A Systematic Analysis of Direct and Indirect Casualties Associated with Atlantic Basin Tropical Cyclones

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Abstract

Major tropical cyclones (TCs) often produce tremendous property damage and significant loss of life. As tropical cyclones track inland and dissipate, their impacts can be substantial. This study provides a detailed view of the various factors and the resulting deaths using data from the last 40 years of tropical cyclone history. It documents all reported TC related deaths of 106 tropical cyclones from 1970 to 2011. A database of all-cause TC deaths associated is created to understand the number of indirect and direct deaths and the spatial distribution of the deaths relative to the shoreline and tropical cyclone track. Various tropical cyclone attributes, including size, strength, and speed of movement are related to the spatial pattern of deaths and their location relative to the cyclone track. Loss of life occurs as far inland as 700 km from the shoreline and as far as 700 km from the center of the track. The spatial distribution of the deaths around a TC vary according to the type of impact that caused the death. Rain-related deaths tend to be equally distributed across the track and well inland from the shoreline, while wind-related deaths remain concentrated close to the track and close to the shoreline.

1. Introduction

Previous research (Rappaport 2000) has focused on "direct deaths", which result from factors directly connected with the TC, such as the high winds, tornados and storm surge. Casualties that are not directly attributed the TC typically go unreported. Hurricanes, however, as with other hazardous environmental events, can cause human deaths by means other than direct contact with the event's physical forces and can create conditions that contribute to increased mortality well after the wind and rain have ceased

(Combs et al. 1996). These "indirect deaths" result from a range of causes before, during, and after the TC event. Because the exact cause of an indirect death is not limited to contact with storm-driven impacts, the list of possible causes of these deaths is endless (McKinney et. al. 2010). For example, deaths occur while people are preparing for the storm, such as falling off a rooftop, or from such events as being crushed by a tree during cleanup, debris preventing timely emergency care, or carbon monoxide poisoning from generators.

1.1 Impact Types

The majority of cyclone research has focused on economic losses and loss reduction rather than casualties (Borden and Cutter 2008). In 1972 the American Meteorological Society found that 90% of hurricane-related deaths were due to storm surge along the coastline (AMS 1973, Rappaport 2000).

Storm surge alone does not cause all fatalities linked to tropical cyclones. Drowning can occur from freshwater flooding associated with rainfall occurring hundreds of miles inland (Rappaport 2000). For example, inland floods from Hurricane Floyd in 1999 claimed 50 lives in the United States (Rappaport 2000). In a more recent study Rappaport found that rainfall induced freshwater floods accounted for about a quarter of the direct deaths (2014) associated with TCs. The main impacts from tropical cyclones tend to revolve around flooding, wind, and storm surge (Rappaport 2000).

TC impacts also produce indirect deaths, which were not addressed in Rappaport's original 2000 research and follow up 2014 study. Indirect deaths include heart attacks, house fires, electrocution from downed power lines, and vehicle accidents on wet roads (Rappaport 2000). There is a wealth of undiscovered deaths indirectly associated with the

wind, including deaths from fallen trees in post recovery efforts and electrocution from downed power lines. Zane et. al. (2011) found that 64% of deaths from Hurricane Ike (2008) resulted from injuries associated with carbon monoxide poisoning (18%), drowning (11%) and other illnesses such as cardio vascular failure (16%). This research suggests a strong need to systematically document the number and the nature of deaths that are not normally attributed to a TC.

1.2 TC Attributes

The attributes of a TC, specifically its speed of movement, size, and strength play a key role in the determining the number, the nature, and the geographic distribution of deaths. Some studies focus on TC behavior post landfall (e.g. Kaplan and DeMaria 1995), while others focus on the TC impacts along a specific coastline (Kruk et. al. 2010). Few studies have examined the relationship between the aforementioned TC attributes and the spatial distribution of deaths along the shoreline and from the center of the track. Kaplan and DeMaria (1995) examined the role that storm motion speed at landfall played in the prolonged TC impacts as the storm moved inland. They found that storm motion speed is just as critical as the storm intensity upon landfall in affecting the spatial distribution of deaths (Kruk et. al. 2010).

In this study, a database of all TC- related deaths, both direct and indirect is constructed. From this database, GIS is employed to determine spatial pattern of deaths relative to the shoreline and each TC track. The size, speed of movement, and intensity of the TC sample are calculated and associated with the geographic distribution of deaths.

2. Data and Methodology

2.1 Study Area

The study area encompasses the eastern United States, focusing on all TCs that made landfall along the Atlantic and Gulf coasts or came within 100km of those coastlines (Figure 1). Any TCs that made landfall along the coast of Mexico or along the Canadian Atlantic provinces were excluded from the analysis.

2.2 Data Sources

This study collected data from three primary sources: AmericasNews Bank, National Oceanic and Atmospheric Administrations (NOAA) Storm Events Database, and Edward Rappaport's study on "Loss of life in the United States associated with Recent Atlantic tropical cyclones" (2000). Each of these sources has several limitations.

Newspaper articles were key to recording indirect deaths associated with the TC's in the study. Newspaper articles are biased towards urban locations and tend to lack geographic coordinates. Specifically the information from the newspapers is geo-coded to either the street, municipal area, or county depending on the specificity of the information provided in the article (Kovach and Konrad 2014). The newspaper archive used AmericasNews Bank (http://infoweb.newsbank.com), and this created time period limitations, as the archive only contains newspapers from 1985 on and prior to 1990 the articles are sparse. To find deaths associated with each storm, several keywords were used, including the storm name, the relevant date range, and the specific words "death", "died", and "killed".

In addition to the keywords, a buffer of two days before and after the storm dates was added to capture related death news articles. The two day buffer was selected because more than two days after the storm the data became less relevant. Additional data sources

(listed below) are included to help overcome this. Once the related articles were listed, each article was individually searched for direct and indirect deaths. Deaths found in an article were recorded along with the article source.

The second source, NOAA Storm Events Database (http://www4.ncdc.noaa.gov/cgi_wind/wwcgi.dll?wwwEvent~Storms), is a database that contains much information about each severe weather event from 1950 to present, including every death (both direct and indirect) reported by NOAA. Storm events information is provided by the National Weather Service and other sources, including news media, law enforcement, agencies, and citizen's reports. NOAA's Storm Event database was used as a supplemental source to add any deaths that may not have been reported in the newspapers.

To find deaths using the Storm Events database, storms were searched individually by using a date range, the state name, and type of impact (e.g. high winds, storm surge, etc). Previous studies have found biases in this database, including underreporting of casualties from small impact events (e.g. lightning and hail) (Ashley and Ashley 2008). For this database search, the date range was extended to include five days before and five days after the actual storm event. The query results included but were not limited too individual death information, including city, county, death description, direct and indirect, and if available, the gender and age of the deceased, and the date and time. The National Weather Service and other sources, such as news media, law enforcement agencies and citizen's reports provide the data for Storm Events (Kovach and Konrad 2014).

The final data source is Edward Rappaport database of direct deaths, developed for the period: 1970 through 1999. His data was used to compliment and verify direct deaths

for TC's between 1970-1999. It was used specifically to collect death information from 1970-1985 due to the lack of available information for this time period in the previous two sources.

From these three sources, the information gathered included the state, county where the death occurred, the type of impact, the cause of death, a description of the death, and in some cases, the date and time in which the death occurred.   In some cases, the city or the street of the death was not provided in which case just the available information was recorded (e.g. state and county).   Most of the information was readily found in newspapers, however, in some cases indirect deaths that were found in newspapers were only listed by the number of deaths that occurred in a state. In this case, other newspaper articles were searched from those states to find more specific geographical information. In some cases the information was found, in others none. Although three distinct data sources were used, care was taken to ensure no deaths were recorded twice.

2.3 Death Categories

For this study casualties (aka deaths) are classified into two major categories: direct deaths and indirect deaths. Direct deaths are deaths that occur during the storm and are attributed to direct impacts from the storm. Indirect deaths are deaths that occur prior to, during, and after the storm event. Table 2 outlines how Rappaport 2000 classified deaths.

2.4 Death Locations

To relate deaths to actual storm systems, a geocoded location is created for each death. Using the GPS Visualizer website, the most precise location provided with the death (city, street, county, or state) was typed into the search engine on the site producing latitude and longitude coordinates. This information was recorded in the database created for this study. The database

was then imported into GIS to produce a map identifying the locations of all deaths documented in this study.

2.5 Storm Analysis

The ArcMap Geographic Information System (GIS) software package was used to develop a spatial perspective Specifically, it was used to estimate the size and speed of movement of each TC, and the location of each death relative to the storm's track and the nearest shoreline. Archived surface maps were first examined to determine if each death recorded was associated with the storm.

The ArcMap near-distance tool, which allows the measurement from a data point to a line, allowed for an estimation of the distance of a death from the respective storm track. An option in this tool provides a measure of the angle of a data point from the storm track line, which was exploited to ascertain whether each data point fell to the left or the right of the storm track.

For each death the distance from the death data point to the nearest true shoreline (either the Gulf or Atlantic Coast) was calculated using GIS. For the shoreline the angle of the data point was not used because each death occurred to the left (inland) from the shoreline.

2.6 Storm Size

The size of each TC was determined using daily surface weather maps from the HPC database between 2003 and 2011, then from the NOAA Central Library US Daily Weather Maps projects between 1970 and 2002. Using the same methodology as Kovach (2014), the size of the storm was then estimated by measuring the area inside the outermost closed isobar using NOAA's daily weather maps (http://www.hpc.ncep.noaa.gov/dailywxmap/) at

the time closest to the storm landfall (Figure 1.3).   Weak or very small TCs that did not

have an outermost closed isobar were recorded as zero. TCs were stratified into three

tercile groups (small, medium, and large) on the basis of their size. With the size listed in

ascending order, the first third of the storms were put into the small category (0-151,711

sqkm), the middle third in the medium category (151,711-432,002 sqkm), and the upper

third put into the large category (432,002-1,664,994 sqkm)

2.7 Storm Track

A storm track is simply the path traced by the center of the system as it moves

across the region. For each storm, a shape file was created for the track to determine

where TC deaths occurred relative to the storm track. An existing outline map of the US

was imported into a blank map in ArcMap and transformed into the North American Datum

(NAD) 1983 projection. To create the line representing the storm path, track points were

plotted using latitude/longitude coordinates imported into ArcMap from the North Atlantic

Hurricane Database (HURDAT), based on the year. Track points were plotted at six hour

intervals. Using the line tool in ArcMap the points were then connected and saved as a

track shapefile for use in later analysis. Figure 1 shows all tracks of all TCs whose deaths

were examined in this study.

2.8 Storm Speed of Movement

The TC's speed of movement was measured as the distance traversed by the center

of the TC with respect to time. Using the individual track points determined in the track

analysis, the speed of movement for each storm was determined from the position

information given in the NHC's HURDAT database. Kovach (2014) employed a similar

methodology to determine speed of movement. The present study focuses on the distance

travelled as the TC makes landfall (e.g. from the last point at sea to the first point inland)

rather than in the first 24 hours after landfall. Table 3 summarizes the categorization of

storm speed, size, and intensity.

2.9 True Shoreline

 For this study, a "true shoreline" of the Gulf and Atlantic coast was created. The

"true shoreline" is defined as any part of the coastline that touches the Gulf of Mexico or

Atlantic Ocean. This true shoreline excludes certain areas that touch large bodies of water,

for example the North Carolina Sounds and the Chesapeake Bay. For the Florida Keys the

true shoreline extended the Florida shoreline to include the outer shorelines of the Florida

Keys. Using this definition the shoreline was drawn in GIS using an existing United States

shoreline file as a guide.

2.10 Intensity

The intensity of a TC is defined by the maximum sustained wind speed. The

HURDAT data was used to determine maximum wind speed at the 6-hour time closest to

the storms landfall.

2.11 Hurricane Katrina (2005)

Hurricane Katrina [2005] was excluded from the study analysis for several reasons.

First there were an exceptionally large number of indirect deaths that occurred after the

storm, many of which are poorly documented. Second, there is an unknown degree of

underreporting of deaths with the Hurricane. The flooding from the levee breaches caused

80% of New Orleans to be flooded, generating more than 1,100 fatalities, most of which

occurred in the lower 9th ward of New Orleans (Rappaport 2014). Third, the exceptional

number of deaths would strongly bias the study results (i.e. exert a disproportional

influence on the relationships). Rappaport (2014) in fact found that Katrina was responsible for more than 40% of the TC fatalities in the past 50 years.

3. Results and Discussion

3.1 Overview

The purpose of this research is to develop a detailed analysis of all deaths related to TCs, both direct and indirect, and the spatial distribution of the deaths based on storm characteristics (size, speed, intensity), geographical landfall location (Gulf versus Atlantic coasts), the distance from the shoreline, and the distance and spatial relationship (left or right) to the storm track. The goal is to look for distinctive patterns in the data that yield insight into the relationship between TC deaths and the various characteristics.

The analysis consists of 106 Atlantic basin tropical cyclones that made landfall or came within 60 kilometers of the continental United States between 1970-2011 and caused one or more fatalities (Fig. 1). Of the 106 TCs, 70 (66%) made landfall along the Gulf coast, 23 (22%) made landfall along the Atlantic Coast, and 13 (12%) did not make landfall. In terms of intensity, 56 storms were sub-tropical or tropical (53%), 36 storms were Category 1 or 2 (34%), and 14 storms were Category 3, 4, or 5 (13%).

A total of 1,408 direct and indirect fatalities were recorded and categorized (Table 4). An additional 74 fatalities were recorded, but records were insufficient to determine the specific cause and location of death. These additional deaths are included in storm death totals, resulting in 1,482 total fatalities. Overall, roughly two-thirds of fatalities were classified as direct and one-third as indirect. About half of the fatalities were rainfall related (e.g. associated with freshwater flooding, post storm flooding, and heavy rain).

Atlantic land falling storms accounted for 28% of the total deaths, Gulf storms accounted

for 67%, and non-land falling storms resulted in 5% of the deaths.

Each death location was analyzed to determine distance from the nearest shoreline,

distance from the center of the storm track, and whether the death occurred to the left or

the right of the track. For Atlantic land-falling TCs 61% of the deaths occurred to the left of

the track, and for Gulf storms, 50% of the deaths occurred to the left of the track.

In terms of individual storms, the largest loss of life was associated with Hurricane

Rita (2005), with over 140 fatalities attributed to the storm. Many of these fatalities were

indirect and associated with health complications (i.e. heart attacks, oxygen tank depletion

etc.) in Texas. After Rita, Hurricane Agnes (1972) was the deadliest tropical cyclone during

the study period, accounting for over 130 fatalities. Roughly 41% percent of these fatalities

occurred as Agnes tracked inland after making landfall. Overall, the top 5 storms were

responsible for about a third of all recorded fatalities. Again, Hurricane Katrina (2005) was

excluded from this study, due to the strong bias on the study sample.

3.2 Geographic Distribution of Deaths

The results of a geographical analysis of death locations across the entire eastern US

shows a concentration in the states near an Atlantic or Gulf coastline (Figure 3a).

However, when deaths are compared on a per capita versus a per area basis, different

states are highlighted with respect to risk. Texas, Louisiana, Florida, South Carolina, and

North Carolina account for the most fatalities per capita (3b), ranging from 1.2 to 1.9

deaths per 100,000 residents. In terms of fatalities per unit area (3c), Florida is again

amongst the top states, however, Massachusetts, New Jersey, and Delaware actually have

more fatalities per 100 square kilometers, due to a high number of deaths within a small area.

3.3 Deaths per Storm

To explore the relationship between storm characteristics and impact type, Table 5 shows both total deaths and the average number of deaths per storm stratified by storm strength, size, and speed. The impact types examined are rain, wind, tornado, and surf, but exclude evacuation, unknown, and others. The analysis provides several counter-intuitive results.

In terms of intensity (Table 5a), Category 1 and 2 hurricanes account for nearly 50% of the total deaths (675), in spite of representing only 34% of the storms studied. Additionally, Category 1 and 2 storms have a similar death per storm value (18.8) as Category 3, 4, and 5 storms (19.8), both of which are more than double the Tropical storm value (9.5). Also of note, in terms of impact type, rain related deaths are higher for Tropical storms (6.2) than for Category 1 and 2 hurricanes (5.0). This relationship of higher death per storm for rain related impacts also holds true with small storms (5.0) versus medium storms (3.1) (Table 5b).

Larger storms, as expected, generate more deaths due to covering a wider land area, however the deaths per large storm (21.2) is more than double the deaths for medium (11.8) and small (9.0) (Table 5b). Conversely, medium speed storms (17.3) and fast moving storms (16.5) both have more than double the deaths of slow speed storms (8.0) (Table 5c).

These results indicate that hurricanes produce twice as many deaths per storm as tropical storms; large storms are twice as deadly as medium and small storms; and higher

speed storms (medium and fast) also produce a doubling of deaths per storm versus slow speed storms. Finally, rain related impacts produce the highest deaths per storm, regardless of storm intensity, size, or speed.

3.4 Distance from Shoreline

One interesting metric of TC deadliness is how far inland TC-related deaths occur after landfall, in particular, the distance from the shoreline in which the TC made landfall (Figure 4). As expected, the number of TC-related deaths decreases with increasing distance inland from the shoreline; however, this decrease is more dramatic for TCs making landfall along the Atlantic coast than the Gulf coast. Specifically, for Atlantic storms, 15% of the deaths occur more than 200 km inland, while for Gulf storms 32% of the deaths occur more than 200 km inland, likely due to the fact that Gulf TCs tend to penetrate further inland (Fig. 1). Also noteworthy is that about 10% of Gulf storm deaths occur more than 600 km inland from the coast.

This study provides more insight by further categorizing death distances from the shoreline by impact type (Figure 5). The data shows that while wind and tornado related deaths are localized within 400 km of the shoreline, significant numbers of rain related deaths extend out to 700 km, with more than half of the deaths related to rainfall occurring more than 200 km inland. Note however that about 20% of these far inland deaths were due to the flooding in Pennsylvania associated with Hurricane Agnes (1972).

The data also shows that wind and tornado related deaths display similar patterns and are more common immediately inland from the coast. Roughly 60% of these deaths occur within 100 km of the shoreline, since wind speeds associated with TCs typically decrease rapidly as the system moves inland.

3.5 Distance from Track

Additional insights are available by considering the variables of distance from the storm track (instead of just shoreline), stratified by Atlantic versus Gulf storms and impact type, and further categorized by the storm characteristics of intensity, size, and speed.

In general, Gulf coast storms produce deaths across a much wider area around the storm track than Atlantic storms (Figure 6). Specifically, Atlantic coast storms produce more than 50% of deaths within the first 100 km of the track (Figure 6b), while Gulf coast storms produce more than 60% of deaths at distances greater than 100 km (Figure 6a).

Wind-related deaths occur closer to the center of the track (Figure 7b) than rain-related deaths (Figure 7a), with a significant number of rain related deaths extending out to 700 km. While both rain and wind related deaths decrease rapidly as the distance from the track increases, tornado related deaths (Figure 7c) are more evenly distributed up to 500 km from the track, highlighting a more constant threat level for tornados even at great distances.

Additional insights are found by augmenting the distance from track analysis to include storm categories (Figure 8). As expected, regardless of intensity, size, or speed, the most deaths occur within the first 100 km. Note that while hurricanes produce more than 50% of deaths within the first 100 km, tropical storm deaths are more evenly spread across the 700 km distance from the TC center (Figure 8a). Of particular interest is the decrease in percentage of deaths in the first 100 km as storm size increases (Figure 8b).

Viewing the data based on storm speed (Figure 8c) shows that fast moving storms produce more than half of deaths in the first 100 km, slow moving storms also have a high number of deaths within 100 km. Storms with a medium speed of movement show a high

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proportion of deaths within 300 km of the track. These results indicate that TC attributes

play a strong role in shaping the spatial pattern of deaths.

3.6 Distance left and right of the storm track

The final extension to the study investigates how the deaths are distributed left and

right of the storm track. The distribution of deaths in Gulf and Atlantic-landfalling storms

is very distinct (Figure 9). Gulf storms produce significantly more deaths within the first

100 km to the right of the track than to the left, while the opposite is true for Atlantic

storms (Figure 9b). This difference is likely due to the fact that the right semicircle of many

Atlantic storms remains largely off the east coast, while this region in Gulf storms always

makes landfall. Also of note is the wider distribution of deaths for Gulf storms, up to 700

km, in comparison with Atlantic storms, in which nearly all deaths occur within 500 km.

The distribution of deaths is further stratified according to the impact type (Figure

10). Rain related deaths (Figure 10a) occur most frequently and display a normal

distribution up to 700 km from the storm track. Rain related deaths decrease with

increasing distance from the track, as the outer bands of the TCs tend to be less

concentrated and weaker than the inner bands and the eye wall. Rain can cause both

indirect and direct deaths, and the data shows that approximately 20% of all rain-related

deaths were classified as indirect (e.g. auto-accidents caused by wet roads).

As expected, wind related deaths (Figure 10b) and tornado related deaths (Figure

10c) happen more frequently to the right of the storm track and additionally, tornado

related deaths often happen farther from the track than wind related deaths. Specifically,

more than half of all wind related deaths occurred to the right of the TC track, which is

consistent with previous studies (Kruk et al 2010) that determined the right quadrant of a

TC contains the strongest winds, increasing the possibility that a tornado will be generated up to 600 km from the storm track.

Surf related deaths have an unusual and somewhat erratic pattern in both the distance from the track and the geospatial location (Figure 10d). This result indicates that any community within the vicinity of a TC can be affected by surf events (e.g. rip currents and undertow) that can cause deaths, with little predictability based on distance or orientation to the storm track.

The final result further stratifies the number of deaths left and right of the storm track by storm characteristics (Figure 11). Tropical storms and strong hurricanes show a similar distribution with deaths concentrated in the region 100 km to the right of the TC track. Weak hurricanes, in contrast, show a peak 100 km left of the TC track; however, this is due to a disproportionate contribution of deaths from Hurricane Rita (2005), which accounts for a little more than 20% of all deaths in that interval.

Storm size (Figure 11b), clearly plays a strong role in how far from the center of the track the TC effects can be observed, with large storms causing deaths farther from the center of the track than small storms. Note that Hurricane Rita continues to influence the data heavily with a peak in the 0- 100 km bin for medium size TCs.

The final storm characteristic, storm speed (Figure 11c), shows that the distance and location of deaths varies dramatically based on storm speed. There is a large difference in the distribution to the left and the right, and the various storm speeds. Fast moving storms enhance the already strong winds on the right side of the track, resulting in 40% of all deaths to the right of the track being wind related. Slow moving storms have a

surprisingly wide distribution of deaths, and medium speed storms deliver a large number of deaths out through 300 km on both sides.

4. Conclusion

This study provided a sophisticated and detailed analysis of all deaths related to TCs, both direct and indirect. The spatial distribution of the deaths were analyzed and stratified according to three storm characteristics (size, speed, intensity), the coast in which the TC made landfall (Gulf versus Atlantic coast), the distance from the shoreline, and the distance and location (left or right) of the storm track.

The results provide a nuanced, insightful perspective on TC related deaths and the relationship to storm properties. Specifically, TC-related deaths are heavily influenced by factors beyond simply TC intensity. The location of landfall (Gulf or Atlantic), the distance from the center of the storm track or the nearest shoreline, and the geospatial location to the left or right of the storm track all heavily influence the quantity and cause of deaths produced by tropical cyclones.

Several broad conclusions result from the analysis. Rain related impacts produce the highest deaths per storm, regardless of storm intensity, size, or speed. While both rain and wind related deaths decrease rapidly as the distance from the track increases, tornado related deaths are more evenly distributed up to 500 km from the track, highlighting a more constant threat level for tornados even at great distances. Overall, these results strongly indicate that the size and speed of the storms play as large a role in death distribution characteristics as storm intensity.

Categories	Sustained Winds
Tropical Depression	0-38 mph
Tropical Storm	39-73 mph
Category 1 Hurricane	74-95 mph
Category 2 Hurricane	96-110 mph
Category 3 Hurricane	111-130 mph
Category 4 Hurricane	131-155 mph
Category 5 Hurricane	Greater than 155 mph

Table 1: Classifications of Saffir Simpson Scale (http://www.nhc.noaa.gov/sshws.shtml)

Indirect Deaths	Direct Deaths
Power Outage (e.g. house fires from unattended candles, carbon monoxide poisoning)	Drowned in Storm Surge, Rough seas, Rip Currents and Freshwater floods
Electrocution from downed power lines	Deaths from lightning
Auto-Accidents on wet roads (e.g. hydroplanes, poor visibility)	Deaths from wind-related events (e.g. flying debris, collapsing structures)
Health Issues (e.g. Heart Attacks, Stress, Heat-Related)	Deaths from tornado debris (e.g. crushed by tree, flying debris)
Deaths occurring during clean up or during preparation	Auto-Accidents (e.g. drowning, collision with downed trees)

Table 2: Indirect and Direct Deaths as defined by Edward Rappaport (2000)

Intensity	Minor	Minor	Major	Major
	Category 2 Hurricane or Lower		Category 3 Hurricane or Higher	
Size	Small	Medium	Large	
	0-151,711 sq km	151,711-432,002 sq km	432,002-1,664,994 sq km	
Speed	Slow	Medium	Fast	
	5.54– 17.66 km/hr	17.66 – 24.95 km/hr	24.95 – 52.90 km/hr	

Table 3: Storm classifications for this study

Category	Direct Deaths	Indirect Deaths	Total
Freshwater	426	13	439
Flood	91	49	140
Heavy Rain	48	76	124
High Wind	159	78	237
Tornado	34	7	41
Power Outage	0	92	92
Storm Surge	20	0	20
Surf	88	43	131
Offshore	52	5	57
Evacuation	0	127	127
Total	918	490	1408

Table 4: Deaths stratified by the nature of the impacts.

a. Storm Strength

Storm Strength	Deaths per Storm	Rain Related	Wind Related	Tornado Related	Surf Related
Tropical Storm	9.5 (530)	6.2 (348)	0.4 (21)	0.3 (14)	1.2 (66)
Category 1 & 2	18.8 (675)	5.0 (181)	4.9 (176)	0.4 (13)	1.2 (42)
Category 3,4,&5	19.8 (277)	7.1 (99)	8.1 (113)	1.0 (14)	1.1 (16)

b. Storm Size

Storm Size	Deaths per Storm	Rain Related	Wind Related	Tornado Related	Surf Related
Small	9.0 (315)	5.0 (176)	1.2 (42)	0.4 (15)	1.1 (38)
Medium	11.8 (425)	3.1 (110)	2.1 (75)	0.1 (5)	0.9 (34)
Large	21.2 (742)	9.8 (342)	5.5 (193)	0.6 (21)	1.5 (52)

c. Storm Speed of Movement

Storm Speed	Deaths per Storm	Rain Related	Wind Related	Tornado Related	Surf Related
Slow	8.0 (279)	5.3 (186)	0.7 (23)	0.1 (4)	0.8 (28)
Medium	17.3 (624)	6.3 (227)	2.8 (101)	0.5 (18)	1.1 (41)
Fast	16.5 (579)	6.1 (215)	5.3 (186)	0.5 (19)	1.6 (55)

Table 5: The average number of deaths per storm stratified by storm characteristics: (a) Strength, (b) Storm size, (c) Storm speed of movement. Values in parenthesis represent the total number of deaths.
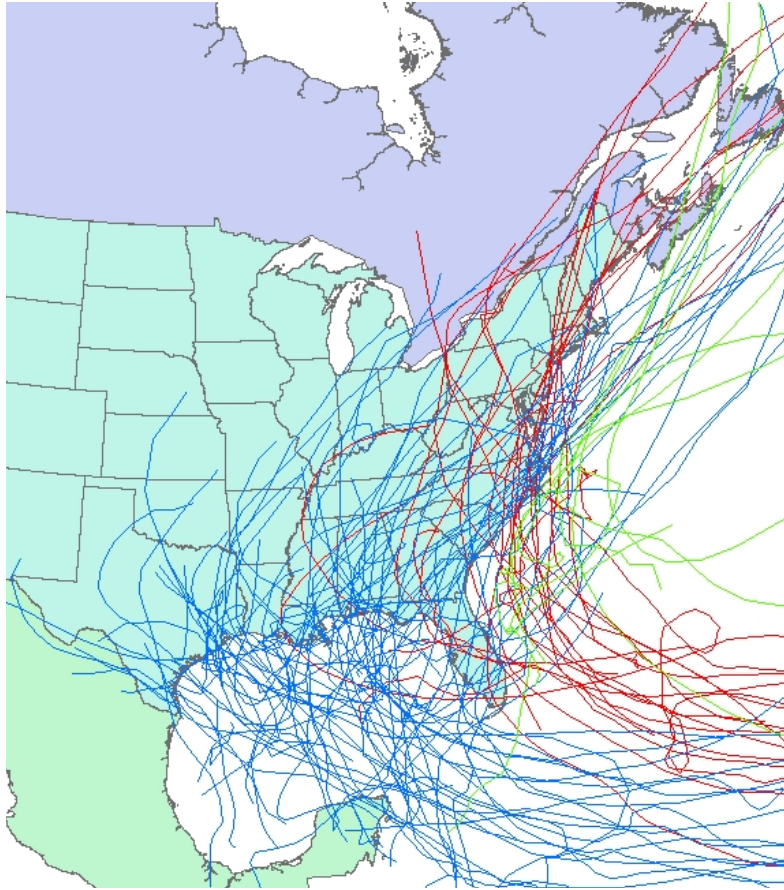
Figure 1: The tracks of tropical cyclones (TCs) making landfall along the Gulf (blue), Atlantic (red) and moving within 60 km of the coastline (green) during the study period.
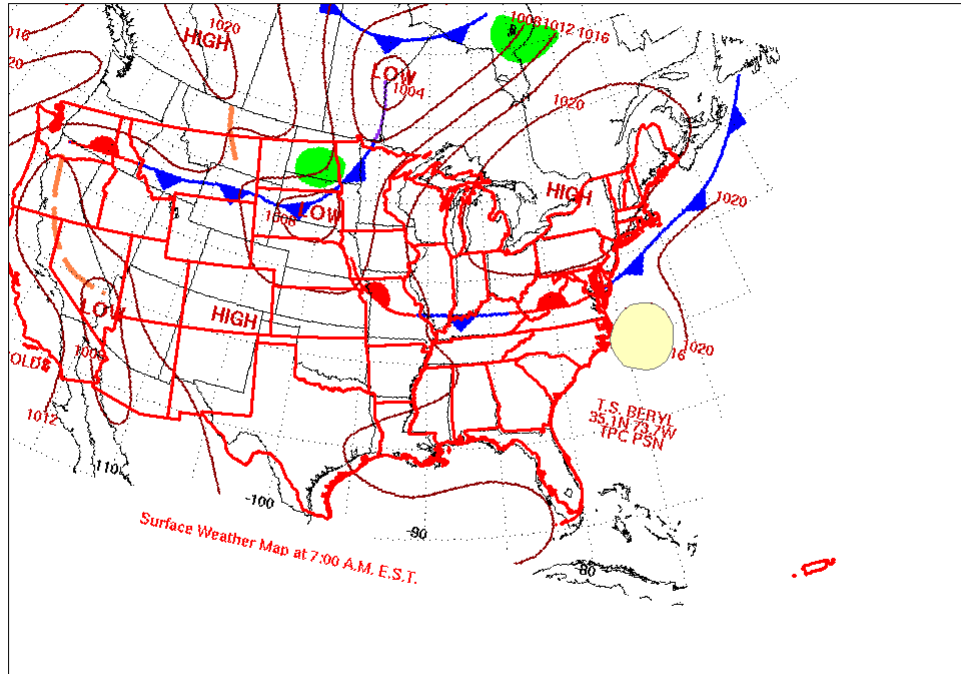
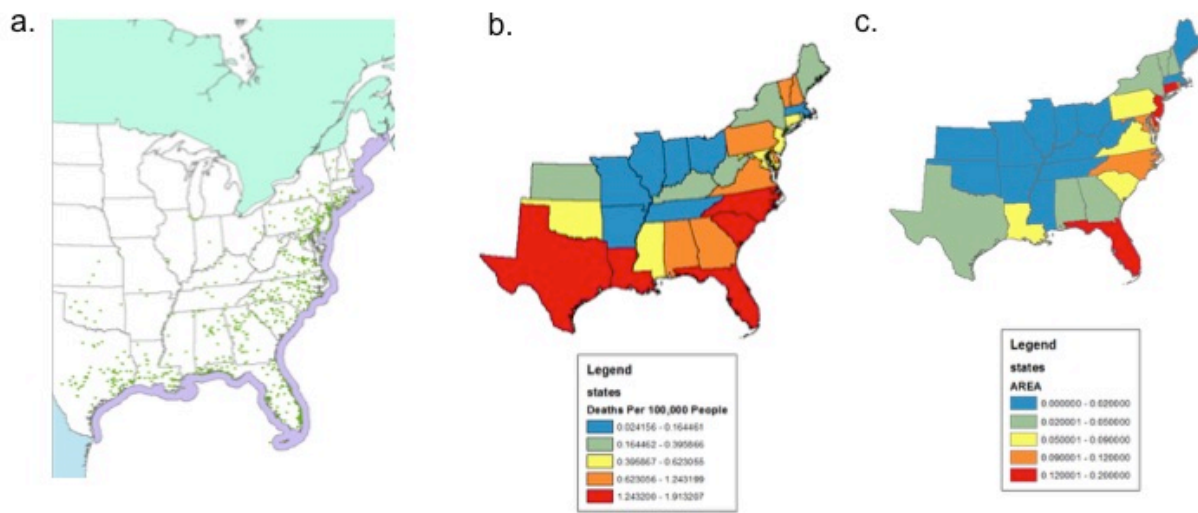Figure 2: An example of the area contained within the outer most isobar for Beryl 2006 (yellow shading).

Figure 3: The locations of each TC death in the study (a), the number of deaths per capita by state (b), and the number of deaths per unit area (100 km²) (c).
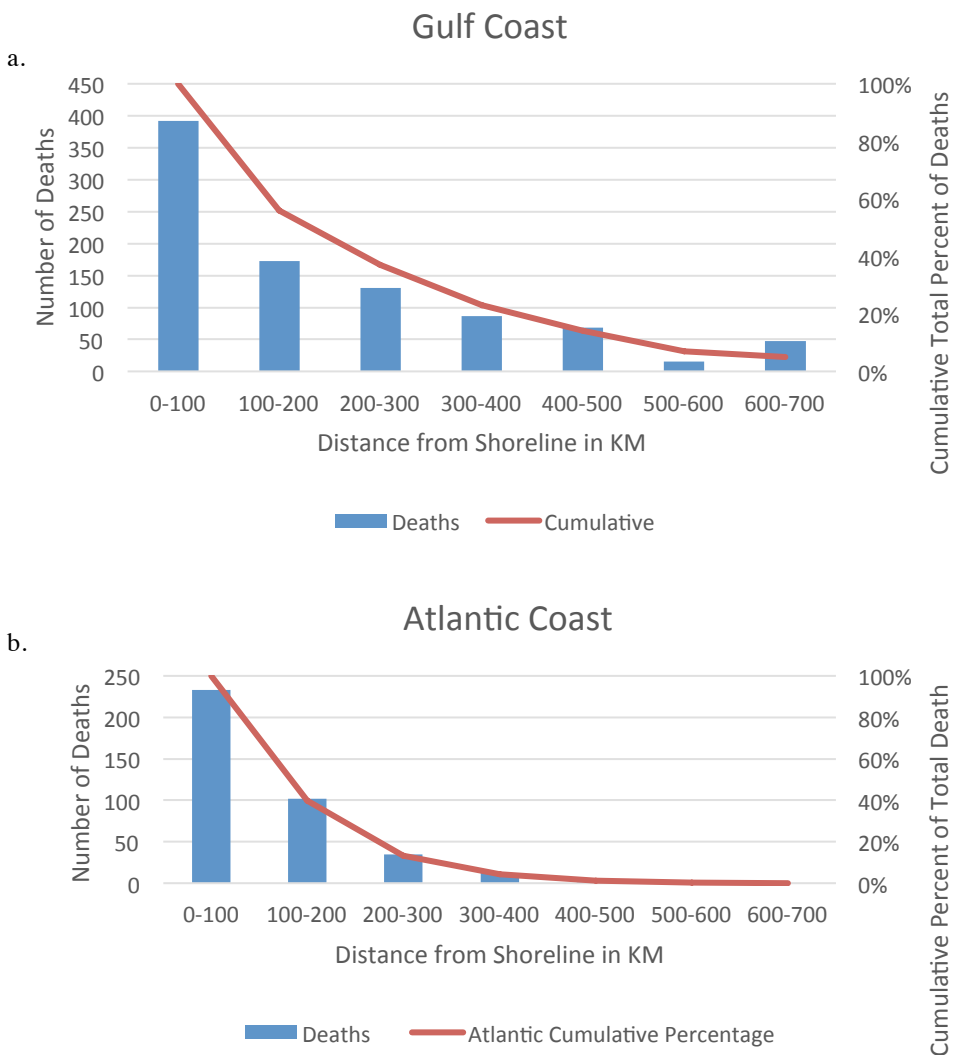
Figure 4: The number of deaths stratified by the distance inland from the shoreline for TC landfalls along the a) Gulf Coast and b) Atlantic Coast. The red line identifies the cumulative percentage of deaths from far inland (i.e. 600-700km) to the coastline).
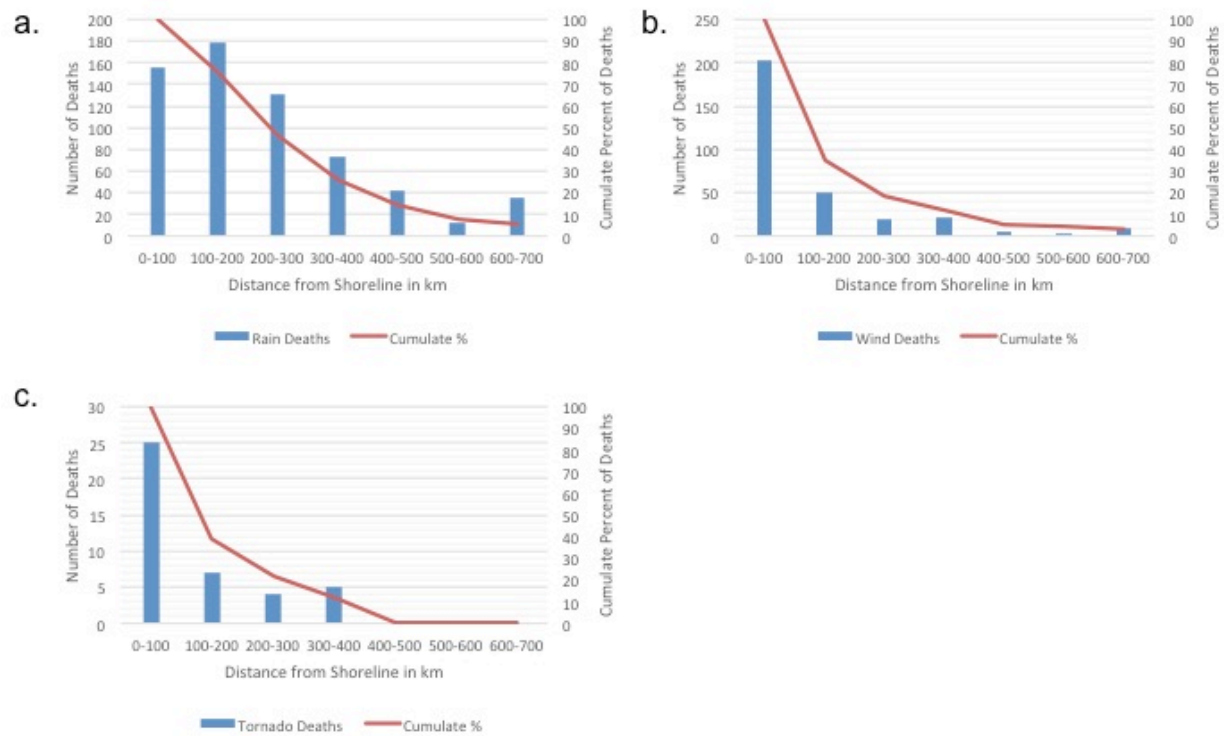
Figure 5: Same as Figure 4, except for rain related (a), wind-related (b), and tornado related (c).
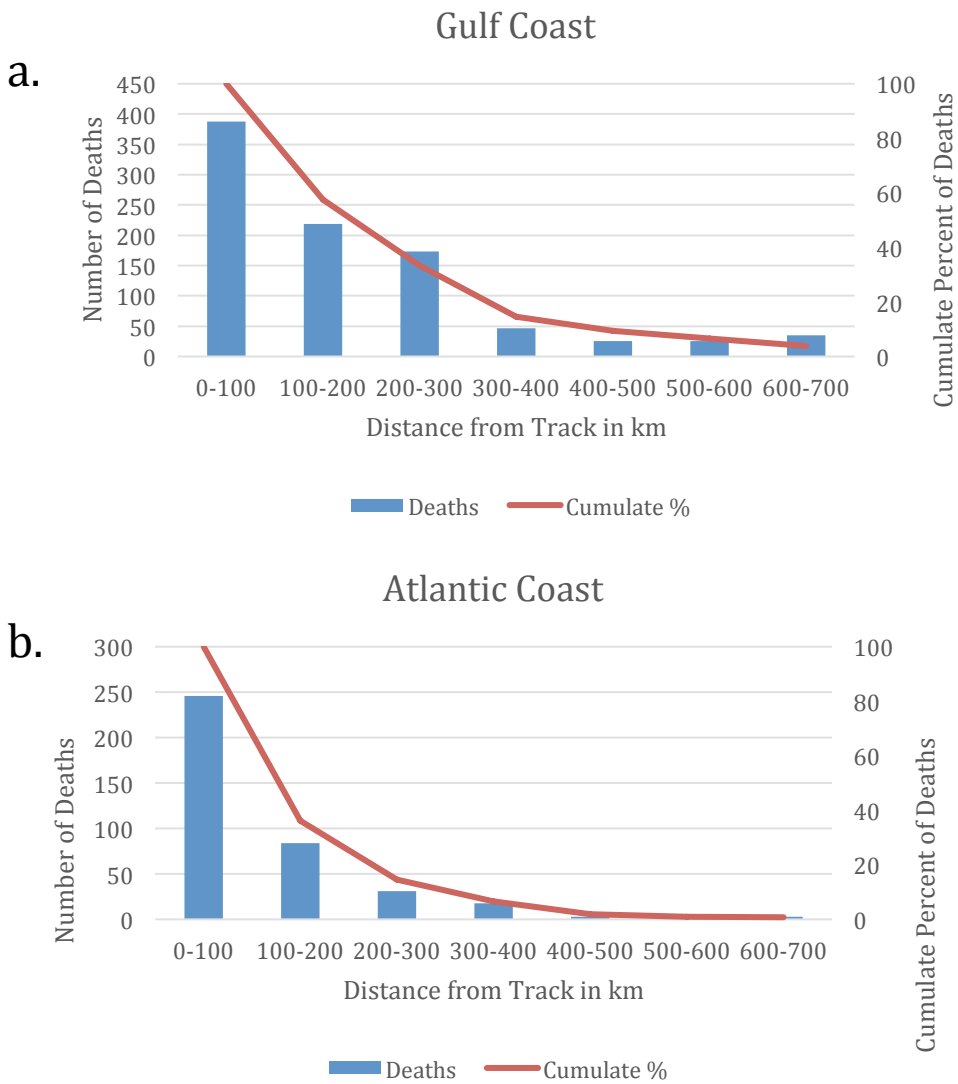
Figure 6: The number of deaths stratified by distance from the TC track for TC landfalls along the a) Gulf Coast and b) Atlantic Coast.
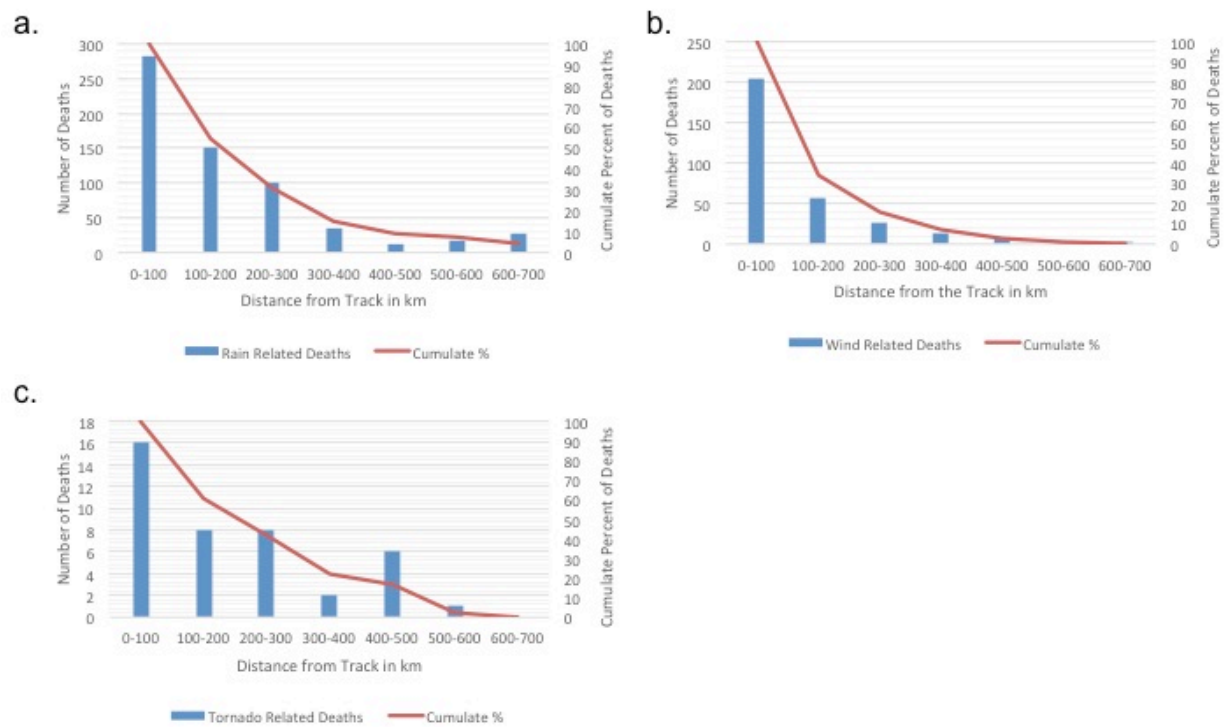
Figure 7: Same as Figure 6, except for rain related (a), wind-related (b), and tornado related (c).
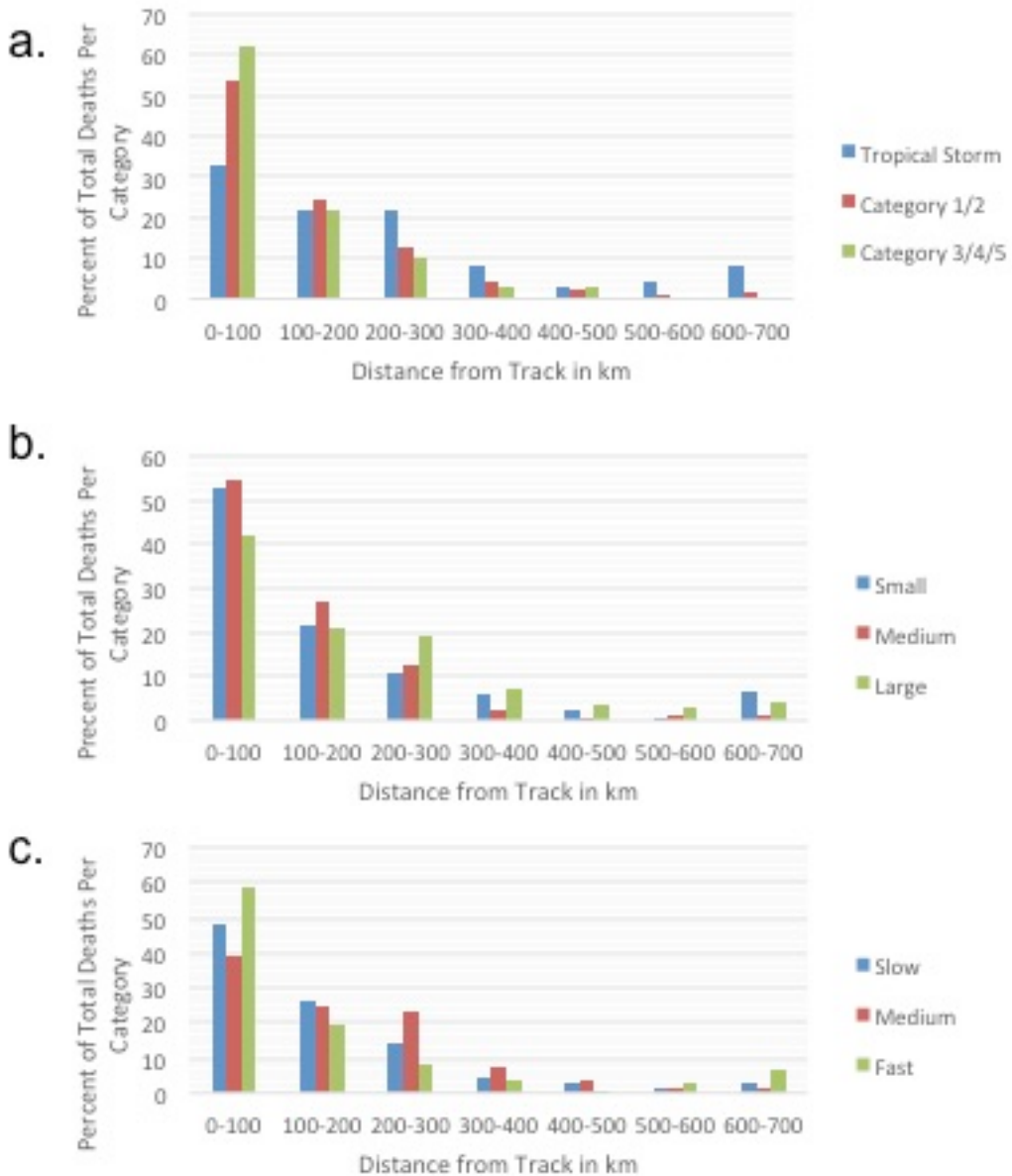
Figure 8: The percentage of the total number of deaths stratified by distance inland to the TC track across TC tercile classes of: (a) strength, (b) size, and (c) speed of movement.

a.

Gulf Coast

Number of Deaths

250
200
150
100
50
0

600-700 500-600 400-500 300-400 200-300 100-200 0-100 0-100 100-200 200-300 300-400 400-500 500-600 600-700

Deaths

Distance from Track in km

b.

Atlantic Coast

Number of Deaths

160
140
120
100
80
60
40
20
0

600-700 500-600 400-500 300-400 200-300 100-200 0-100 0-100 100-200 200-300 300-400 400-500 500-600 600-700
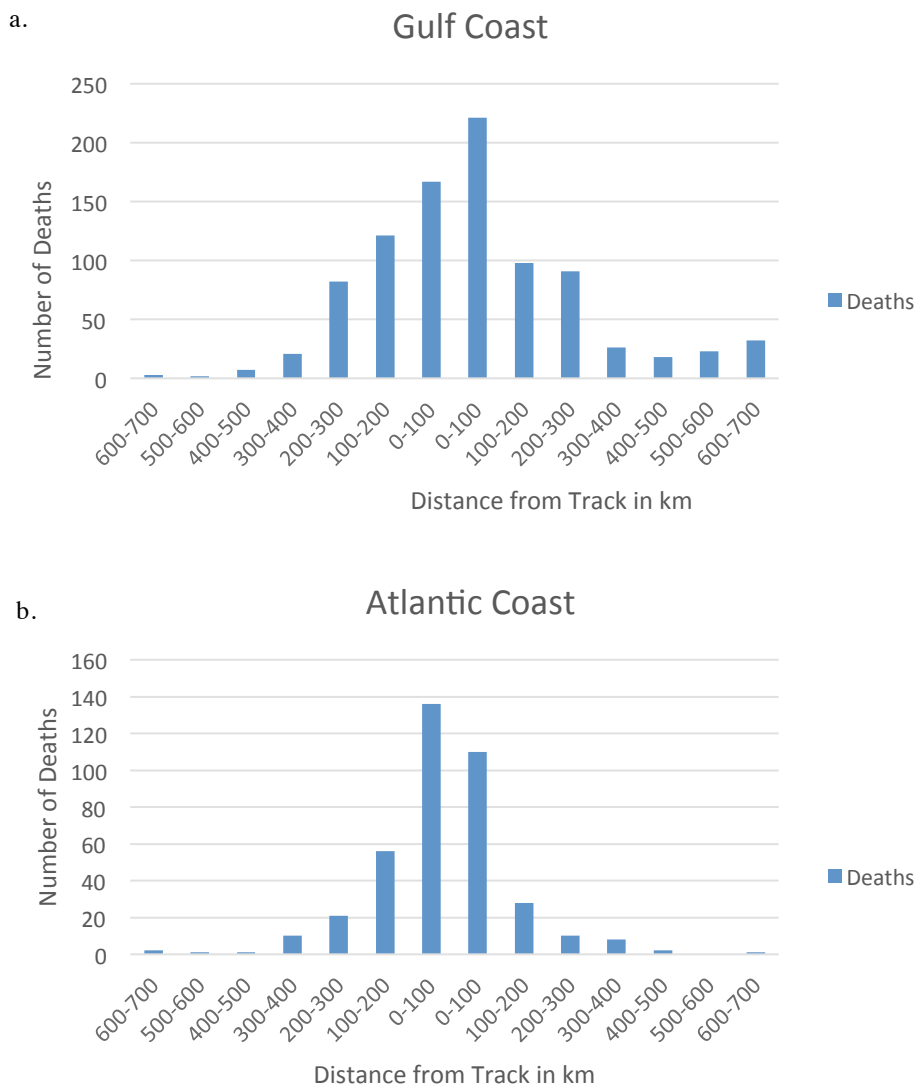
Deaths

Distance from Track in km

Figure 9: The number of deaths and the distance (km) left and right of the TC track for TC landfalls along the a) Gulf coast and b) Atlantic Coast
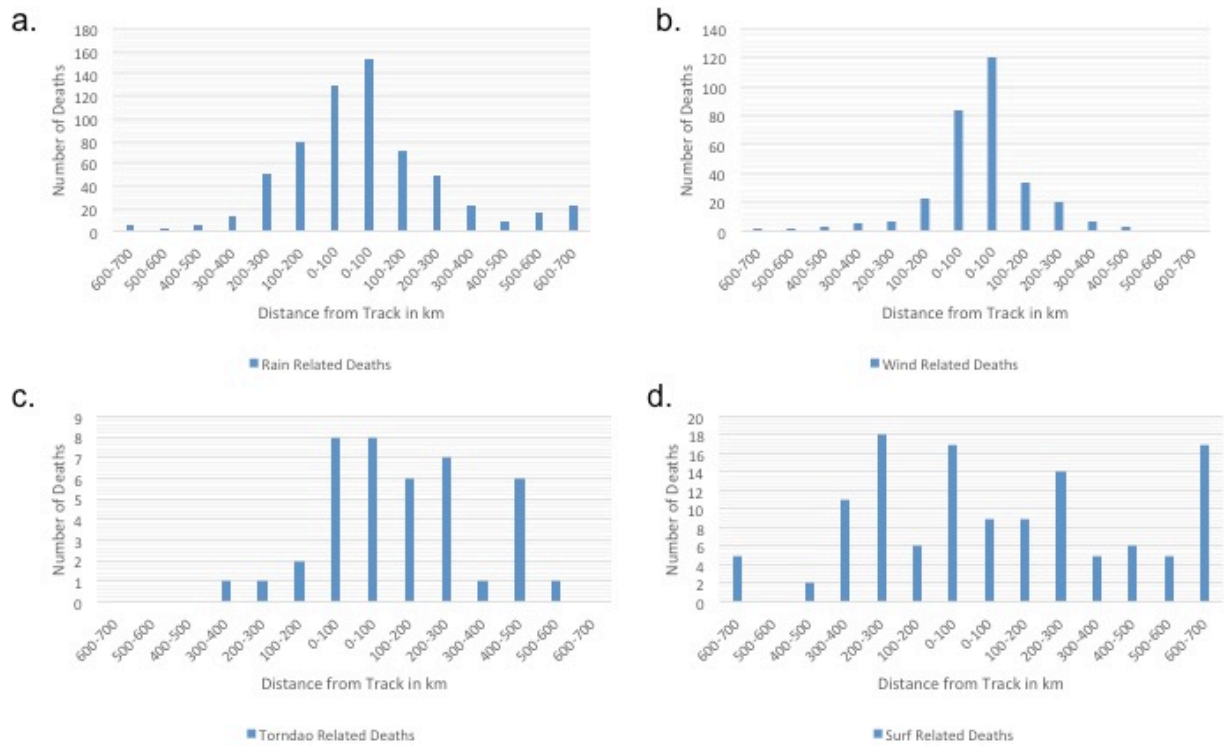
Figure 10: Same as Figure 9, except for (a) rain-related impacts, (b) wind-related impacts, (c) tornado-related impacts, and (d) surf- related impacts.
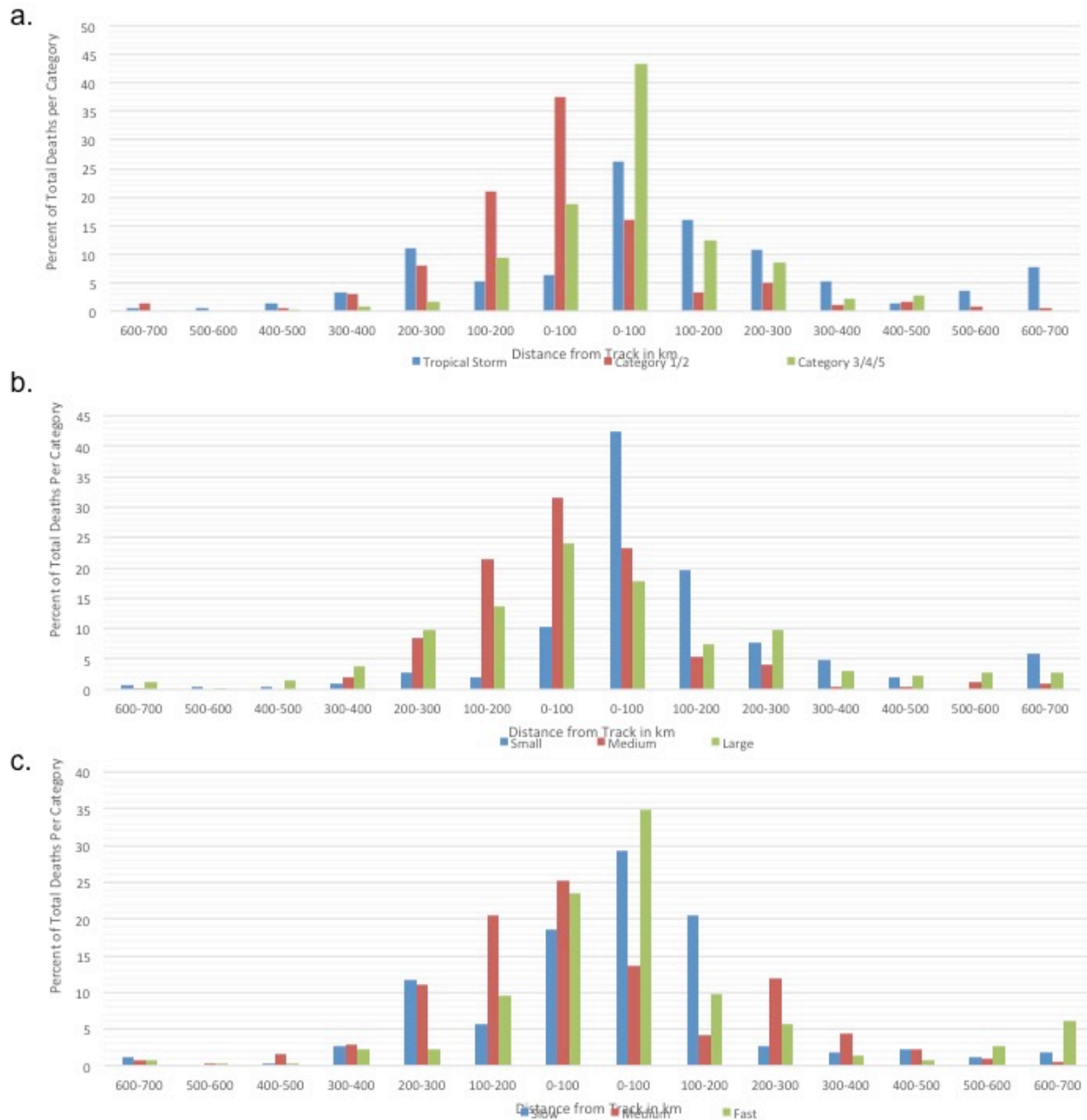
Figure 11: The percentage of the total deaths stratified by (a) strength, (b) size, and (c) speed of movement.

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