cause weakening.

Source: NOAA.

Gray Swan Tropical Cyclone Events in South Florida

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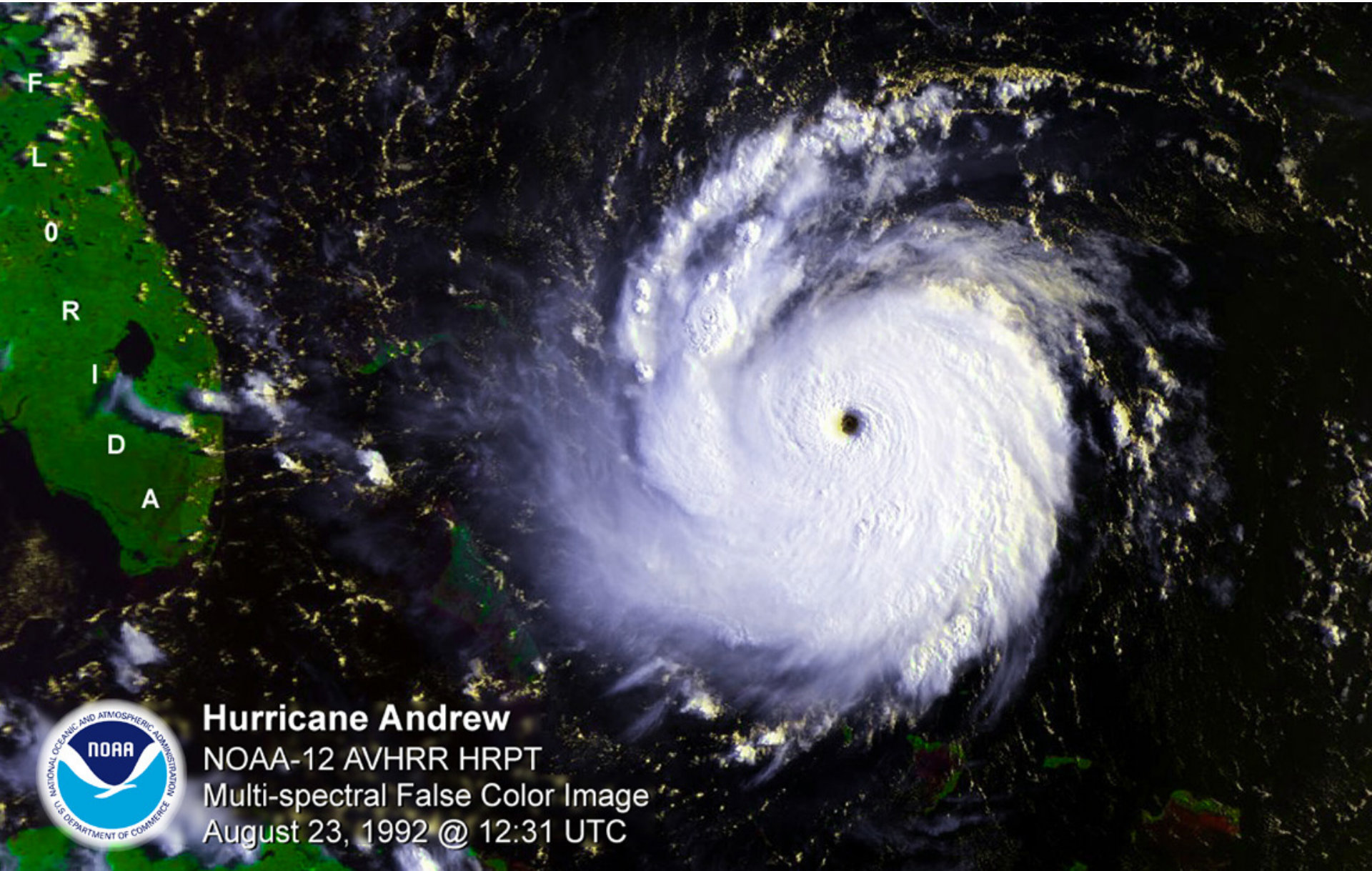

Gray Swan TC Events in South Florida
1900 – 2015 Empirical Return Period vs Area

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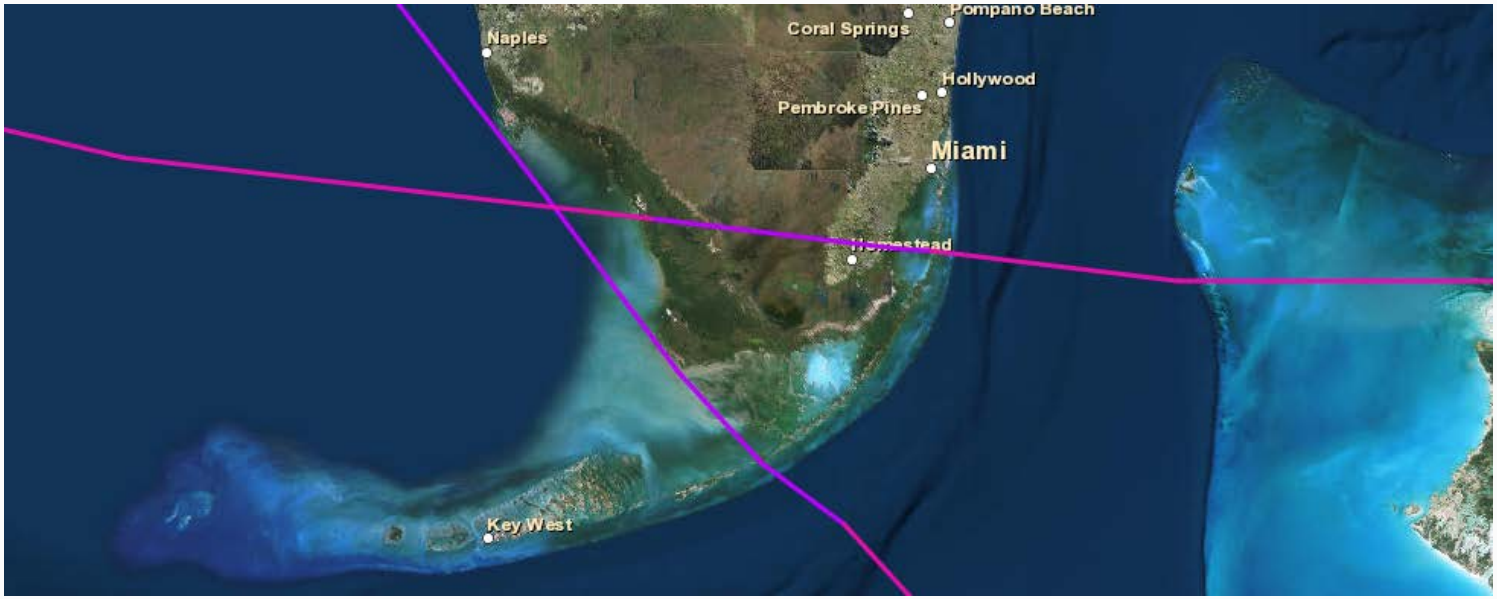
Search Radius @ Miami	Cat 4 Hurricane	Cat 5 Hurricane
50 km	29 Years (4)	116 Years (1)
100 km	19 Years (6)	116 Years (1)
150 km	12 Years (10)	68 Years (2)



Source: NOAA.

Gray Swan TC Events in South Florida

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Sustained
1-min wind over water


1,000

151 kts
(174 mph)


500

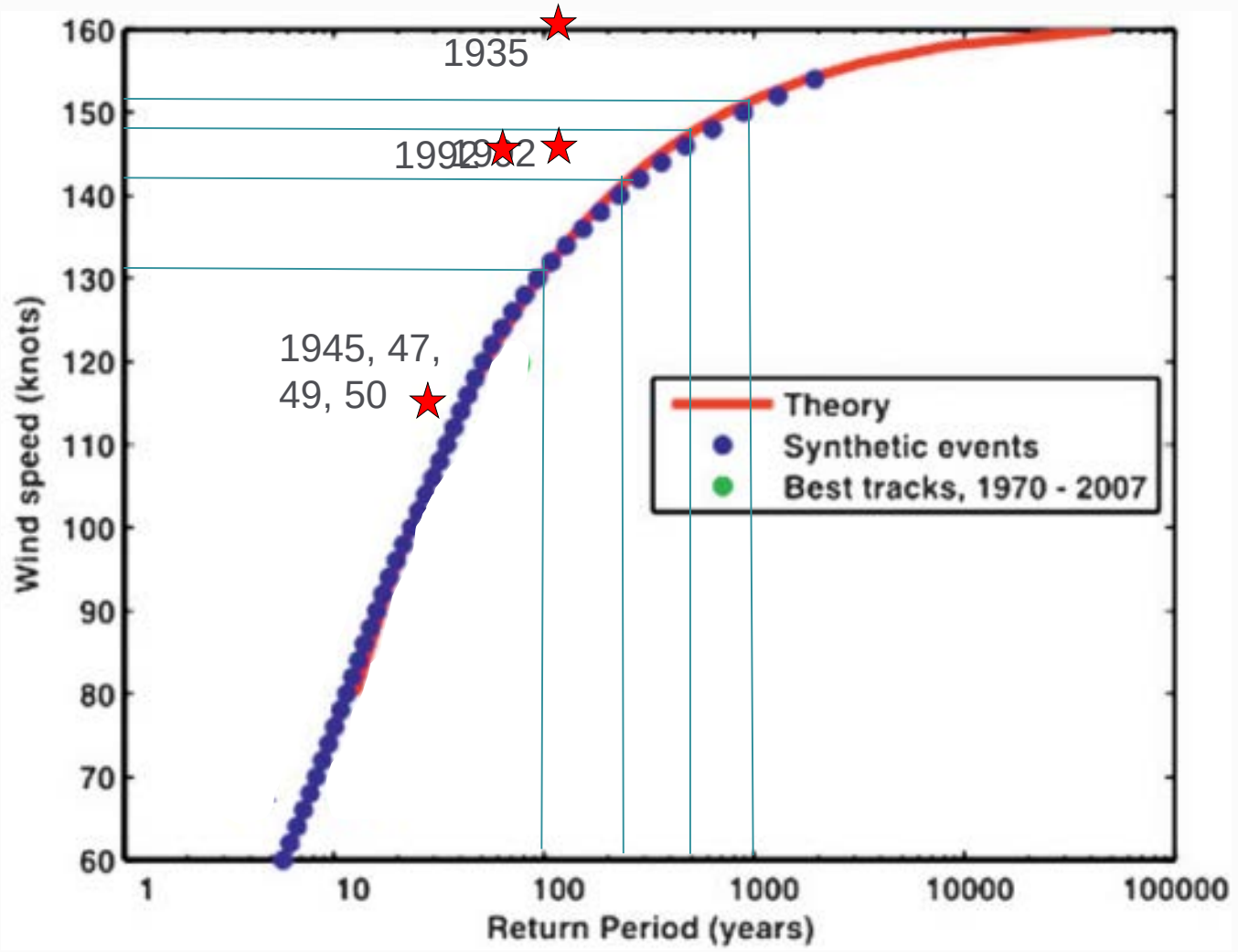
148 kts
(170 mph)


250

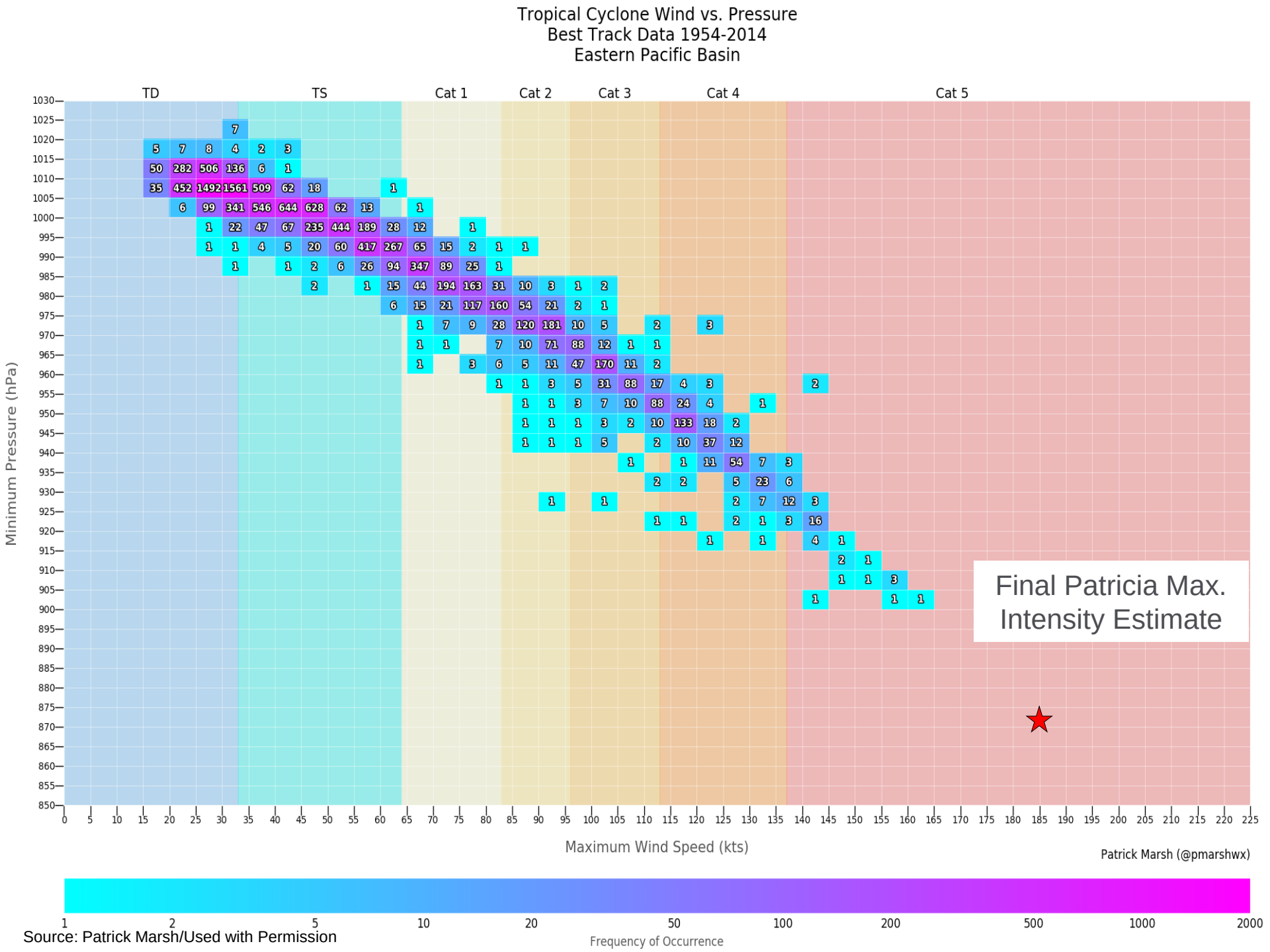
142 kts
(163 mph)


100

131 kts
(150 mph)



Source: Emanuel, K., and T. Jagger, 2010: On estimating hurricane return periods. *J. Appl. Meteor. Clim.*, **49**, 837-844.



Source: Patrick Marsh/Used with Permission

Gray Swan TC Events in South Florida
Learning from Hurricane Patricia

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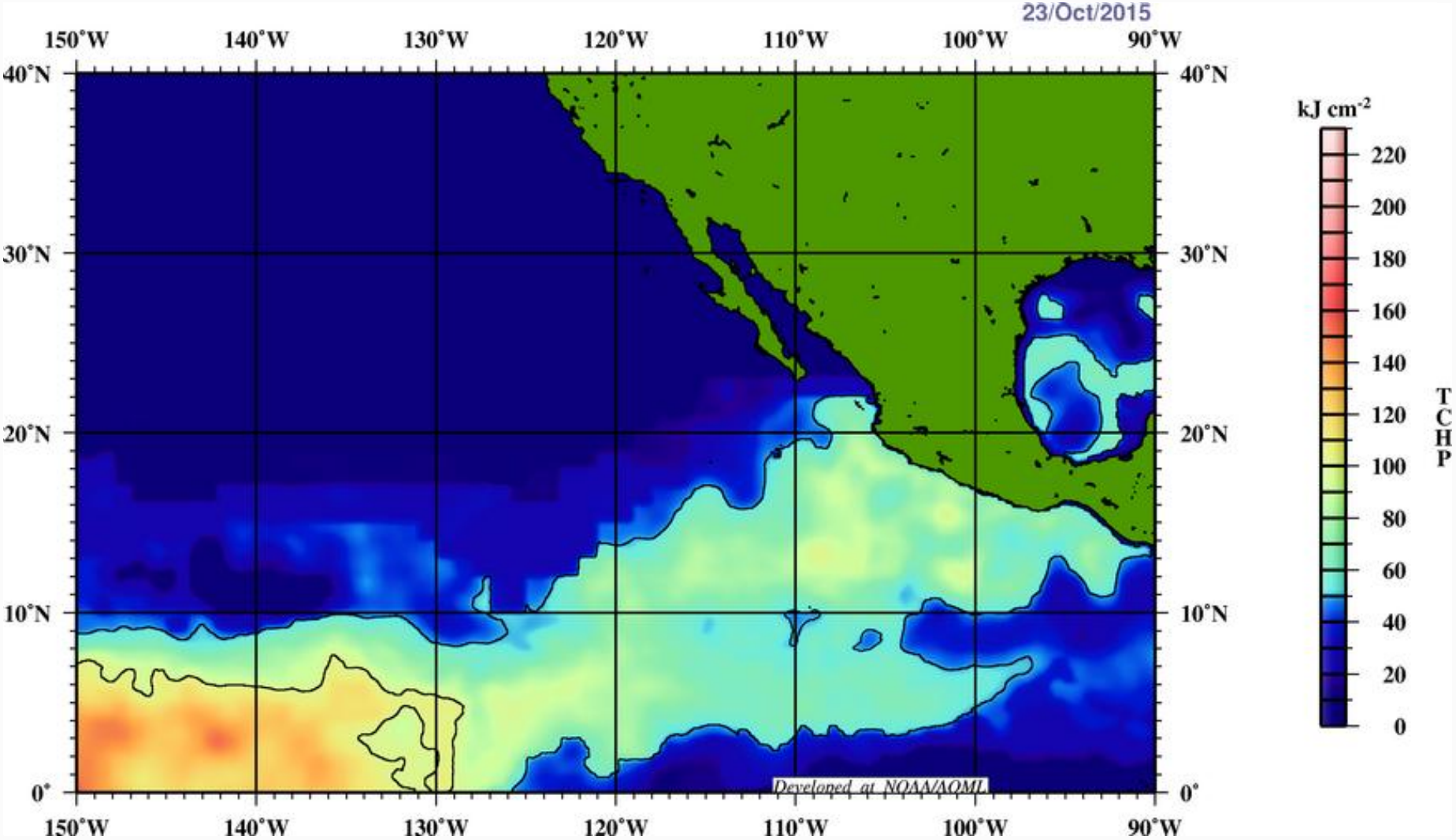

Source: NOAA.

Gray Swan TC Events in South Florida
Learning from Hurricane Patricia

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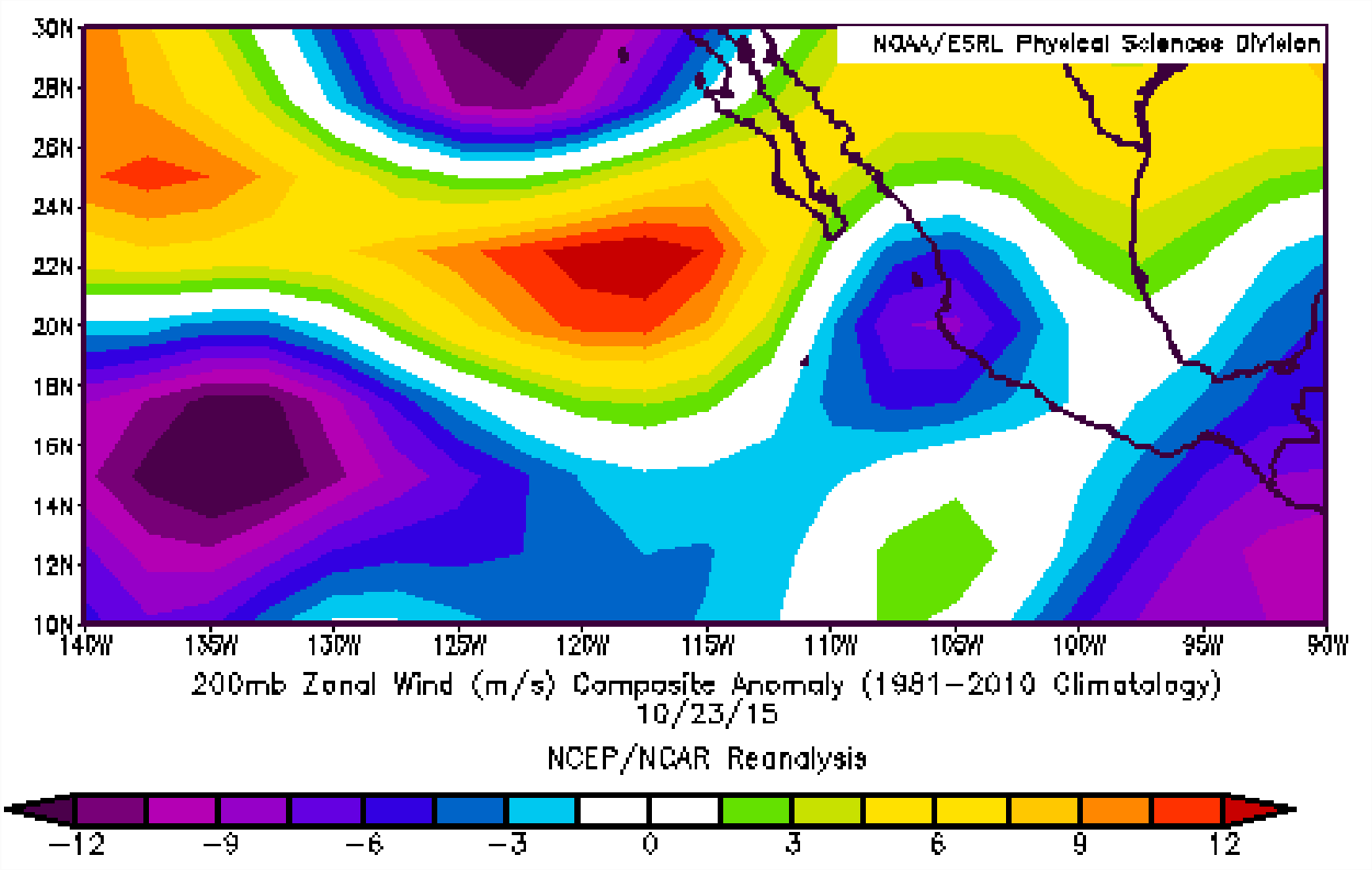

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Gray Swan TC Events in South Florida
Learning from Hurricane Patricia

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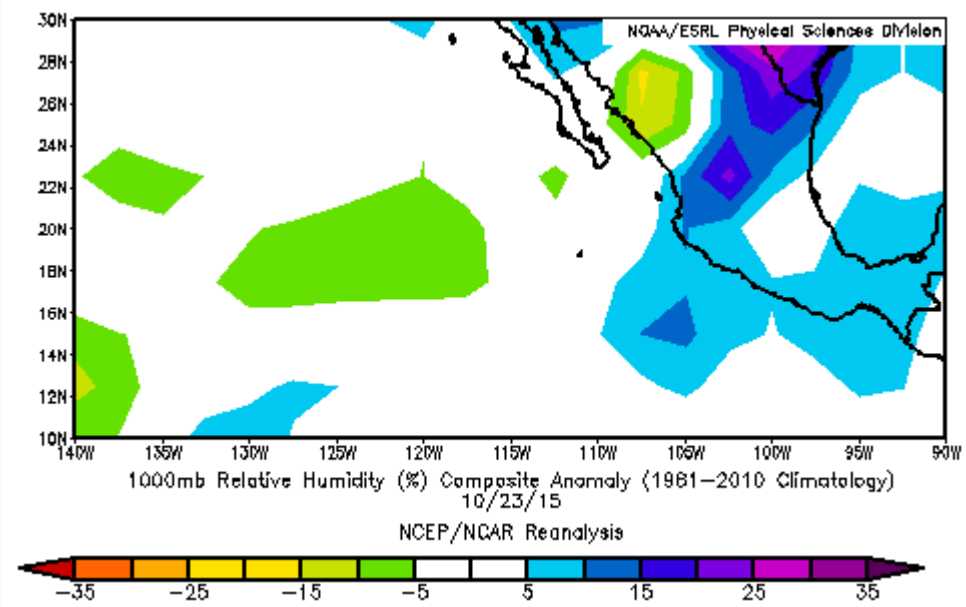
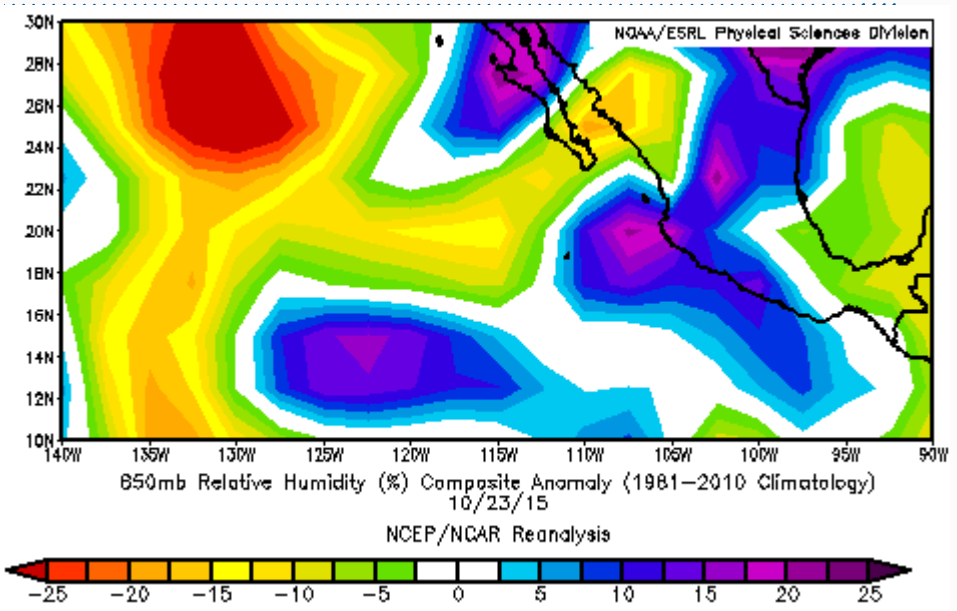
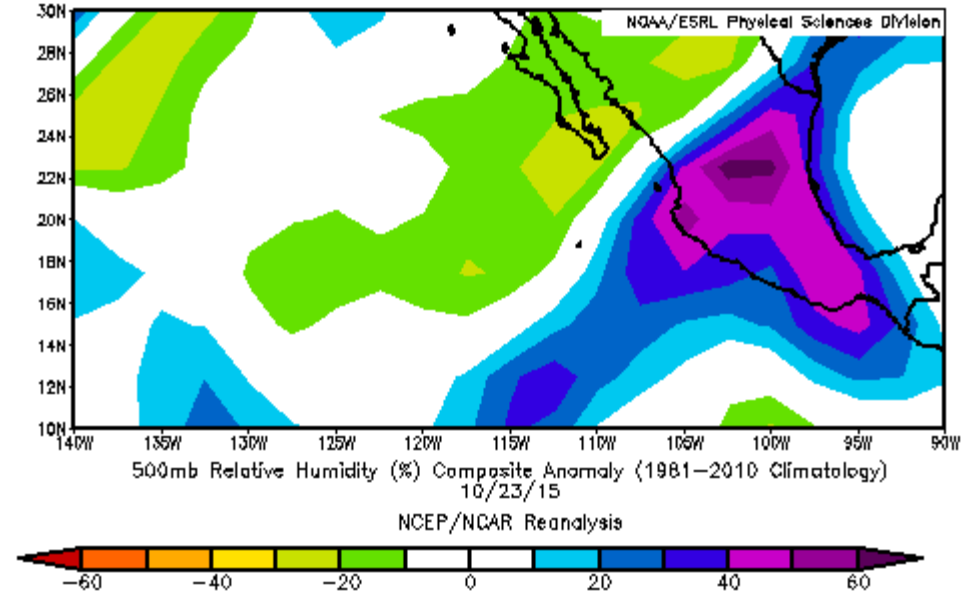
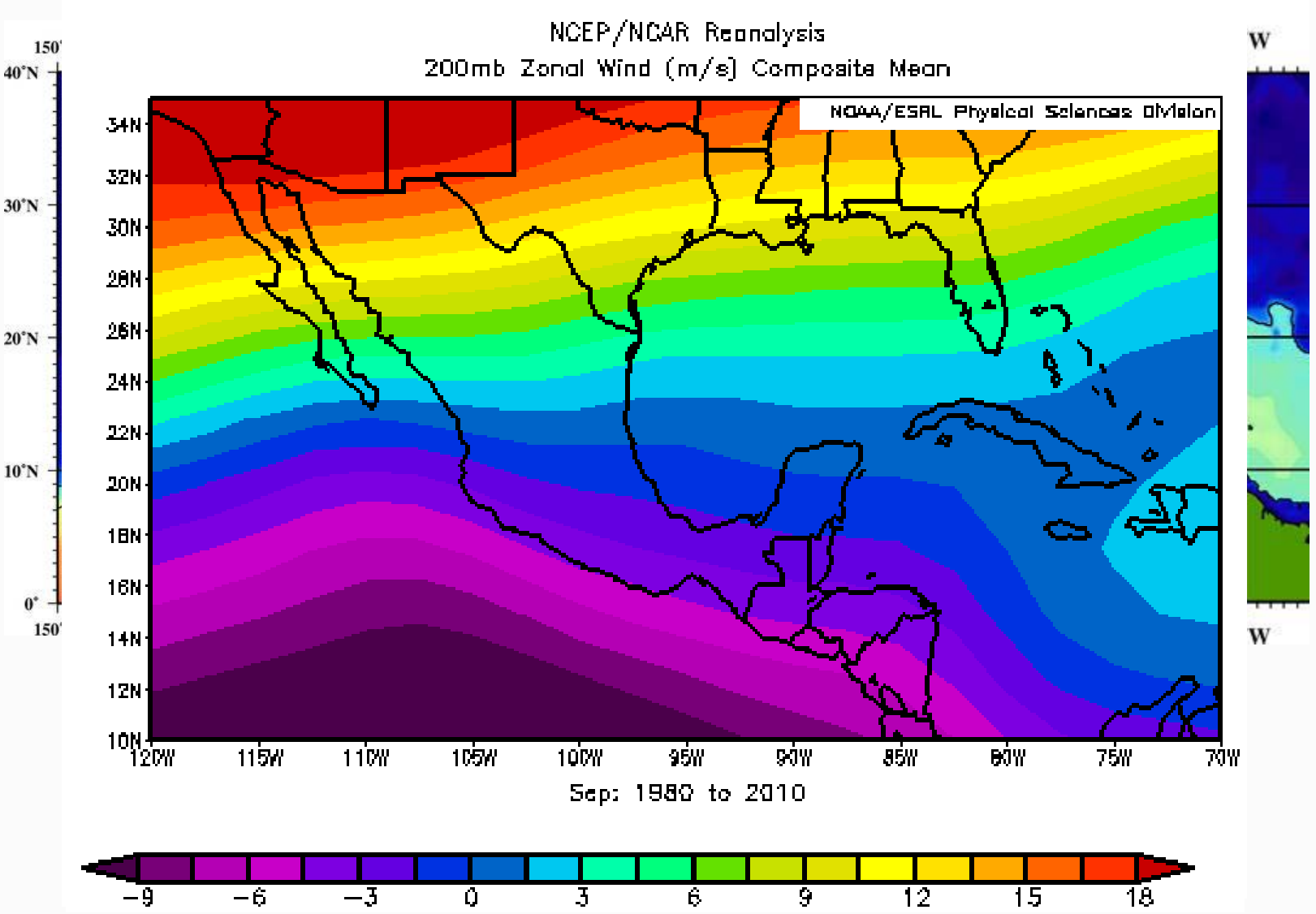






Source: NOAA.

Gray Swan TC Events in South Florida
Mean Conditions: SW Mexico vs. South Florida



Source: NOAA.

Gray Swan TC Events in South Florida
Some Educated Guesses

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- With two Category 5 landfalls in region (160 kts, 145 kts) over past 116 years; 100 year RP intensity probably lies within this range.
- For higher return period gray swan events, ΔV_{max} will decrease quickly as we approach theoretical limits.
  - From an insurance & vulnerability standpoint – is there really much difference in impacts between these intensities?
  - In the tail, other storm parameters will have a bigger impact on its exceedance probability / return period, such as Rmax, Forward Motion, Hurricane Force Wind Radii.
- From meteorological viewpoint, extreme gray swans are likely “pinhole eye” type storms. However, from insured perspective, “Annular” Hurricanes may drive tail loss.

Sustained
1-min wind (over water)

100 Year:
~155 knots
(178 mph)

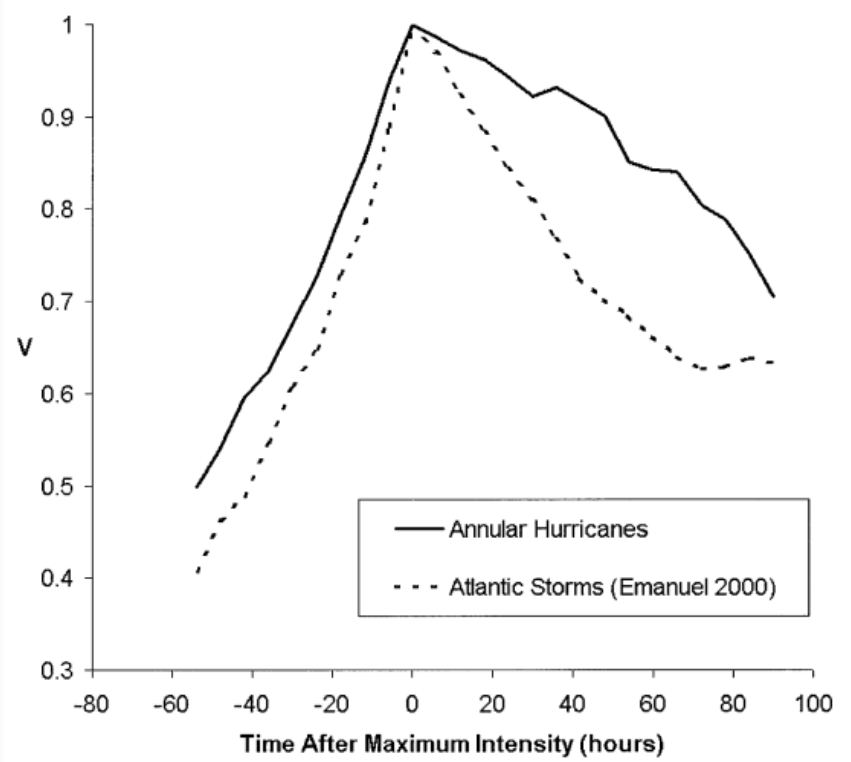
250 Year:
~166 knots
(190 mph)

500 Year:
~172 knots
(198 mph)

1,000 Year:
~175 knots
(201 mph)

Gray Swan TC Events in South Florida
What is an Annular Hurricane?

- Average or above average eyewall size.
- Eye completely surrounded by deep convection
- No convection outside of central dense overcast.
- Tends to maintain intensity longer in open ocean, warm water conditions.



Source: Knaff J. A., Kossin, J. P., and M. DeMaria, 2003: Annular Hurricanes. *Weather and Forecasting,* **18**, 204-223.

Source: NOAA.

Evaluating Gray Swan Events in Statistical Peril Models

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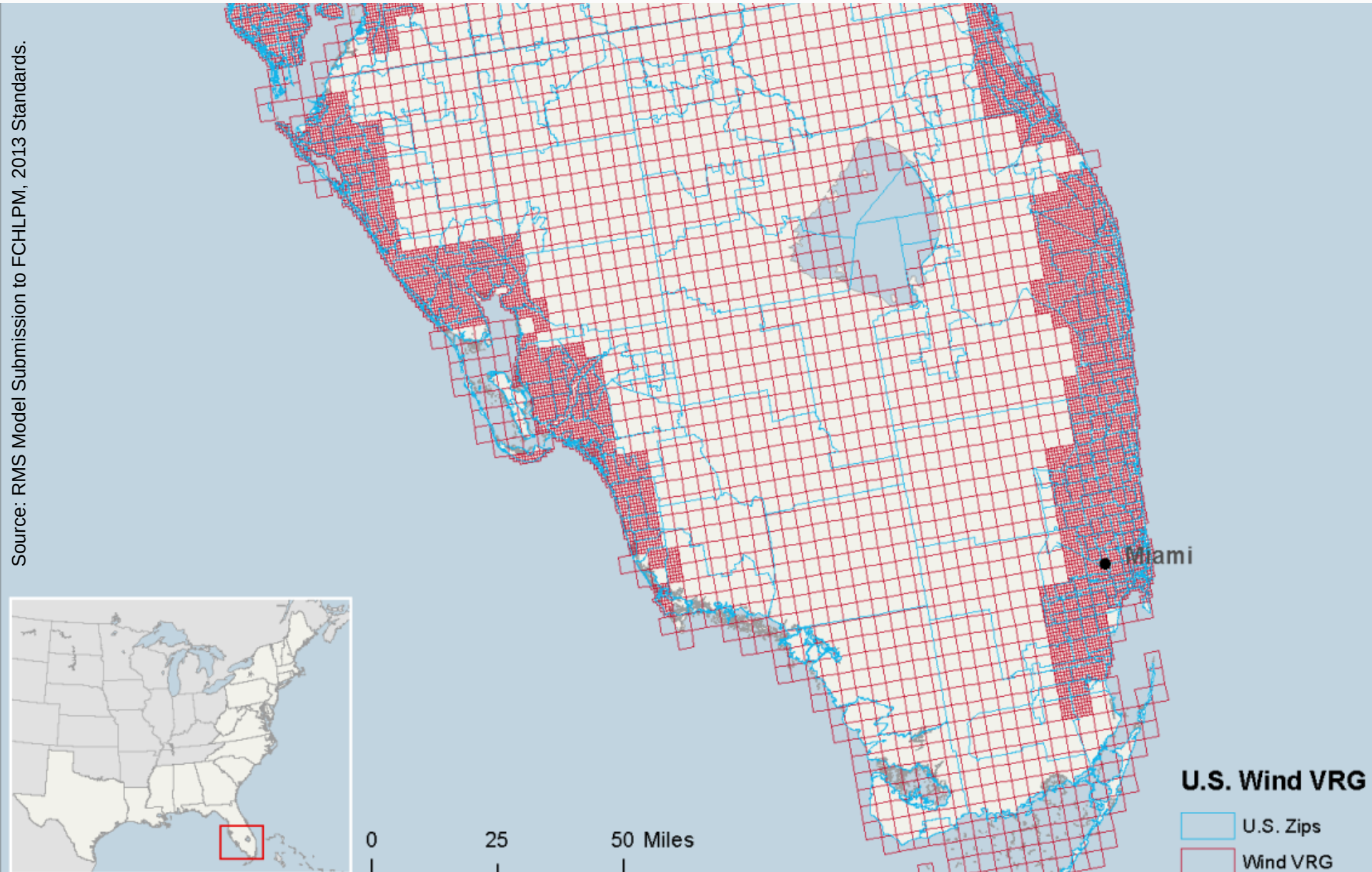

Evaluating Gray Swan Events in Statistical Peril Models
Some Pre-emptive Caveats

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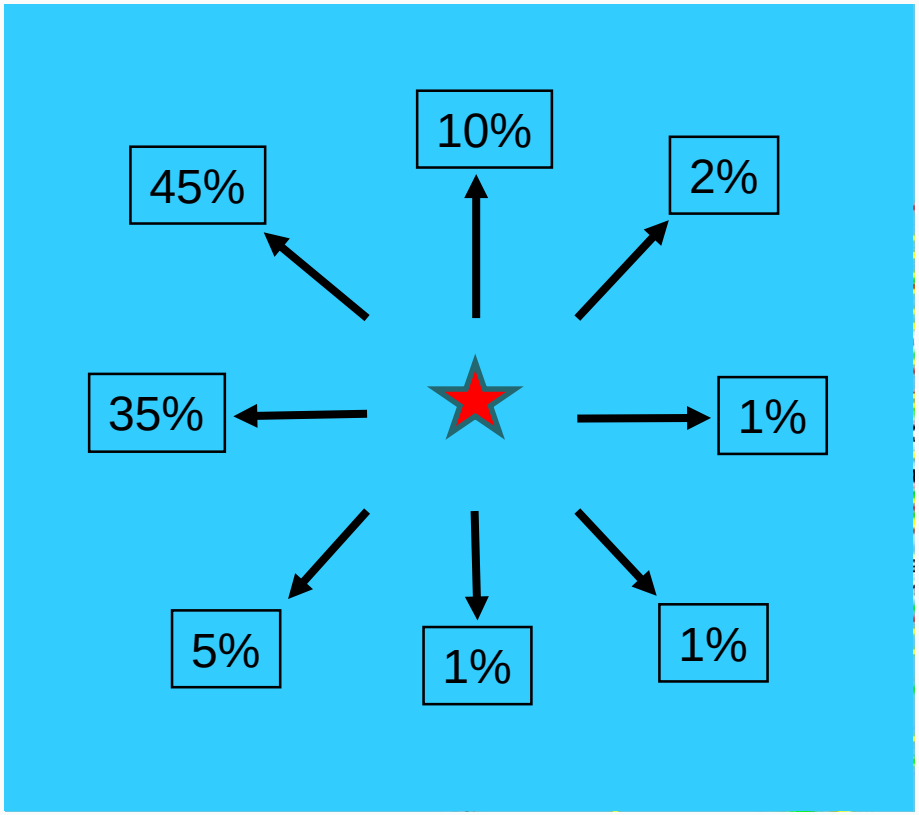
- All catastrophe models are wrong!
- Overall, catastrophe modelers do an excellent job at generating realistic event sets for the peril of hurricane.
- Due to limited data and modeling assumptions, there can be legitimate disagreements in modeler opinion regarding what gray swan events might look like. However, they should still be physically realistic.
- Model output shown in this section is publically available from the Florida Commission on Hurricane Loss Projection Methodology (FCHLPM).

Evaluating Gray Swan Events in Statistical Peril Models
Statistical Modeling (1)

- Most of the stochastic event sets our industry uses are generated by statistical models. This means that the characteristics of an event are based on a set of probability distributions, each representing a parameter of the peril in question.
- For the peril of tropical cyclone, this includes probability distributions for:
  - Genesis / Lysis
  - Storm Heading
  - Storm Forward Velocity
  - Central pressure
  - Maximum sustained winds
  - Radius of maximum winds
  - Post-landfall decay rates
  - Etc.

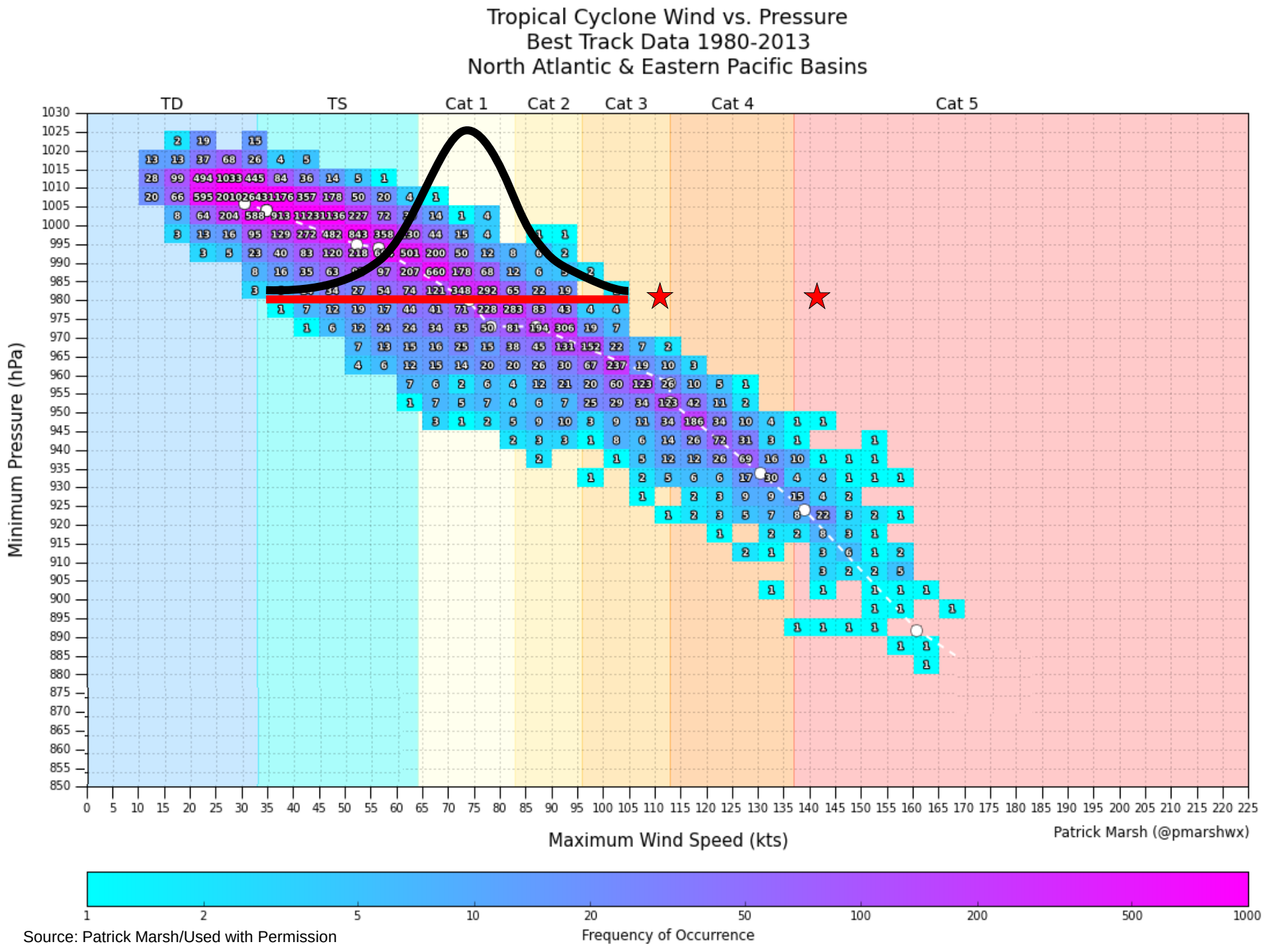


Source: NOAA.

Evaluating Gray Swan Events in Statistical Peril Models
Statistical Modeling (2)

- Unlike numerical models, statistical models **do not have any inherent physical understanding** of how a given peril behaves.
- This creates two questions that modelers must address when creating their stochastic event set:
  - Does the model correctly accurately represent the dependencies and correlations between two (or more) different parameters?
  - Does each parameter's probability distribution function in the model correctly represents all possible states that could occur in reality?

Photo: NASA



Source: Patrick Marsh/Used with Permission

Evaluating Gray Swan Events in Statistical Peril Models
100-Year & 250-Year Gray Swan Events

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Model	A	B	C	D	E
Max Historical	145 mph	154 mph	133 mph	155 mph	177 mph
Max 100-Year	116 mph	120 mph	110 mph	129 mph	139 mph
Max 250-year	127 mph	136 mph	117 mph	140 mph	156 mph

- All values are 1-minute sustained winds, assuming **open terrain** conditions.
- * Max observed historical is 1935 Labor Day Hurricane, HURDAT2 estimated sustained winds of ~160 kt (190 mph) over open water. Due to landfall in keys, winds speeds likely higher than listed here.
- All model vendors say sustained wind speeds from 1935 Labor Day Hurricane are greater than their stochastic 250-year max sustained wind in Florida. Why?

Source: Florida Commission on Hurricane Loss Projection Methodology, 2013 Standards.

Evaluating Gray Swan Events in Statistical Peril Models
Wind Radii

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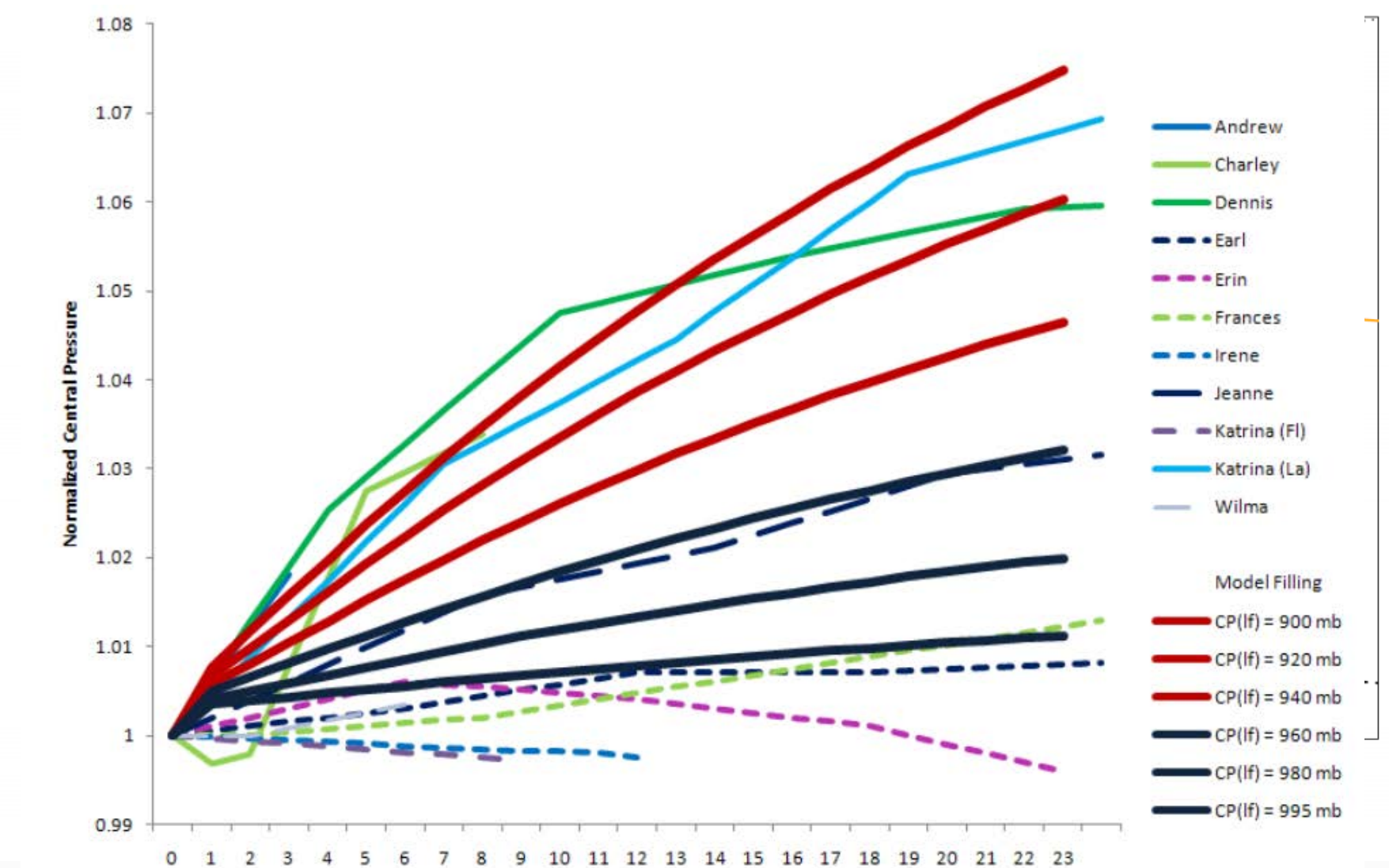
Model	A	B	C	D	E
R_{max} Min/Max	5/40	6/33	4/36	5/33	4/50
R_{100kt} Min/Max	11/62	23/80	8/66	11/69	11/123
R_{64kt} Min/Max	28/100	36/182	13/129	21/127	20/288
R_{34kt} Min/Max	103/204	82/530	25/258	42/276	47/603

- All values in miles, for stochastic events with central pressures of 920 – 900 hPa.
- Are R_{max} minimums too large to capture some pinhole-eye gray swan events?
- What data are they using to inform the 100 knot radius?
- How do these relationships vary by region?

Source: Florida Commission on Hurricane Loss Projection Methodology, 2013 Standards.

Evaluating Gray Swan Events in Statistical Peril Models

Inland Filling Rates



Source: Model Submissions to FCHLPM, 2013 Standards.

Evaluating Gray Swan Events in Statistical Peril Models
The “Darkest Gray” Gray Swan Event

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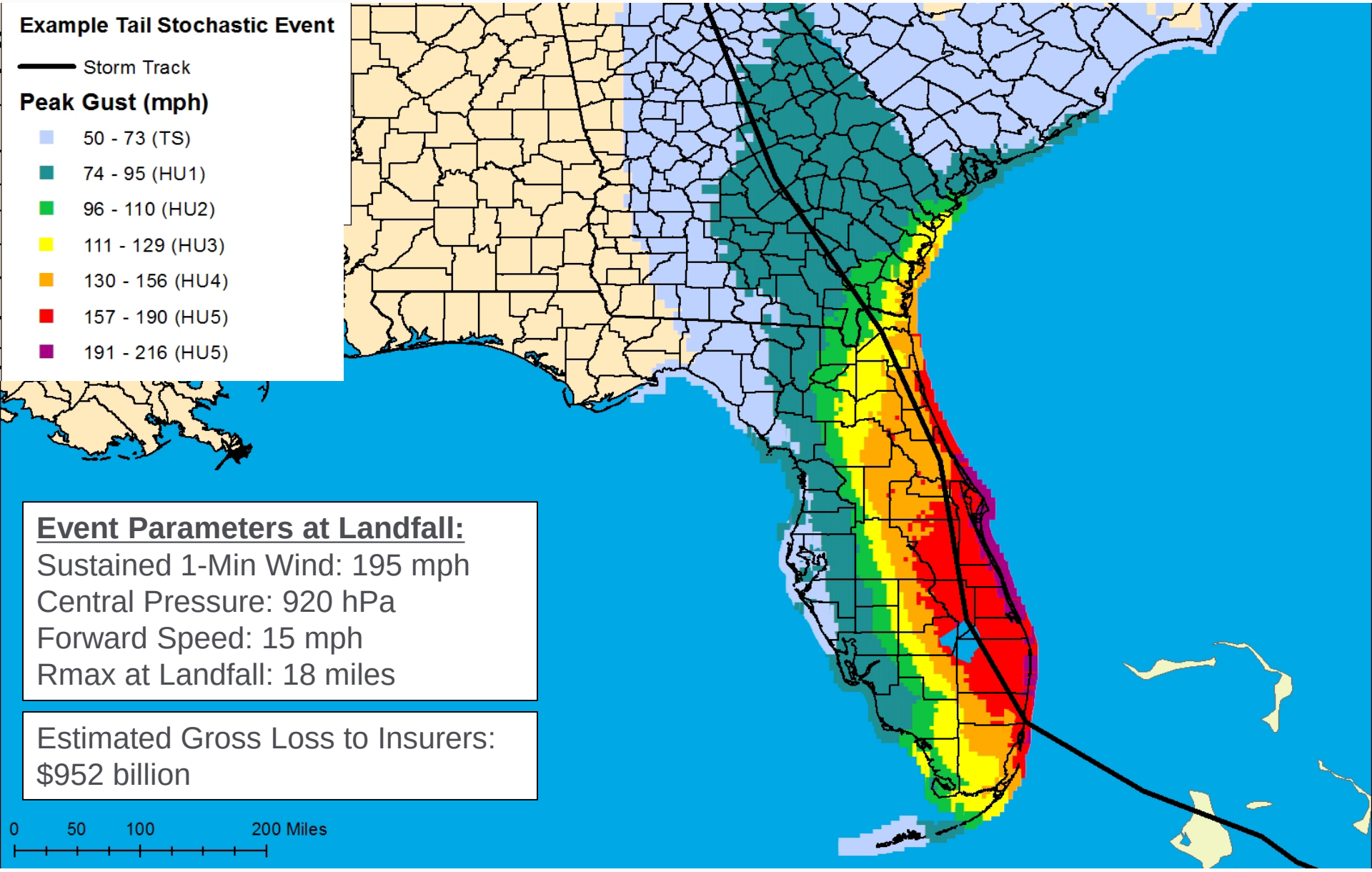

Evaluating Gray Swan Events in Statistical Peril Models
Extratropical Transition

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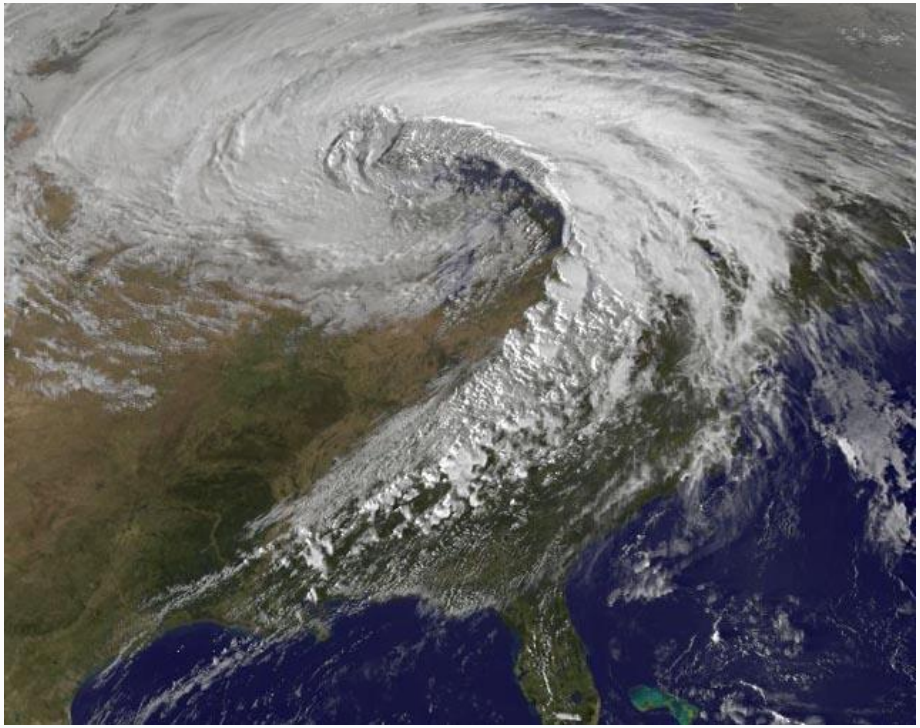
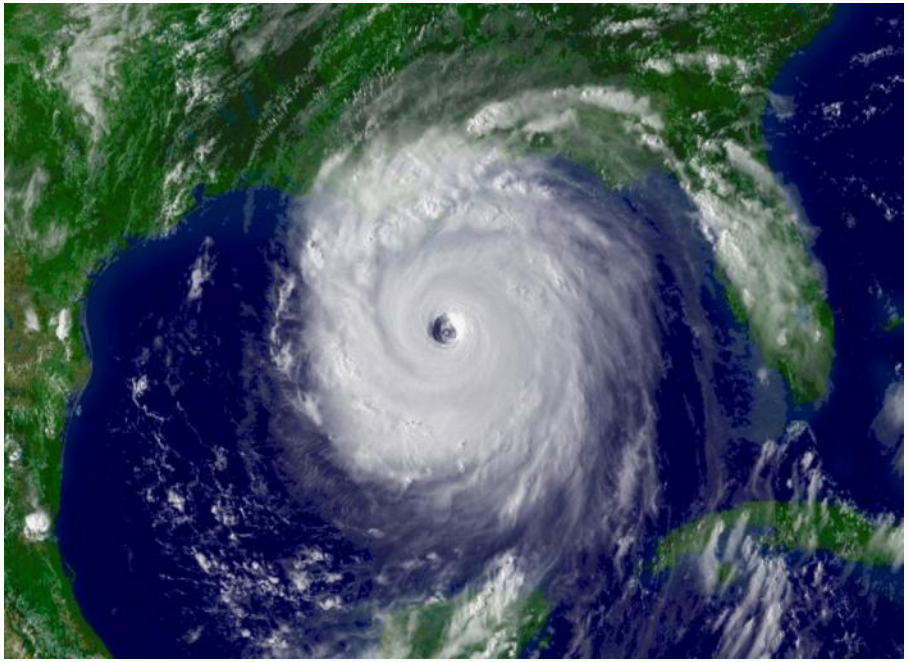
Tropical Cyclones

- Low pressure center warmer than surroundings (Warm-Core Low).
- Develop in air masses of relatively constant temperature and humidity.
- Symmetrical shape.
- Weak upper-level winds aloft.



Source: NASA



Source: NASA

Extratropical Cyclones

- Low pressure center colder than surroundings (Cold-Core Low).
- Develop in areas of temperature gradients between differing air masses.
- Asymmetrical Shape
- Strong upper-level winds critical in development and intensification.

Evaluating Gray Swan Events in Statistical Peril Models

Extratropical Transition

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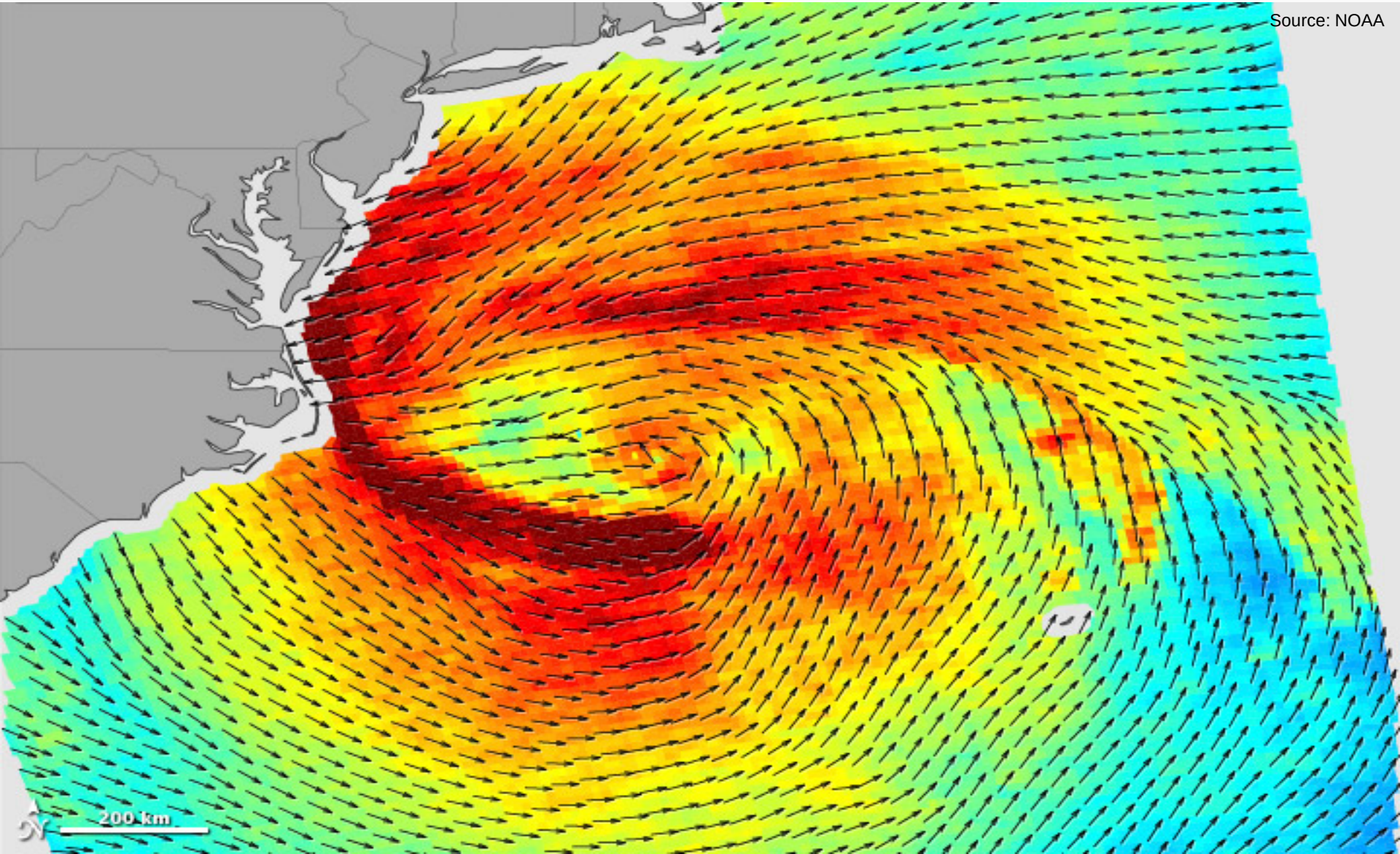

Evaluating Gray Swan Events in Statistical Peril Models
Other Relevant Parameter Relationships

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- Intensity vs. Forward Motion
  - Cat 5 intensity can't be maintained for long in a stationary storm, unless over a very large reservoir of warm water.
  - Cat 5 intensity can't be maintained at very high forward speeds; these situations may also be affected by extratropical transition.

- Far Field Pressure (Radius of Last Closed Isobar)
  - Most models assume standard atmospheric pressure as the far field pressure.
  - What if you have strong high pressure nearby creating a stronger pressure gradient than standard atmospheric pressure?
  - May be more critical for extratropical transitioning storms.

Summary

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- From meteorological perspective, gray swan events in south Florida are likely to be either intense Annular or “Pinhole” Eye hurricanes. From insured loss perspective, Annular hurricanes may be greater threat.
- Statistical peril models do not have any inherent physical understanding of how a given peril behaves. These relationships must be programmed into the statistical model for these relationships to exist in the output.
- Historical data and relationships / correlations between meteorological parameters allow us to make educated guesses about gray swan tail events.
    - Most stochastic gray swan events can be considered plausible.
    - However, some appear to bend (or break) the laws of physics.
- Model vendors spend a lot of time telling us about the strengths of their models, but not the weaknesses. Ask them about their model weaknesses!

THANK YOU! ANY QUESTIONS?

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