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Hurricanes: Current Storms, Future Expectations & Tree Damage

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Hurricanes are large tropical storms which generate high velocity winds, large rain volumes, ocean storm surges, and associated storm bands which produce tornadoes, lightning and flooding. Hurricane intensity varies greatly, but is powered by warm ocean water. Trees and forests are damaged by complex interactions between storm and tree attributes.

When

The hurricane season across the Southeast and South central United States is roughly from July through November, although rarely hurricanes can be generated from May through January. Figure 1. The months of August through October usually see the most intense hurricanes and the greatest number of storms. September 10th each year is considered the peak of the hurricane season having had the most number of storms over recent history. (NOAA, 2014)

Where

Hurricanes tend to strike land areas which project out into the Atlantic Ocean and the Gulf of Mexico. Figure 2. New England and the Carolina coast are points of Atlantic hurricane landfalls. Florida, which juts out into both Atlantic and Gulf waters, receives many landfalls. States with Gulf coasts are prime targets for hurricane landfall. Normal hurricanes pathways usually move West across the Atlantic, through the Carribean, and begin to curve Northward and Eastward over time.

Strike Chances

For Atlantic Ocean hurricane landfalls, the percent chance of a strike varies greatly. Places like the "Georgia bite," or indentation from the ocean, is much less likely to have a hurricane strike than the outer banks of North Carolina which sticks out into the Atlantic. For example for all Atlantic Ocean hurricanes, Florida has a 40% chance of a landfall, while North Carolina has a 16% chance, and Georgia has a 7% chance of being struck per year. In this case, Georgia has a chance of being struck by a hurricane once every 15 years based upon historic data.

Intensity / Severity

Hurricane intensity is usually defined by wind speed, although new measures can include rainfall amounts, ground speed, and storm surge. The most common hurricane wind scale is the Saffir-Simpson

Hurricane Wind Scale. Figure 3. This wind scale divides hurricanes into five categories, each with a range of sustained wind speeds. The three highest categories (categorizes 3-5) are considered major hurricanes. This wind scale was modified in 2012 to correct some rounding errors and measurement unit conversions. (NOAA, 2012)

Hurricanes are generally described by their category number. Each category has a descriptor name and associated tree damages with associated utility damage estimate. Figure 4. Hurricane severity range from dangerous (cat. 1-2), devastating (cat. 3), and catastrophic (cat. 4-5). Associated tree damage ranges from branches broken and trees toppled to massive tree loss. Power outages, many associated with tree failures, are described by how long the power will be out – days to a month.   (NOAA, 2014)

Storm Tracking

Hurricane tracks for all storms are kept by NOAA for each category type across the United States. In Georgia, for example, category 1-5 hurricane landfalls and tracks are shown in Figure 5. The Gulf coast hurricanes are shown in blue, and have usually been reduced in intensity from their landfall state. The Atlantic Ocean hurricanes are shown in red. Due to sustained winds, slow weakening, and slow movement, hurricanes can carry great energy well inland damaging trees and forest hundreds of miles from their landfall. (NOAA, 2018)

Increasing Energy

Projections of hurricane severity and associated ocean temperatures over the period of 1930 - 1990 have not varied greatly. Since 1990, there has been a significant change in storm intensity and sea temperatures. This increase in hurricane energy in the Atlantic Ocean — Northern Hemisphere continues to trend upward. Figure 6. (NOAA data). Hurricanes have tended to be more numerous, more severe on either side of the hurricane peak season, and with rising sea temperatures are showing a maximum of 22% – 30% greater storm energy.

Sampling Category 4

One unique way of viewing hurricane intensity changes over time is given in Figure 7. This figure shows increasing severity of hurricanes over the last 40 years. (Englander, 2014). Category 1-3 storms are declining while category 4-5 storms are increasing in numbers. In this case, total hurricanes are not increasing, but individual hurricane intensity is increasing.

The most intense storms normally impacting the Southeast are category 4 hurricanes (130 – 156 mph sustained winds). Figure 8 provides a distribution by month when these severe storms have made landfall. September and October have almost 70% of all category 4 landfalls. Figure 9 traces 112 category 4 hurricanes over 165 years by percent of all hurricanes and average number of category 4 hurricanes per year. Note the average number of category 4 storms per year has been increasing.

Tree Damage

Figure 10 shows tree damage by hurricane category number. This figure has the category number, sustained wind speeds in miles-per-hour, and tree impacts. An additional column was added to this figure by the author which represents the pounds of force applied to trees per square feet of surface area open to the wind. Note this mid-point wind pressure value is not part of the official hurricane wind scale, but can help show the large wind loads trees face. Major tree losses are accelerated when wind loads exceed ~100 mph or wind pressures of >28 pounds of force per square feet of tree surface.

An addition form of tree and site damage is applied by hurricanes through ocean storm surge. Storms surge is a rapid (i.e. within hours) rise in sea water levels flooding coastal trees and forests, pushed ashore by hurricanes. Storm surge varies greatly by each storm and coastal location. Figure 11 shows for each hurricane category, with associated sustained wind speed and wind load pressure, a maximum storm surge which could be expected.

Moving Inland

As hurricanes make landfall, tree damage in the area can be severe. The wind speed decay rate for hurricanes moving inland is relatively slow, and tree damage well inland can also be severe. Figure 12 demonstrates the maximum wind speed from a category 3 hurricane as it moves inland. Note hurricane level wind speeds can remain within the storm as much as 190 miles inland from landfall. Figure 13 provides a general 60 miles-per-hour wind line inland from a category 3 hurricane landfall. Note all the land area and cities potentially impacted. (NOAA data).

Tree Loading

Tree resist and fall back against the wind. Wind loads exceeding tree resistance to twist, bend, up-rooting will cause tree failures and catastrophic loss. Trees are loaded by wind and gravity, with wind loads being large, variable, and beyond average load adjustments. Figure 14 provides a list of wind speed in miles-per-hour and associated wind pressure in pounds per square foot of tree surface. In graphical form, wind load greatly increases with increased wind speed. Figure 15. Doubling wind velocity, nearly quadruples wind load pressure on trees. In other words, small wind speed increases translate into large wind loads increases for trees and forest stands.

Figure 16 provides the Coder Wind Scale (C-Scale) of loads on trees. The figure provides the C-Scale number (1-10), associated wind speed in miles-per-hour, and the wind force on a tree in pounds per square foot of tree surface area exposed. Also included are two load thresholds where tree resistance to wind loads change rapidly. Threshold T1 is at 56 mph / 8.3 pounds per square foot where trees have reached the limit of falling back against the wind and reconfiguring to reduce drag. Threshold T2 is near 95 mph / 24 pounds per square foot of exposed tree surface area where the biological safety factors of tree structure have been reached.

Figure 17 is another way of considering wind loads on trees. This figure shows the Coder Tree Wind Damage Assessment with wind speed in miles-per-hour, wind pressure in pounds per square foot, and expected tree damage description. As wind loads increase, tree damage accelerates until failure. Note that category 1 hurricanes generate tree wind loads starting at 5.6 C-scale / 14.4 pounds per square foot of exposed tree surface.

Return Rates

The return period in years between hurricanes making landfall along the Gulf and Atlantic coasts are shown in Figure 18. Generally the farther North, the longer time between hurricanes, with notable exceptions like the outer banks of North Carolina. Far South Florida has a return rate of one hurricane (on average) making landfall every 10 years. In Georgia, the return rate is one hurricane every 75 years surrounded by coasts to the North and South which have return rates of every 40 years. (NOAA data)

For example, in Georgia both Savannah and Brunswick has sustained catastrophic hurricane damage in the past. Figure 19 shows the expected return rate in years and when each city was last struck over roughly 160 years. For major hurricanes (categories 3-5), both cities have an estimated return rate of about 35 years. For all categories of hurricanes, the estimated return rate is roughly every 10 years. Given the probabilities of a major hurricane's direct landfall on each city, Savannah is 84 years over-due (120 years since last major hurricane) and Brunswick is 91 years over-due (125 years since last major hurricane). (Blake & Gibney, 2011)

Little Spinners

One consequence of hurricane landfall is rain storm bands impacting surrounding areas at significant distances away from the hurricane center of rotation. These bands of storms can generate strings of tornadoes. Figure 20 shows the increasing trend for tornado numbers in the United States since 1950. (NOAA data). A significant number of these tornadoes are associated with hurricanes and their remnants. Figure 21 provides the Enhanced Fujita Tornado Scale categories and associated wind speed, wind load pressure on trees, and tornado damage descriptor. Figure 22 shows tree damage impacts from tornadoes of various EF categories. (NOAA data)

Sparking

Lightning damage to trees is an important result of hurricane derived rain storm bands. Lightning ground strikes (of variable energy and polarity) are concentrated in and around tornadoes and thunderstorms. These lightning strikes further damage trees beyond what wind loads impacts have been generated.

Flooding

Hurricane energy delivers large amounts of rain. The slower moving the storm, the greater amount of rain deposited on any given site. For example, Figure 23 shows the area in Georgia where flooding is expected to occur in significant amounts under a category 4 hurricane. The red hatched area is storm surge related flooding, and the blue lines shows areas with major fresh water flooding events expected. (GEMA, 2015)

In Georgia, watersheds closer toward the Atlantic coast than the red line (Figure 24) could be inundated with 15-25 inches of rain in a short time frame (20 – 40 hours). The watersheds most at risk from a major Atlantic hurricane flooding event are the Savannah, Ogeechee, Altamaha, Satilla, Suwannee, and the St. Mary. Heavy flooding could occur more than 100 miles inland. Gulf coast hurricanes and remnants can also drench areas along their pathways with large amounts of rain.

Future Expectations

The hurricanes coming at us in the future are predicted to be different than historical storms. Hurricane intensity has increased over the last 30 years, and this trend is expected for the next century. There is significant debate about whether more hurricanes will occur, but much greater confidence in each hurricane which does occur will be more severe. Hurricane intensity increases include larger peak and sustained wind speed, greater rain amounts over shorter periods, and more storm energy. (Williams et.al. 2009)

In two 2018 science journal articles (Nature & Journal of Climate), a more clear picture was formed regarding what future hurricanes in the next 17 years will look like. Depending upon the extent of atmospheric warming and associated ocean surface warming, modeled to have atmosphere temperature increasing from +4^{o}F to +9^{o}F in the next 20 years, hurricane energy will increase. Research models show a +11% increase in category 3, 4, and 5 hurricanes, with category 5 storms increasing by +3.6 times. (NOAA – Nature, 2018; NCAR – Journal of Climate, 2018; Williams et.al. 2009)

Predictions for hurricanes include a +6% increase in wind intensity along with faster storm spin-up, 20% slower forward land speed movement of hurricane eyes, and +24% more hurricane rainfall. In other words, larger hurricanes staying over one spot longer with more wind and rain is expected. (NOAA – Nature, 2018; NCAR – Journal of Climate, 2018; Williams et.al. 2009)

Southeastern US

Minimum expectations for hurricanes in the Southeast United States by 2100 are a +5% increase in storm energy, a +10% increase in sustained winds, and a +20% increase in hurricane associated rainfall. (Ingram et.al. 2013c) With an increase in sustained wind speeds there has been initial discussion regarding a new hurricane category being needed.

Category 5 hurricanes have sustained wind speeds over 157 miles-per-hour. By 2100 category 5 hurricanes are expected to be fourteen times (14X) more likely. A proposed category 6 hurricane would have sustained speeds greater than 178-182mph. There have been four Northern Hemisphere hurricanes in the past which reached or exceeded this wind speed level. A category 6 hurricane could push a storm surge as high as 36 feet in some locations.

Conclusions

Hurricanes have, and will, severely impact tree health and structure. Over the next two generations of people, climate and extreme weather events are expected to be more intense. Tree and forest risk management processes need to consider changes occurring currently, as well as expected changes into the future.

Trees are biologically / genetically designed to respond to wind load challenges by increasing root anchorage, responding to mechanical stress and strain with modified tissues or tissue placement in new locations, increasing taper, and increasing diameter to tree height / branch length ratios. Tree survival depends upon making mechanical adjustments to withstand current conditions, and generating a large enough structural safety factor for future hurricane events.

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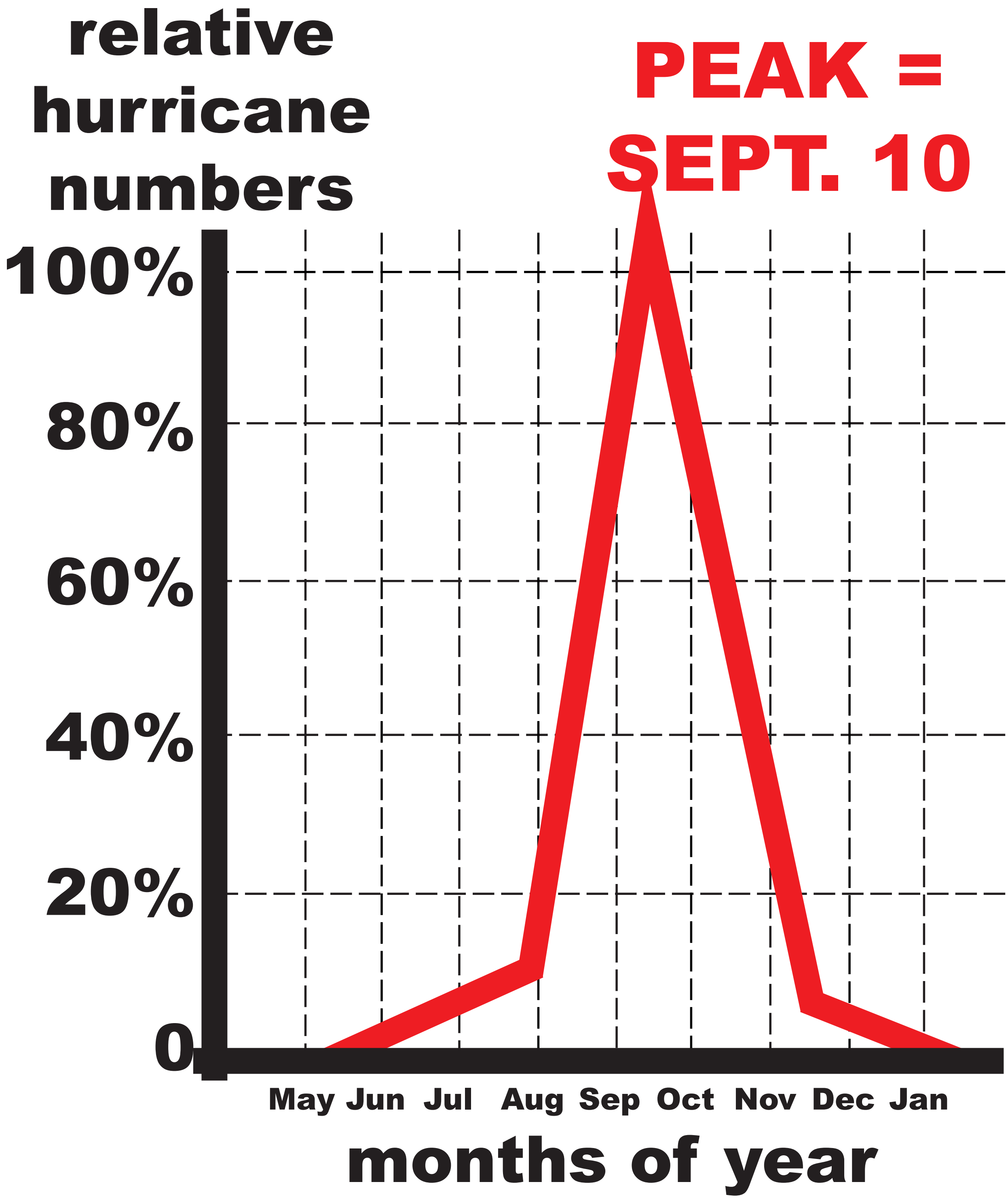

Figure 1: Relative number of hurricanes by month.
(NOAA 2014)

HURRICANE STRIKE LOCATIONS

Figure 2: Historic hurricane landfalls over a 50 year period in the Eastern United States. (from NOAA data)

Modified Saffir-Simpson Hurricane Wind Scale
(NOAA 2012)

category number	sustained wind speed
cat. 1 –	74 - 95 mph
cat. 2 –	96 - 110 mph
cat. 3 –	111 - 129 mph
cat. 4 –	130 - 156 mph
cat. 5 –	>157 mph

Figure 3: Modified Saffir-Simpson Hurricane Wind Scale giving sustained wind speeds for each hurricane category. Note category 3, 4, & 5 storms are considered major hurricanes. (NOAA 2012)

HURRICANES DESCRIPTORS

Cat. 1 – Dangerous

branches broken, some trees toppled – power out for days

Cat. 2 – Extremely Dangerous

shallow rooted trees snapped or uprooted – power out for week

Cat. 3 – Devastating Major

many trees snapped or uprooted – power out for weeks

Cat. 4 – Catastrophic Major

most trees snapped or uprooted – power out for many weeks

Cat. 5 – Catastrophic Major

massive tree loss – power out for month

Figure 4: Terms describing hurricanes, tree impacts, and associated power outages. (NOAA 2014)

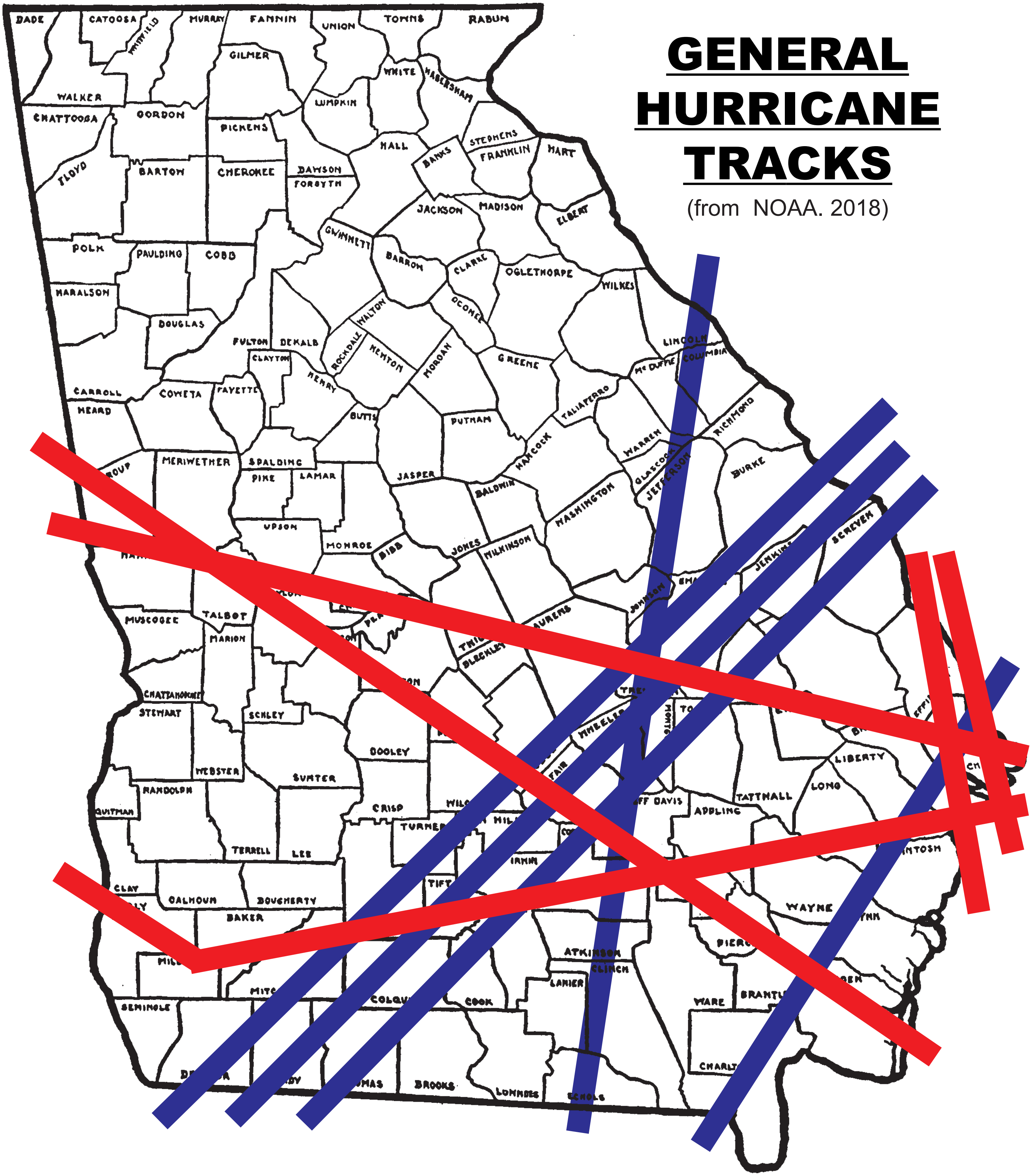

Figure 5: Historic summary of general hurricane (cat. 1-5) tracks across Georgia (blue = Gulf; red = Atlantic).

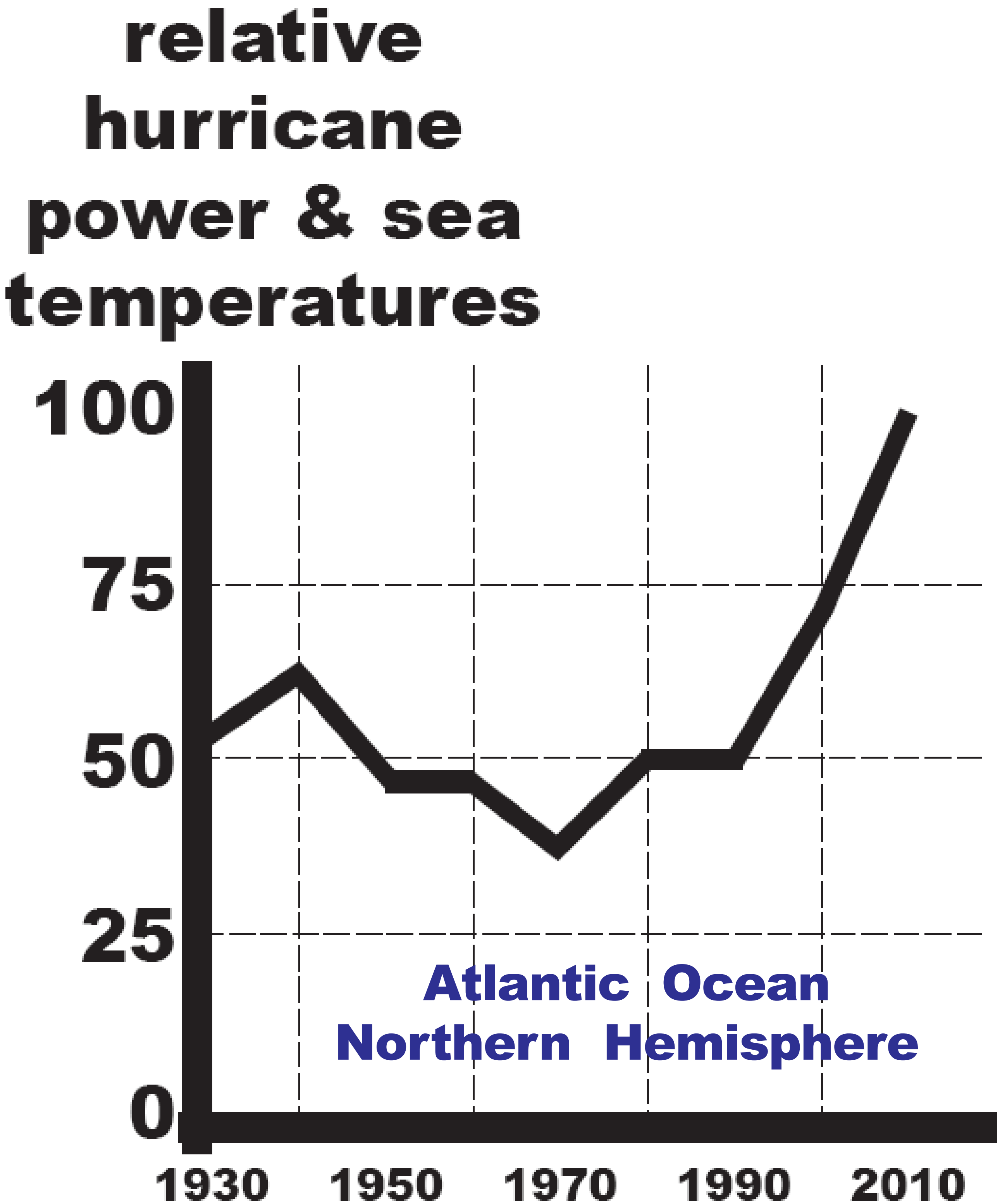

Figure 6: Combined relative hurricane intensity level and sea temperature between 1930 & 2010. (NOAA data)

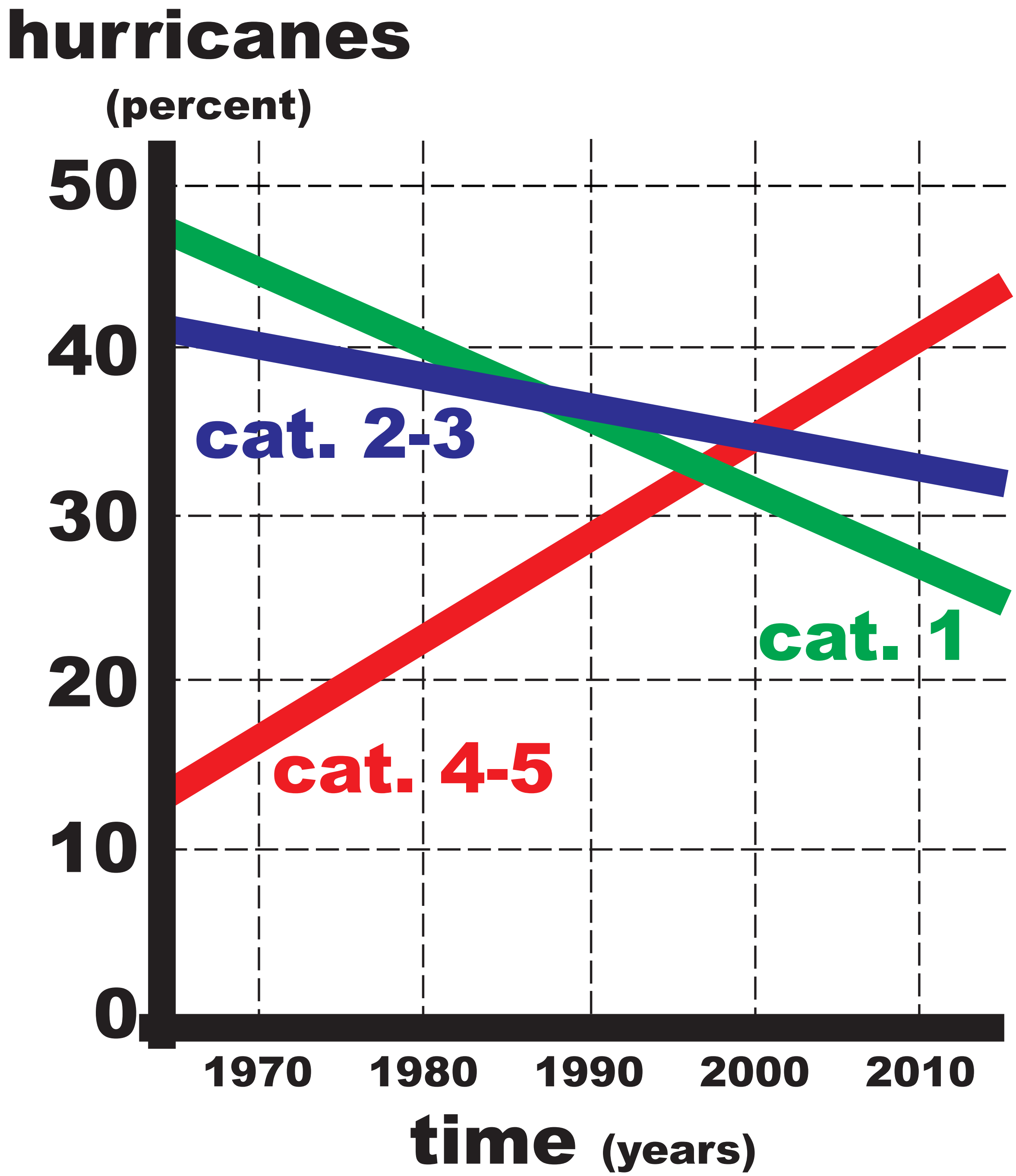

Figure 7: Increasing severity of hurricanes over last 40 years. (after Englander 2014)

Cat. 4 Hurricanes
-- Occurrence --

July	1%
August	26%
September	36%
October	33%
November	4%

(cat. 4 = 130 - 156 mph)

Figure 8: Category 4 hurricane occurrence by month

Cat. 4 Hurricanes

(112 hurricanes)

years	cat. 4 %	number per year
1851-1900	12%	0.26
1901-1950	26%	0.58
1951-1975	20%	0.88
1976-2000	21%	0.96
2001-present	21%	1.40

Figure 9: Category 4 hurricane occurrences by years compared with all hurricanes, and number of category 4 hurricanes on a per year basis.

storm category	wind speed mph	mid-point wind pressure* lbs/ft^2	tree impacts
1	74-95	19	branch & tree failures
2	96-110	28	major tree failures
3	111-129	38	large tree failures – leaves gone
4	130-156	54	massive tree blow-downs
5	> 157	> 63	most trees down

(* column is not part of wind scale but added by author)

Figure 10: Saffir-Simpson Hurricane Wind Scale with tree impacts.

STORM SURGE

storm category	wind speed mph	mid-point wind pressure* lbs/ft²	storm surge feet
1	74-95	19	4-5
2	96-110	28	6-8
3	111-129	38	9-12
4	130-156	54	13-18
5	> 157	> 63	> 18

(* column is not part of wind scale but added by author)

Figure 11: Saffir-Simpson Hurricane Scale and associated ocean storm surge levels.

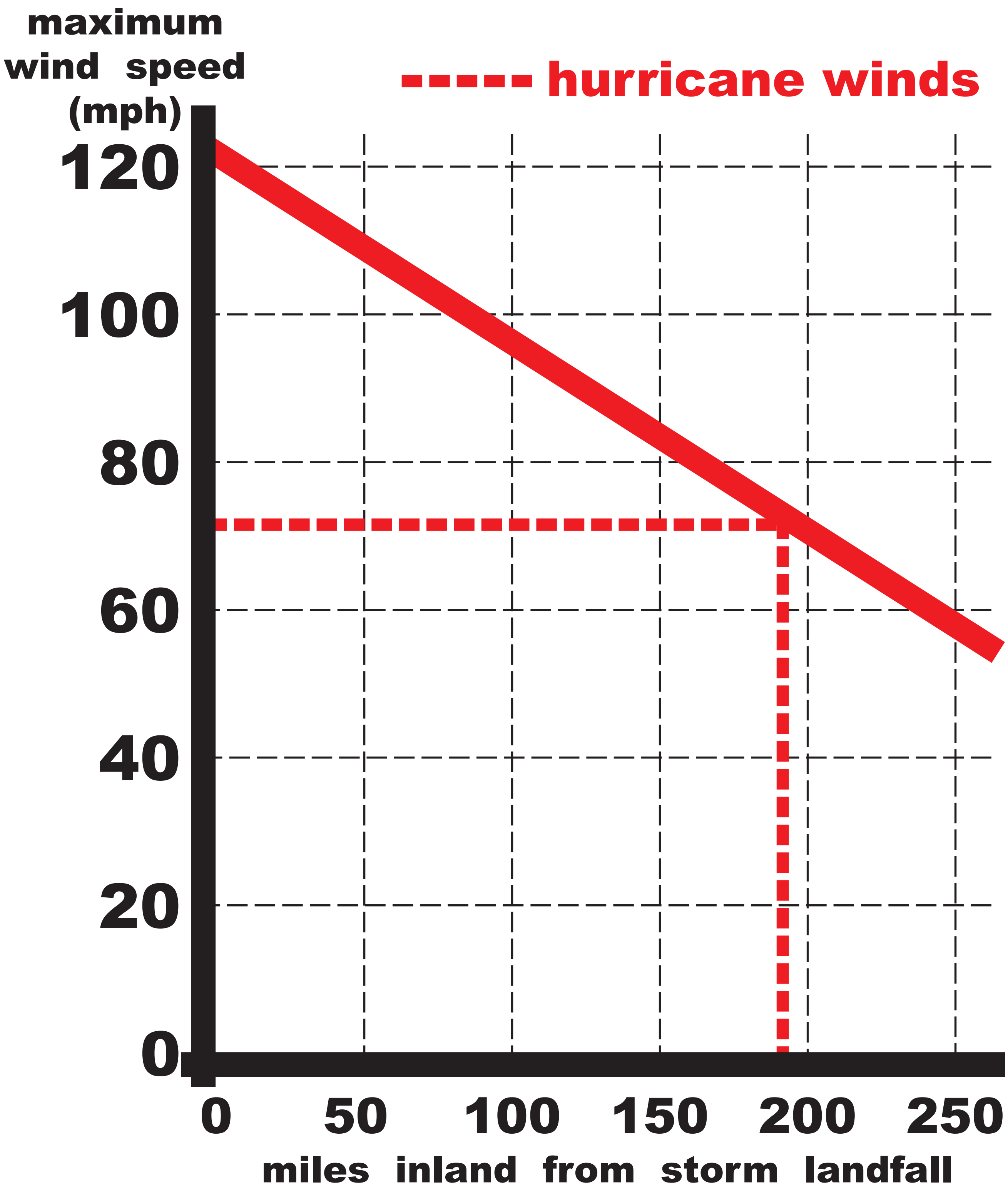

Figure 12: Estimated maximum wind speed at various distances inland from a catagory 3 hurricane landfall.

(NOAA data)

SUSTAINED 60mph WINDS

Figure 13: Estimated sustained ~60 mph wind speed line for inland areas after a catagory 3 hurricane landfall.

(after NOAA data)

wind velocity (mph)	pounds per square feet (lbs/ft^2)	wind velocity (mph)	pounds per square feet (lbs/ft^2)
5	0.1	80	17
10	0.3	85	19
15	0.6	90	21
20	1.1	95	24
25	1.7	100	26
30	2.4	110	32
35	3.2	120	38
40	4.2	130	45
45	5.3	140	52
50	6.6	150	59
55	8.0	175	81
60	9.5	200	105
65	11	225	133
70	13	250	165
75	15	275	199

wind pressure in pounds per square foot = (0.013) X (wind speed in mph X (0.45))^2

Figure 14: Estimated wind pressures in pounds per square feet (lbs/ft^2) calculated under standard conditions for various wind velocities in miles per hour (mph).
(drag coefficient = 1.0)

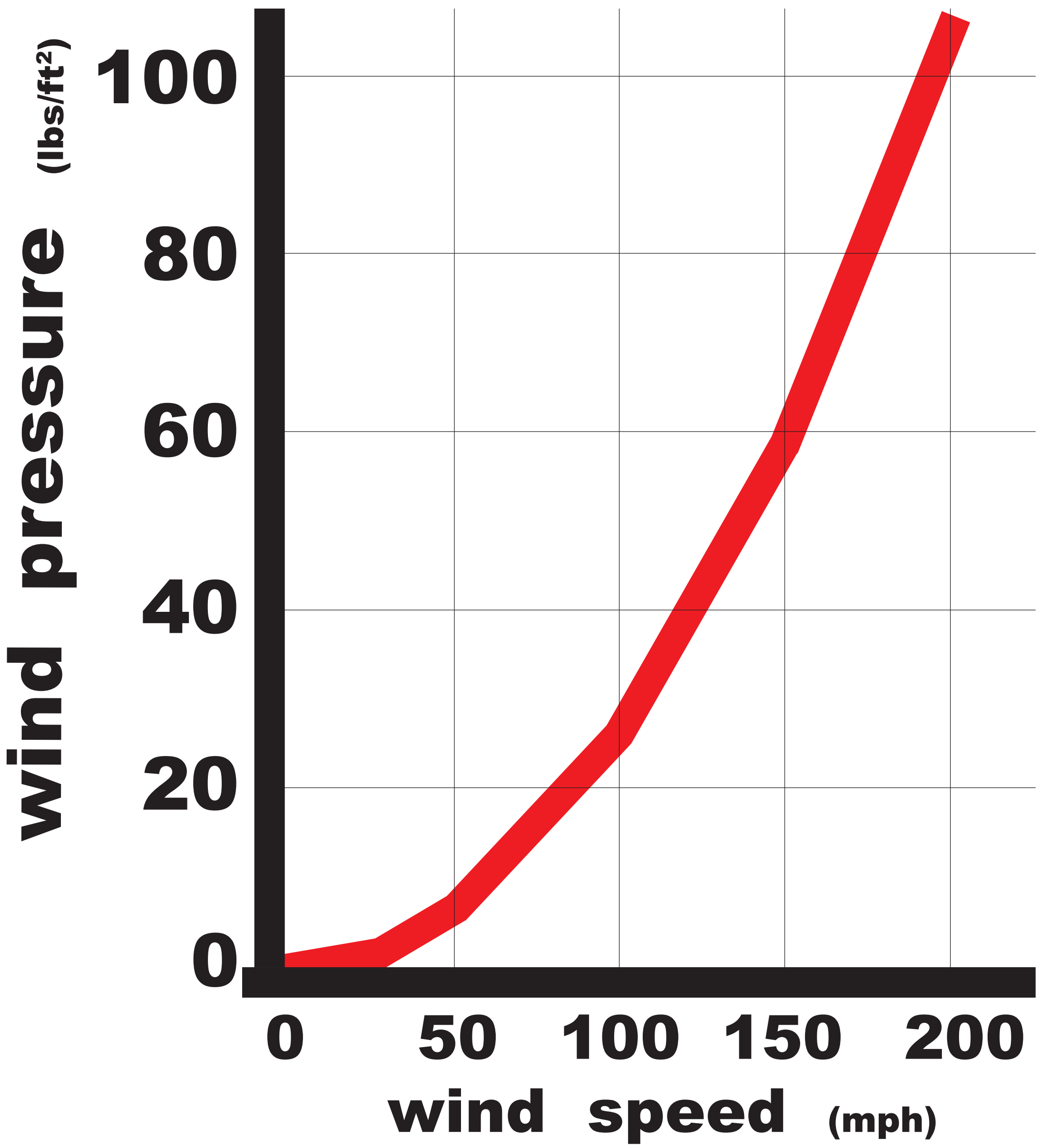

Figure 15: Estmated pressure of storm winds at different wind speeds applied to trees. (drag coefficient = 1.0)

wind pressure in pounds per square feet =
$(0.013) \times (\text{wind speed in miles per hour} \times (0.45))^2$

C-scale value	wind speed mph	wind force lbs/ft²
1	1.0 mph	--
2	5.7	0.09
3	15.6	0.64
4	32	2.7
5	56	8.3
T1		
6	88	20.4
6.2 T2	~96	~24]
7	130	44.5
8	181	86
9	243	156
10	316	263 lbs/ft²

Figure 16: Coder Wind Scale (C-scale) of wind loads on trees with associated wind speeds in miles per hour and wind loading force in pounds per square foot. (drag coefficient = 1.0)

$(\text{C-scale value})^{2.5} = \text{wind speed mph}$

$((\text{C-scale value})^{2.5} \times 0.45)^2 \times 0.013 = \text{wind force lbs/ft}^2$

Coder Tree Wind Damage Assessment

wind speed (mph)	wind pressure (lbs/ft²)	tree damage descriptor
20	1.1	root / soil interface fractures initiated
40	4.2	major stem & crown sway – branch failures
		** T1 = *end of crown drag reconfigurations* = ~56mph (~8 lbs/ft²) **
60	9.5	stem breakage – uprooting
90	21	major tree failures
		** T2 = *tree safety factors consumed* = ~96mph (~24 lbs/ft²) **
125	41	catastrophic tree losses
>160	67	massive tree destruction

Figure 17: Coder Tree Wind Damage Assessment showing wind velocity in miles per hour, wind pressure in pounds per square foot (drag coefficient = 1.0), potential tree damage, and two wind load thresholds where tree resistance to loads change rapidly.

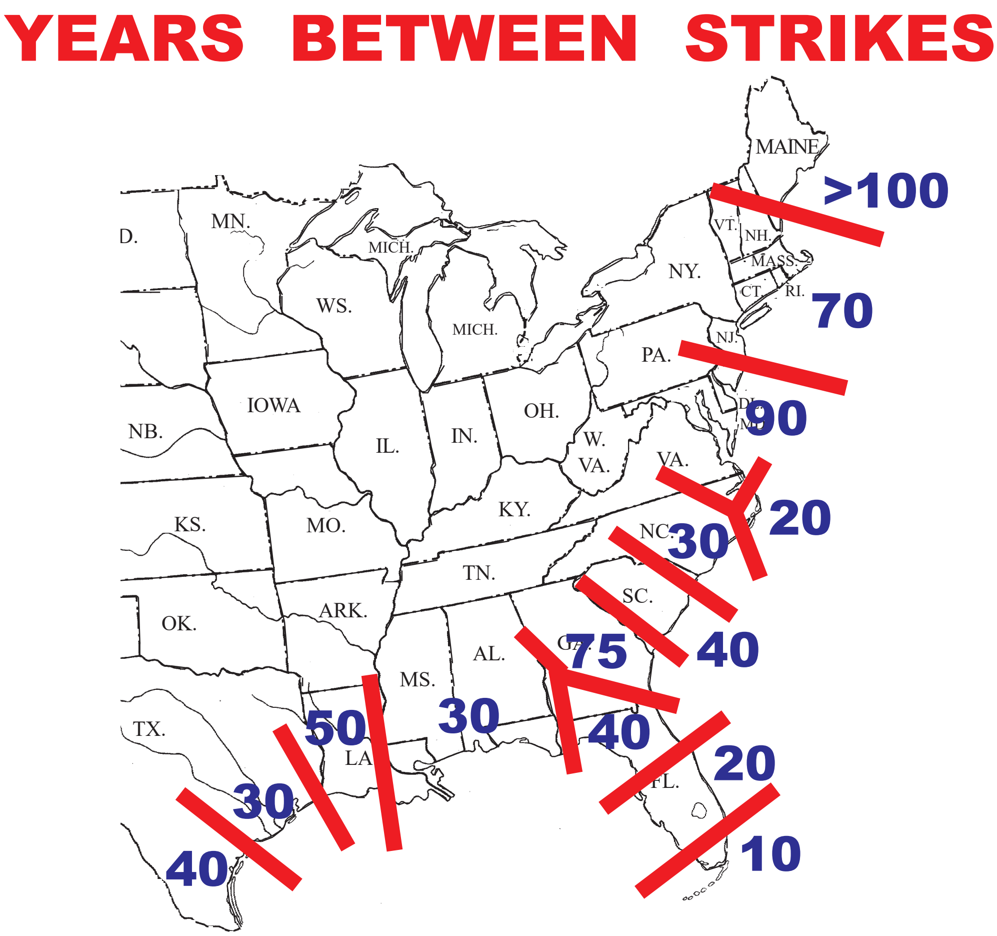

Figure 18: Estimated number of years between a catagory 3 hurricane landfall. (after NOAA data)

HURRICANE RETURN RATE & LAST STRIKE

city	return rate	last hit
Savannah		
major cat. 3-5	36yrs	1898
all cat. 1-5	10yrs	1979
Brunswick		
major cat. 3-5	34yrs	1893
all cat. 1-5	11yrs	1928

(within 57 miles -- dates = 1851-2010)

Figure 19: Hurricane return rate for major hurricanes (category 3-5), and all hurricanes (category 1-5), for two major Georgia coastal cities, and the last time a hurricane struck each city. (Blake & Gibney, 2011)

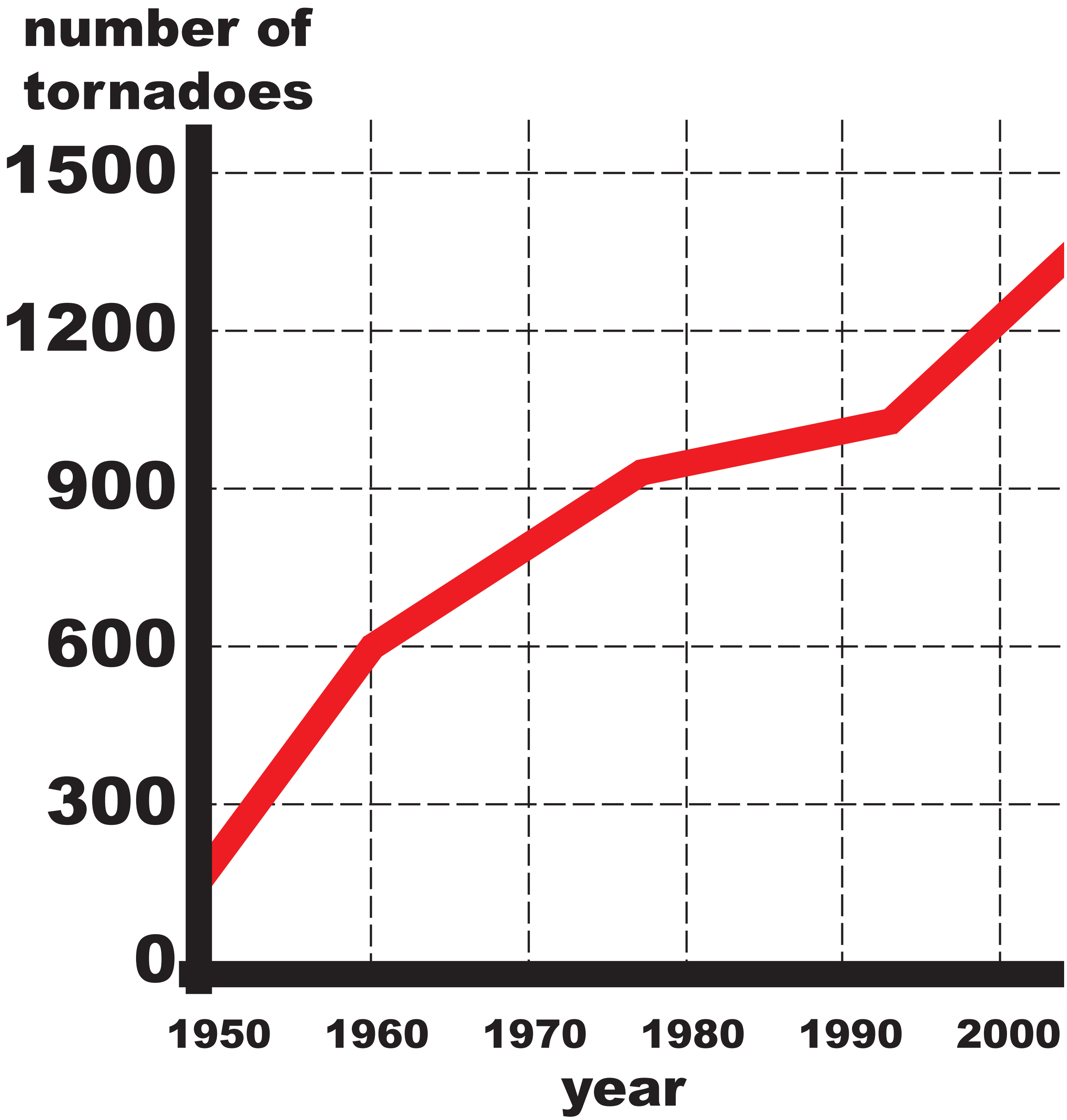

Figure 20: General trend line for tornado numbers in the United States. (NOAA data)

category	wind speed range (mph)	mid-point wind pressure (lbs/ft^2)*	tornado damage descriptor
EF0	65-85	15	light
EF1	86-110	25	moderate
EF2	111-135	40	considerable
EF3	136-165	60	severe
EF4	166-200	88	devastating
EF5	> 200	>105	incredible

(* column is not part of the wind scale but added by the author)

Figure 21: Enhanced Fujita Tornado Scale categories with wind speed, wind load pressure on trees, and damage descriptor. (used after 2/1/2007) (NOAA data)

category	wind speed range (mph)	mid-point wind pressure (lbs/ft^2)*	tree impacts
EF0	65-85	15	branches break
EF1	86-110	25	trees uproot, trees snap
EF2	111-135	40	trees debarked - only branch stubs remain
EF3	136-165	60	trees destroyed
EF4	166-200	88	
EF5	> 200	>105	

(* column is not part of the wind scale but added by the author)

Figure 22: Enhanced Fujita Tornado Scale with tree impacts. (used after 2/1/2007) (NOAA data)

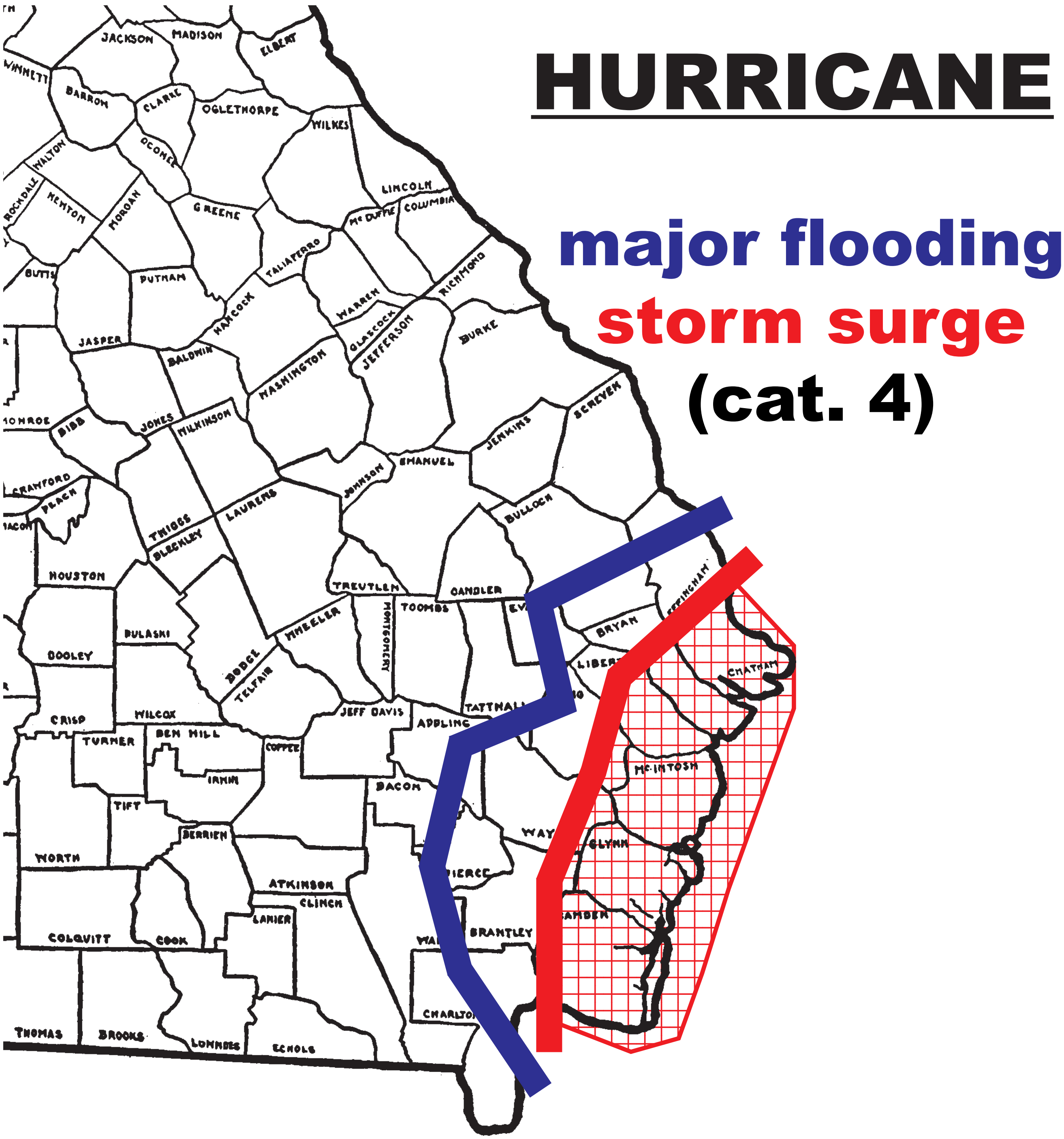

Figure 23: Potential storm surge area (1-10 feet deep) in red, and extent of major flooding area (blue) under a category 4 hurricane with landfall along the Georgia coast.
(after GEMA, 2015)

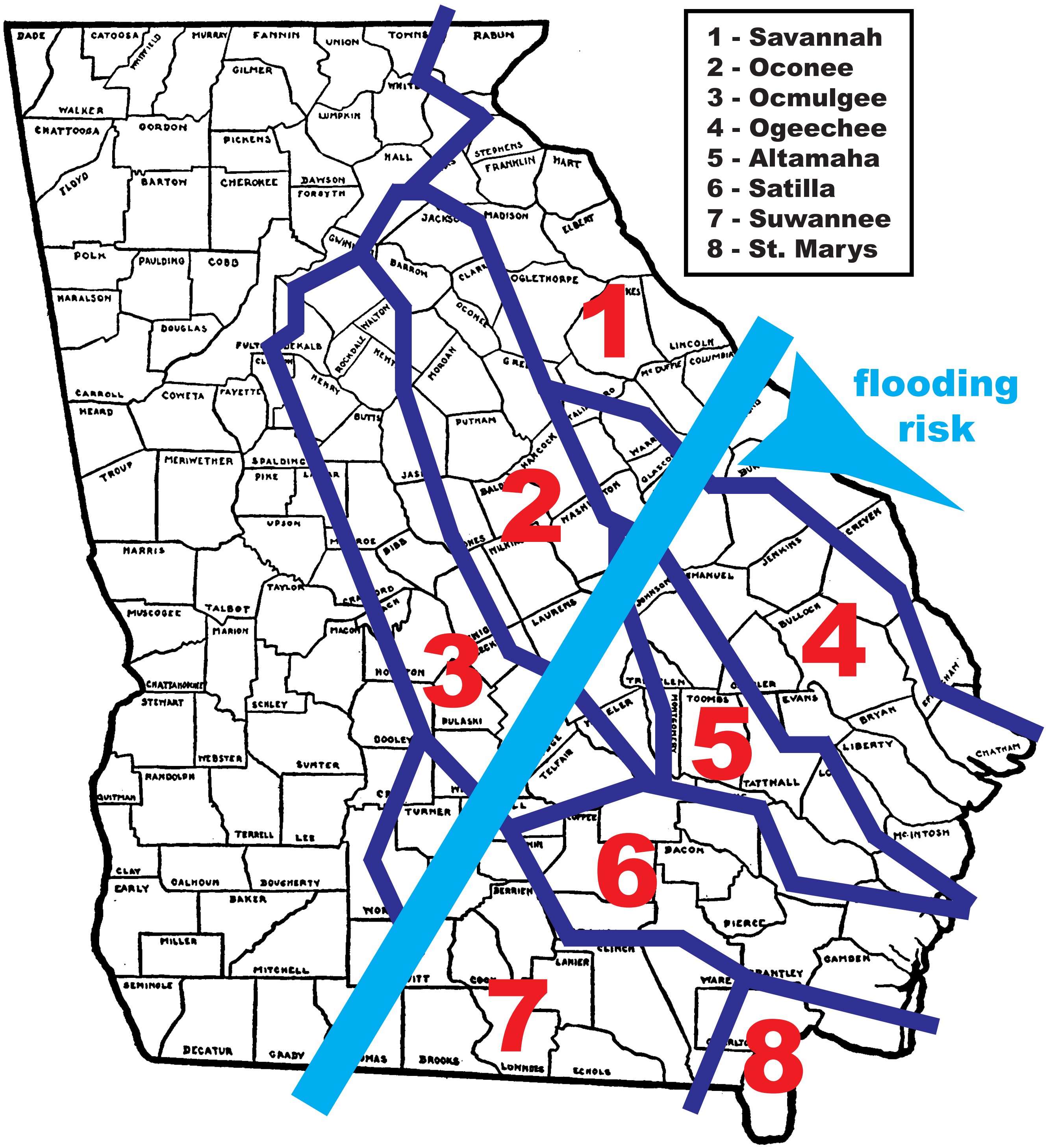

Figure 24: Major watersheds of Georgia potentially impacted by massive flooding from Atlantic coast hurricane land-fall.