United States Landfall Probability Webpage

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A webpage that displays tropical cyclone landfall and wind gust probabilities for the entire United States coastline from Brownsville, Texas to Eastport, Maine has recently been developed. Most individuals who live along the United States coastline are unaware of the statistical chances of hurricane spawned high-winds striking their particular region or county in any particular year. The webpage has recently been updated to include the probability of coastal states being impacted by hurricanes and major hurricanes. This webpage is a joint project between the Tropical Meteorology Project at Colorado State University (CSU), Fort Collins, CO and the GeoGraphics Laboratory at Bridgewater State College, Bridgewater, MA.

1. Introduction

Tropical cyclone landfall and wind gust calculations have been made for eleven regions from Brownsville, Texas to Eastport, Maine. These regions were created based on frequency of intense or major hurricane (Category 3-4-5 on the Saffir-Simpson scale) landfalls during the 20th century (1900-1999). Figure 1 displays these eleven regions. The Gulf Coast/East Coast division has been placed near Cedar Key, FL (north of Tampa). Storms that made landfall in the vicinity of Tampa, Sarasota and Fort Myers are considered to be East Coast landfalls. All 205 coastal and near-coastal counties from Brownsville to Eastport are within these eleven regions. Table 1 displays the number of counties that are in each region. The sources of data utilized for these calculations are listed in the following section.

Online Data Sources

Hurricane data:

Landfalling hurricane data from the National Hurricane Center's webpage: http://www.nhc.noaa.gov

Population data:

United States government year 2000 census data from the Census Bureau's webpage: http://www.census.gov

Coastline data:

Estimated from the United States Geological Survey's (USGS) webpage: http://nmviewogc.cr.usgs.gov/viewer.htm

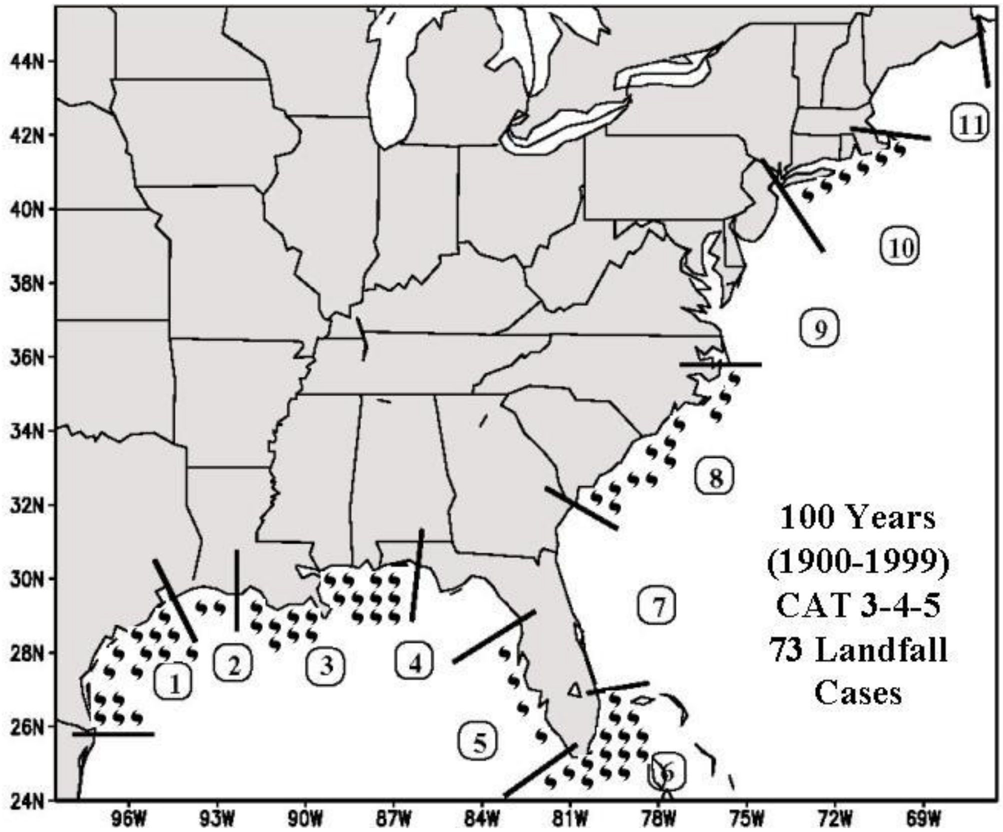

Figure 1: The eleven coastal regions for which landfall probabilities are calculated.

Table 1: Breakdown of the United States coastline into regions and counties.

Geographical Area	**# of Counties**
Gulf Coast – Region 1	22
Gulf Coast – Region 2	10
Gulf Coast – Region 3	32
Gulf Coast – Region 4	17
East Coast – Region 5	8
East Coast – Region 6	5
East Coast – Region 7	25
East Coast – Region 8	23
East Coast – Region 9	30
East Coast – Region 10	18
East Coast – Region 11	15
Gulf Coast – Subtotal (Regions 1 - 4)	**81**
East Coast – Subtotal (Regions 5 - 11)	**124**
Entire U.S. Total	**205**

2. Calculating Probability of Tropical Cyclone Landfall

To calculate the probability of tropical cyclones making landfall and associated wind gust probabilities, all tropical cyclones that occurred along the United States coastline from 1900-2006 were tabulated. Probabilities have recently been updated with data through 2006 and extended as far back as the 1850s for some regions utilizing recently-available data from the HURDAT Reanalysis Project produced by the Hurricane Research Division (HRD) and the Atlantic Oceanographic and Meteorological Laboratory (AOML). Starting dates for each region are displayed below (Table 2):

Table 2: Starting dates for each United States tropical cyclone landfall region.

Region	**Year Start**
1	**1880**
2	**1880**
3	**1880**
4	**1880**
5	**1900**
6	**1900**
7	**1880**
8	**1851**
9	**1851**
10	**1851**
11	**1851**

For maximum wind speeds at landfall for hurricanes, from 1851-1914 and 1980-2004, wind speed estimates were taken from the HURDAT database (http://www.aoml.noaa.gov/hrd/hurdat/ushurrlist.htm). For 1915-1979, wind speeds were interpolated from the Saffir-Simpson Scale category listed in the HURDAT database at landfall using the following table. To convert from knots to miles per hour, multiply the wind speed in knots by 1.15. For storms between 1915-1979, estimated maximum wind speeds were interpolated as follows (Table 3):

Table 3: Scale utilized to assign maximum sustained wind intensities (in knots) for various Saffir-Simpson scale categories.

Saffir-Simpson Scale Category	Max Wind (kts)
1	75
2	90
3	105
4	125
5	140

Wind speed estimates for tropical storm landfalls from 1851-1914 were taken from the HURDAT database. For 1915-1994, tropical storm landfall intensities were estimated from the 6-hour intensity of the storm prior to landfall, and from 1995-2006, tropical storm landfall intensities were taken from the National Hurricane Center Tropical Cyclone Reports. Locations of landfall from 1851-1998 were taken from "Tropical Cyclones of the North Atlantic Ocean, 1871-1998." (Neumann et al. 1999). Landfall locations from 1999-2006 were taken from the National Hurricane Center webpage: http://www.nhc.noaa.gov.

A. Calculating probability of a tropical cyclone landfall for a region

The total number of named storms, hurricanes and intense hurricanes that made landfall in each region were calculated, and probabilities were derived from this information. For example, in Region 1, 57 named storms, 35 hurricanes and 15 intense hurricanes made landfall from 1900-1999. In calculating the probability for any particular year, one must consider that some years in the past had more than one storm make landfall. For example, the 57 named storms that made landfall in Region 1 of Texas did so during 45 years. To approximate the future likelihood of storms, a Poisson regression model was used. Analysis of the numbers of landfalling tropical cyclones over the last century shows that landfalling frequency very closely conforms to a Poisson distribution. The formula for the Poisson distribution is as follows:

$$EP = (e^{-p}) (p^{x}) / x!$$

Where: EP = Expected Probability

p = Annual average number of tropical cyclones that have occurred in the past 100 years

x = Number of storms expected in the upcoming year based on the Poisson formula

x! = Factorial. If x = 3, then x! = 3*2*1 = 6

If x = 4, then x! = 4*3*2*1 = 24

e = 2.71828

For example, the Poisson-derived Expected Probability (EP) of exactly one named storm making landfall in Region 1 where 57 named storms made landfall over the past 100 years (p = 0.57) is calculated as follows:

$EP = (e^{-p}) (p^{x}) / x!$ (Poisson formula)

p = 0.57; x = 1

$EP = (e^{-0.57})*(0.57^{1})/1!$; 1! = 1

EP = 0.57*0.57

EP = 0.32 or 32%

Therefore, the probability of exactly one storm making landfall in an average year in Region 1 is 32%.

Likewise, for the probability of exactly two named storms making landfall, the calculation would be made as follows:

$EP = (e^{-p}) (p^{x}) / x!$ (Poisson formula)

$p = 0.57; x = 2$

$EP = (e^{-0.57})*(0.57^{2})/2!; 2! = 2$

$EP = 0.57*0.32/2$

$EP = 0.09$ or 9%

The Poisson model indicates that in an average year there is a 9 percent chance of exactly two named storms making landfall in Region 1. Similar calculations can be made for other numbers of tropical cyclones (i.e., 0, 3, 4, etc.) making landfall in a selected period of time.

B. Calculating probability of a tropical cyclone landfall for a county

To calculate the probability of a tropical cyclone making landfall in a county, we begin by calculating the ratio of the coastline distance of the county compared with the coastline distance of the region. For example, Cameron County, Texas has a coastline distance of 55 km, compared with the Region 1 coastline distance of 503 km which gives a ratio of 55 km/503 km = 0.11. Then, assuming landfalls are evenly distributed over the region, we assume that approximately 6.3 (57 * 0.11) tropical cyclones made landfall in the county during the 20th century. Lastly, we fit a Poisson probability distribution in order to obtain the climatological probability of tropical cyclone landfall in Cameron County, Texas based on 20th century data (since it is possible, although unlikely, that two tropical cyclones will make landfall in the same county in the same year). For Cameron County, Texas, the probability of one or more landfalling named storms in a given year based on 20th century data is 6.1%.

C. Calculating 50-Year Probabilities

Fifty-year probabilities of landfalling storms have been included in this study because most structures are built to last at least 50 years, and construction decisions on the cost of hurricane-protecting building materials should be based on the longer period. If a county has a rather large likelihood of a hurricane making landfall over a 50-year period, one would probably want to construct the building to withstand at least minimal hurricane-force winds.

The 50-year probability is calculated by taking the individual year climatological probability into account and then using a binomial distribution. For Cameron County, Texas, the 50-year probability of a landfalling tropical storm based on 20th century data (individual year probability is 6.3%) is calculated as follows (using decimals for all calculations, i.e. 6.3% = 0.063):

$$\text{50-Year Prob.} = 1 - (1 - \text{One-Year Prob.})^{50}$$

$$= 1 - (1 - 0.063)^{50}$$

$$= 1 - (0.937)^{50}$$

$$= 1 - 0.039$$

$$\text{50-Year Prob.} = 0.961 \text{ or } 96.1\%$$

Therefore, one would expect a 96.1% chance of a named storm making landfall in Cameron County, Texas over a 50-year period.

The probability of a tropical cyclone landfall grows considerably as the number of years increases. The example below shows the growth of individual-year probabilities when 1, 5, 10, 25, 50 and 100-year periods are considered for near-climatological conditions. For ease of comparison, probabilities of a named storm making landfall in Cameron County, Texas will be calculated.

1-Year Prob. = $1 - (1 - 0.063)^{1} = 0.063$ or 6.3%

5-Year Prob. = $1 - (1 - 0.063)^{5} = 0.278$ or 27.8%

10-Year Prob. = $1 - (1 - 0.063)^{10} = 0.478$ or 47.8%

25-Year Prob. = $1 - (1 - 0.063)^{25} = 0.803$ or 80.3%

50-Year Prob. = $1 - (1 - 0.063)^{50} = 0.961$ or 96.1%

100-Year Prob. = $1 - (1 - 0.063)^{100} = 0.998$ or 99.8%

3. Calculating Probability of Wind Gusts

A. Calculating the radius of wind gusts based on landfall intensity

A rudimentary estimation of the areal extent of various strength wind gusts is based on estimated maximum sustained wind speeds at landfall. Estimated maximum sustained wind speeds are then converted to wind gusts using the typical conversions utilized by the National Hurricane Center (Table 4).

Table 4: Sustained wind – wind gust conversion utilized for the United States Landfalling Probability webpage.

Sustained Wind (kts)	Gusts (kts)
35	45
40	50
45	55
50	60
55	65
60	75
65	80
70	85
75	90
80	100
85	105
90	110
95	115
100	120
105	130
110	135
115	140
120	145
125	155
130	160
135	165
140	170
145	175
150	185
155	190
160	195
165	200

Winds of every intensity tropical cyclone are assumed to extend out to a radius of 30 km from each cyclone center (60 km diameter). The following formula was used to calculate the wind radii of all tropical cyclones:

$$V_T r^x = \text{constant}$$

Assumptions:

For tropical storm-force wind gusts between 35 - 64 knots, wind radii are estimated to increase linearly from 30 km (for 35 knot wind gusts) to 90 km (for 64 knot wind gusts)

For hurricane-force wind gusts between 65 - 99 knots, we assume x = 0.5

For intense hurricane-force wind gusts greater than 99 knots, we assume x = 0.65

Figure 2 illustrates the wind speeds at various radii away from the center of tropical cyclones utilizing the above-discussed approximations. Intense hurricane-force and hurricane-force wind gusts are assumed to decay at the above-discussed rates. We then assume that the radial extent of tropical storm-force (>= 35 knots) wind gusts are three times that of the radius of hurricane-force wind gusts (>= 65 knots). Figure 3 displays approximate wind radii for four idealized intense hurricanes making landfall along the Texas coast (Region 1).

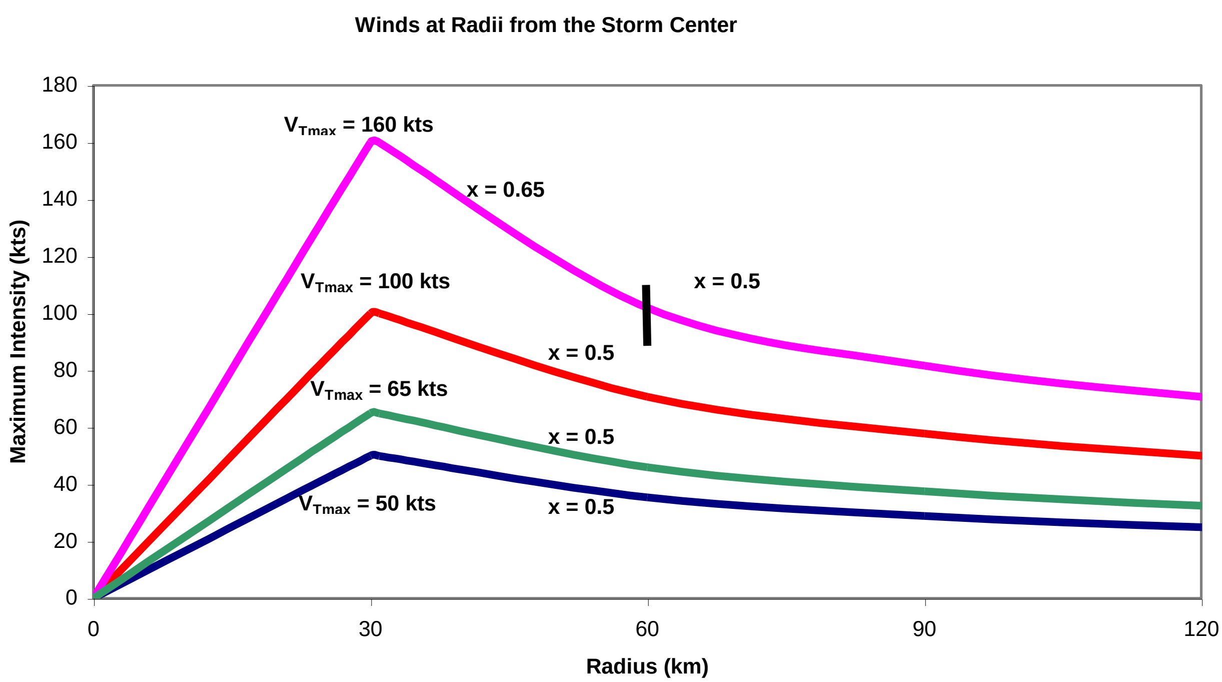

Figure 2: Intensity of winds at various radii away from the center of tropical cyclones with maximum wind gust intensities in knots of 50, 65, 100 and 160, respectively.

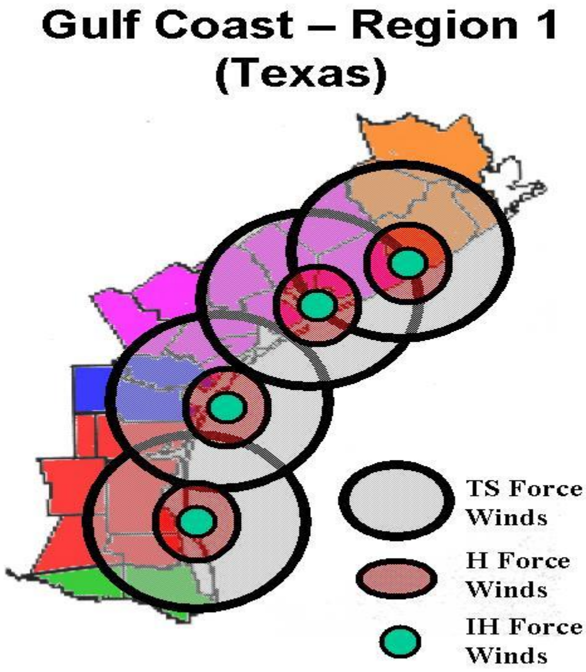

Figure 3: Wind radii for four idealized intense hurricanes that made landfall along the Texas coastline (Region 1).

Utilizing the equations discussed above, a table with approximate radii of tropical storm-force, hurricane-force and intense hurricane-force winds for tropical cyclones that made landfall at various intensities has been created (Table 5). As the storm strength at landfall increases, the extent of damaging winds is also assumed to increase. This does not occur for all storms, but it is a valid assumption for typical differences between tropical cyclones with tropical storm-force, hurricane-force and intense hurricane-force wind gusts.

Table 5: Assumed radial extent of tropical storm, hurricane and intense (Category 3-4-5) hurricane-force wind gusts for cyclones of different intensities.

Sustained Wind Speed (kts)	Assumed Wind Gusts (kts) Corresponding to Sustained Winds	Outer Radius of Tropical Storm-Force Wind Gusts (35 kts)	Outer Radius of Hurricane-Force Wind Gusts (65 kts)	Outer Radius of Intense Hurricane-Force Wind Gusts (100 kts)
35	45	50	0	0
40	50	60	0	0
45	55	70	0	0
50	60	80	0	0
55	65	90	30	0
60	75	120	40	0
65	80	136	45	0
70	85	154	51	0
75	90	173	58	0
80	100	213	71	30
85	105	227	76	32
90	110	241	80	35
95	115	255	85	37
100	120	270	90	40
105	130	300	100	45
110	135	316	105	48
115	140	332	111	51
120	145	349	116	53
125	155	382	127	59
130	160	399	133	62
135	165	417	139	65
140	170	435	145	68
145	175	453	151	71
150	185	490	163	78
155	190	509	170	81
160	195	528	176	84
165	200	548	183	88

This table was used to calculate swaths of tropical storm-force wind gusts, hurricane-force wind gusts and intense hurricane-force wind gusts for all tropical cyclones that made landfall along the United States coastline. Table 6 displays the wind gust swaths for all tropical cyclones making landfall in Region 2 between 1880-2006:

Table 6: Damaging wind swaths for all tropical cyclones making landfall in Region 2 from 1880-2006.

	Region 2 (257 km)					
Year	**Storm Name**	**Sustained Winds (kts)**	**Gusts (kts)**	**Outer Radius of Tropical Storm-Force (35 kts) Wind Gusts (km)**	**Outer Radius of Hurricane-Force (65 kts) Wind Gusts (km)**	**Outer Radius of Intense Hurricane-Force (100 kts) Wind Gusts (km)**
1882	Storm 3	90	110	241	80	35
1886	Storm 1	85	105	227	76	32
1886	Storm 10	105	130	300	100	45
1897	Storm 2	75	90	173	58	0
1898	Storm 5	50	60	80	0	0
1898	Storm 6	50	60	80	0	0
1905	Storm 3	45	55	70	0	0
1918	Storm 1	105	130	300	100	45
1938	Storm 2	75	90	173	58	0
1940	Storm 2	90	110	241	80	35
1940	Storm 6	40	50	60	0	0
1941	Storm 1	40	50	60	0	0
1943	Storm 6	40	50	60	0	0
1946	Storm 1	35	45	50	0	0
1954	Barbara	40	50	60	0	0
1957	Audrey	125	155	382	127	59
1957	Bertha	60	75	120	40	0
1959	Arlene	40	50	60	0	0
1971	Edith	90	110	241	80	35
1978	Debra	50	60	80	0	0
1979	Claudette	45	55	70	0	0
1982	Chris	55	65	90	30	0
1985	Danny	80	100	213	71	30
1985	Juan	75	90	173	58	0
1986	Bonnie	75	90	173	58	0
1987	Unnamed (1)	40	50	60	0	0
2005	Rita	100	120	270	90	40
	Total			**4107**	**1106**	**356**
	Prob. Per Year			**25.2%**	**6.8%**	**2.2%**

From this information, calculations were made for the probability of obtaining tropical storm-force, hurricane-force, and intense hurricane-force wind gusts as follows. The total radius covered by a particular strength wind gusts, for example, tropical storm-force wind gusts was calculated. The radii of all tropical storm-force wind gusts over the entire period (1880-2006) were then added and multiplied by 2 to obtain the diameter of tropical storm-force winds. Then, we divided by the coastal length of the region, resulting in the probability per year that any point in the region would be affected by wind gusts of tropical-storm force. This calculation would be made for tropical storm-force wind gusts in Region 2 as follows:

1. Begin by summing the radii of tropical storm-force wind gusts in the region: 4107 km
2. Multiply by 2 to obtain the total diameter of tropical storm-force winds over the 100 year period: (4107 km * 2) = 8214 km
3. Lastly, divide by the coastal length and the number of years in the historical dataset. This gives the probability per year (in percent) of obtaining tropical storm-force wind gusts at any point in Region 2: (8214 km / 257 km /127 years = 25.2%)

One must also consider the probability that a point in the region may experience tropical storm-force wind gusts more than once in any particular year. Therefore, these annual probabilities are then fit to a Poisson distribution, as was done with landfall numbers. When this is done, the probability of receiving tropical storm-force wind gusts one or more times during an average season at any point in Region 2 is calculated to be 22.3%. Since wind swaths are being calculated, the probability of any point in Region 2 being affected by hurricane-force winds is the same, and therefore, all counties in Region 2 have the same probability of experiencing wind gusts of various forces.

B. Calculating 50-Year Probabilities

As was done with landfalling storms, 50-year probabilities were then calculated. In Region 1, the annual probability of major hurricane-force wind gusts for any point is ~3.9%. Therefore, the 50-year probability is:

$$
\begin{aligned}
\text{50-Year Prob.} &= 1 - (1 - 0.039)^{50} \\
&= 1 - (0.961)^{50} \\
&= 1 - 0.13
\end{aligned}
$$

$$\text{50-Year Prob.} = 0.870 \text{ or } 87.0\%$$

Therefore, one would expect an 87% chance that any point in Region 1 will experience major hurricane-force wind gusts over any 50-year period.

4. Calculating Short-Term Probabilities – To Be Added Shortly

Additional functionality has recently been added to the United States Landfall Probability Webpage. This added functionality allows a user to select a particular county and a time period, and then the odds of landfall and experience wind gusts of particular forces are provided for the given period in that county. These probabilities were calculated by initially counting all landfalls during various ten-day periods throughout the hurricane season. Storms making landfall in Regions 1-4, Regions 5-7, and Regions 8-11 were aggregated together to provide for a more extensive data sample. In general, storms along the Gulf Coast (Regions 1-4), the Florida Peninsula (Regions 5-7), and the East Coast of the United States (Regions 8-11) tend to have unique seasonal landfall distributions. After these summations were made, a table of probabilities was generated. Since this table was created on ~100-150 years of data, the probabilities are somewhat rough. A 1-2-3-2-1 filter was applied to the data to arrive at a smoother distribution. Table 7 displays the smoothed probabilities of landfall for Regions 1-4 (the Gulf Coast) by ten-day period.

Table 7: Smoothed probabilities of storm landfall by ten-day periods for Regions 1-4 (the Gulf Coast). Probabilities are calculated based on all storms making landfall in the Gulf Coast during the period of record.

Date	**Named Storm**	**Hurricane**	**Major Hurricane**
Jan-May	1.4%	0.4%	0.2%
6/1-6/10	3.1%	1.6%	0.7%
6/11-6/20	4.8%	3.0%	1.7%
6/21-6/30	5.2%	4.3%	2.2%
7/1-7/10	4.7%	4.5%	2.7%
7/11-7/20	4.3%	4.6%	2.9%
7/21-7/31	5.1%	5.5%	5.1%
8/1-8/10	6.4%	7.2%	7.7%
8/11-8/20	7.7%	9.1%	10.9%
8/21-8/31	9.0%	10.3%	12.3%
9/1-9/10	10.5%	11.4%	13.5%
9/11-9/20	11.2%	11.3%	13.5%
9/21-9/30	10.3%	10.3%	12.1%
10/1-10/10	7.7%	7.7%	8.5%
10/11-10/20	4.8%	4.9%	4.3%
10/21-10/31	2.3%	2.2%	1.4%
11/1-11/10	1.0%	0.9%	0.2%
11/11-11/20	0.3%	0.3%	0.0%
11/21-11/30	0.2%	0.3%	0.0%
Dec	0.1%	0.2%	0.0%
Total	**100%**	**100%**	**100%**

Ten-day probabilities were reduced to the daily level by simply dividing the ten-day probability by ten. We will now consider an example to help illustrate how these calculations were made.

An individual is planning a trip to Cameron County, Texas from September 23 – September 30. They want to know the climatological odds of tropical cyclone landfall during that time period. We have calculated from previous examples that the probability of a named storm making landfall in Cameron County over the course of a season is 6.3%. We know that approximately 10.3% of all named storms along the Gulf Coast made landfall over the period from 9/21 – 9/30. Therefore, to calculate the probability of landfall over the period from 9/23 -9/30 (80% of the period from 9/21-9/30), the following calculation is made:

Probability of Landfall = (6.3%) * (10.3% * 80%)

Probability of Landfall = (6.3%) * (8.2%)

Probability of Landfall = 0.51% or approximately one chance in 200

The climatological probabilities of receiving wind gusts over a short-time period are calculated using the same approach. For example, for Cameron County, the probability of receiving hurricane-force wind gusts (annual probability is 11.7%) over the same time period (9/23 – 9/30) would be calculated as follows:

Wind Gust Probability = (11.7%) * (10.3% * 80%)

Wind Gust Probability = (11.7%) * (8.2%)

Wind Gust Probability = 0.95% or approximately one chance in 105

5. Calculating State Hurricane Impact Probabilities

The National Hurricane Center maintains a database of hurricane impacts that extends back to the mid-19th century (http://www.aoml.noaa.gov/hrd/hurdat/ushurrlist18512008_jun09.txt). At this point, the database is deemed to be quite reliable back to the start of the 20th century, so we have utilized data since 1900 to calculate climatological and current-year probabilities of each state being impacted by a hurricane and major hurricane. Several states can be impacted by the same tropical cyclone, for example, Hurricane Katrina impacted Louisiana and Mississippi as a Category 3 hurricane while impacting Florida and Alabama as a Category 1 hurricane.

A. Calculating probability of hurricane impact for a state

The total number of hurricanes and major hurricanes to impact a state over the period from 1900-2008 were calculated, and probabilities were then derived from this information. For example, in Texas, 44 hurricanes and 16 major hurricanes impacted the state from 1900-2008. In calculating the probability for any particular year, one must consider that some years in the past had more than one hurricane impact. To approximate the future likelihood of storms, a Poisson regression model was used. The formula for the Poisson distribution is as follows:

$$EP = p^x/e^p x!$$

Where: EP = Expected Probability

p = Annual average number of tropical cyclones that have occurred in the past 100 years

x = Number of storms expected in the upcoming year based on the Poisson formula

x! = Factorial. If x = 3, then x! = 3*2*1 = 6

If x = 4, then x! = 4*3*2*1 = 24

e = 2.71828

For example, the Poisson-derived Expected Probability (EP) of exactly one hurricane impacting Texas, where 44 hurricanes impacted Texas over the past 109 years (p = 0.40) is calculated as follows:

$EP = p^x/e^p x!$ (Poisson formula)

$p = 0.40; x = 1$

$EP = (0.40)^1/e^{0.40}1!); 1! = 1$

$EP = 0.40/(1.4918)$

$EP = 0.27$ or 27%

Therefore, the probability of exactly one storm impacting Texas in an average year is 27%.

6. Current-Year Probabilities

Current-year probabilities were calculated by simply multiplying climatological probabilities by the predicted Net Tropical Cyclone Activity value divided by 100. We have shown in several papers that from a long-term perspective, more active tropical cyclone seasons have more United States landfalls. We hope to include some adjustment factor based on analysis of steering current patterns in the future, but this is still currently a work in progress.

If the predicted NTC value for a given year was 130 (seasonal forecast is to have 130% of tropical cyclone activity compared to the average season), all values would be multiplied by 1.3. Storm number values and wind gust probabilities were multiplied by the NTC factor, and then these revised values were fit to the Poisson distribution.

7. Conclusions

To our knowledge, this is the first website available that provides landfalling storm and wind gust probabilities and adjusts them based on the current global climate features and their projected effects on the upcoming hurricane season.

These webpages allow coastal residents to learn of the probabilities of tropical cyclone landfalls and wind gusts for their own local region. This information should be valuable for coastal residents, emergency managers, local governments, insurance companies, business groups and others.

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