

Fatalities in the United States Indirectly Associated with Atlantic Tropical Cyclones

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Tropical cyclones generate a variety of weather- and water-related hazards. When one of these hazards provides the proximate cause for loss of life we can characterize the loss as a “direct” death; that is, we attribute the fatality to a physical manifestation of the storm.¹ The most common examples of direct deaths are drowning in storm surge, storm-driven waves, rip currents, or freshwater flood from rain. They also include physical trauma incurred from windborne debris or structural failure induced by wind (tornadic and otherwise).

Rappaport (2014), henceforth R14, quantified Atlantic tropical cyclone-induced direct deaths in the continental United States over the most recent 50 years, finding that around 2,500 direct deaths occurred during that period. Almost 90% of them resulted from excessive stormwater. Storm surge incidents accounted for about half of the deaths, while flood events from rain took close to one-quarter of the lives.

Minimizing such loss of life represents a humanitarian imperative and the mission of the National Hurricane Center (NHC). NHC forecasts the causative weather and water features, and helps the public—through educational programs and real-time services—to prepare for these dangers. NHC is one of several critical public- and private-sector partners who make up our nation’s tropical weather forecast program. It can be concluded that

the number of direct deaths provides both a measure of public health and a measure of the health of the tropical weather forecast enterprise. Because there is a connection between direct deaths and forecast efficacy, and because it is relatively easy to determine if a death is direct, NHC and other organizations traditionally emphasize or cite only direct deaths in their reports on storm impacts.

But direct deaths do not tell the whole story. They do not include the important class of *indirect* fatalities—casualties that, while not directly attributable to one of the physical forces of a tropical cyclone, would not be expected in the absence of the storm. These losses can occur in significant numbers. Following the spate of seven hurricanes in Florida in 2004–05, the chairman of the Florida Medical Examiners Commission stated,

The vast majority [of fatalities in those storms] are the indirect deaths² that come after the storm, [the number increased]...by people who have pre-existing conditions exacerbated by the stress or strain of the storm. (Nelson 2005).

Jonkman and Kelman (2005) highlighted trauma, vehicle accidents, carbon monoxide poisoning, fires, electrocutions, and heart attacks as factors indirectly associated with fatalities in 13 flood events worldwide, including three U.S. tropical cyclones. In their literature review on the global human impact of tropical cyclones, Doocy et al. (2013) also identified these factors and noted that indirect deaths accounted for 43% of U.S. tropical cyclone fatalities in the 16 storms they considered from 1985 to 2008.

For this study, we sought and analyzed information to identify in additional detail the types and numbers

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¹ For this study, we used the National Weather Service (NWS) definition of direct death located at www.ncdc.noaa.gov/stormevents/pd01016005curr.pdf.

² We found around 125 indirect deaths in Florida for the seven hurricanes.

of deaths indirectly associated with U.S. tropical cyclones that occurred over a longer period—50 years beginning in 1963, aligning with the study period of direct deaths by R14. We examined casualty information for 59 of the 127 tropical cyclones that caused direct deaths. While those 59 represent a little less than half of the deadly storms, they accounted for around 90% of the direct deaths.

We undertook the study with the goal of bringing greater visibility to an important public safety concern in the hope it will help initiate a focused mitigation program for indirect deaths that complements longstanding efforts dedicated to issues associated with direct deaths.

SOURCES OF INFORMATION AND ASSIGNMENT OF INDIRECT DEATHS.

We first needed to determine whether a casualty had *any* association with a storm. Consider the hypothetical example of a reported fatal fall from a ladder outside of a home. Did a gust of wind blow the person off of the ladder and was that gust generated by the storm, which would then qualify the incident as a direct death? Or, was the person putting up or taking down hurricane shutters in quiescent conditions, in which case the death could be considered indirect? Were they simply painting the house or washing the windows, suggesting the accident was not associated with the storm? To answer those questions, one is faced with others. What location and what period should be investigated? More specifically, how far in advance of the storm should one consider for losses associated with preparing for the impact? How far removed from the center of a storm should one look for information? (Indirect deaths can occur where there are no environmental impacts.) What about injuries in the impacted area that led to death days or weeks after the storm; what period after a storm departs should be examined?

Fortunately, the source material itself almost always established these bounds for us. We reviewed in most cases information from the following National Oceanic and Atmospheric Administration (NOAA) sources: *Tropical Cyclone Reports* (originally “Preliminary Reports”; www.nhc.noaa.gov/data/#tcr) from the NHC, the Storm Events Database of the National Centers for Environmental Information (NCEI, formerly National Climatic Data Center) and the Storm Data publication based on those data (<http://forecast.weather.gov/glossary.php?word=STORM%20DATA>), and NWS Forecast Office (WFO) websites. In addition, we conducted Internet searches of books and ar-

ticles and looked at printed books on hurricanes. We also searched electronically at NewspaperARCHIVE.com, an important resource for our research that makes accessible online articles from hundreds of newspapers in our geographic area of interest. Then, if we needed to resolve conflicting information or we concluded that there could be additional information, we initiated communication with a variety of state- and local-level sources. In some cases, we augmented these data with reports from other official sources, like the Centers for Disease Control and Prevention.

Our analysis procedure followed a hierarchy where, at the top, we relied on the conclusions of medical practitioners wherever possible. Next, for about a quarter of the storms, we used raw data obtained directly from one or more of the official sources, such as coroners’ offices, emergency managers, and law enforcement officials. For one of the more involved cases, Hurricane Agnes in 1972—just for the state of Virginia—we communicated with the Appomattox County Office of Emergency Management; Botetourt County Sheriff’s Office; Buchanan County Office of Emergency Management; Buckingham County Clerk of the Circuit Court; Buckingham County Office of Emergency Management; Jones Memorial Library in Lynchburg; *Lynchburg News and Advance* in Appomattox County; NWS Wakefield, VA WFO; Robinson Funeral Home in Appomattox; Virginia Department of Emergency Management; Virginia Historical Society; and the Virginia State Library.

For another important storm, Hurricane Katrina, we reviewed medical logs of more than 1,000 victims provided to us by state officials in Louisiana and Mississippi. We also looked at 750 death certificates from Mississippi and abstracts of 880 death certificates from Virginia for 10-day periods beginning two days before Hurricane Camille’s 1969 passage across those areas.

Where we didn’t have original data or reports, we sometimes used presumed official findings as communicated by the media.

When the available resources ultimately did not provide definitive information we tried to make a judicious decision or conceded that an association with the storm could not be confirmed.

On the other hand, the decision was sometimes obvious or suggestive enough to make a confident conclusion, as when a person succumbs to carbon monoxide poisoning from an improperly ventilated generator during a power outage at their home following the storm’s passage. In a few cases when

details for a storm were not available, we estimated the loss to be the increase in the aggregated number of a particular type of death over the count of such deaths from a representative period of the same duration before the storm.

Finally, for completeness, we recognized the existence of situations for which we could not account. In fact, we excluded two well-known storms completely—Beulah (1967) and Celia (1970)—because while they surely were associated with indirect deaths, we could find no information explicitly referencing them. The lack of information about these two excluded cases reflects a larger issue. Prior to around 1985, sources of storm impact data were few, and those sources usually contained little or no information about indirect deaths. Such information became more abundant with time, helped greatly by the advent of the Internet and major storms striking areas with a large media presence [e.g., Andrew (1992) in Miami, Katrina (2005) in New Orleans, Rita (2005) in Houston, and Sandy (2012) in metropolitan New York and New Jersey].

At the level of individual people, we were not able to determine if a person who would have died from some cause during the normal course of events during the period of the storm survived because the storm altered their behavior or environment in a fortuitous way. Another such situation would be someone who died during the storm and would have died—maybe even for the same reason (e.g., heart attack)—if the storm or storm threat hadn't come. We acknowledge these and other variations but believe their impact on or absence from the database and analyses is small enough for us to characterize accurately the problem of indirect deaths and their approximate distribution.

MAGNITUDE OF THE INDIRECT DEATH PROBLEM. The number of indirect deaths associated with the 59 storms studied was 1,418 people. For perspective, we compared that total to the number of direct deaths from the same storms. To make this comparison, we started with R14's direct death total and adjusted it to account for information about Katrina in Louisiana from the Louisiana State Office

of Epidemiology (LSOE) and for the remnants of Hurricane Juan (1985) that R14 did not see. With these adjustments, we counted 1,803 direct deaths.³

This tells us that at around 44% of the total number of fatalities, *the number of indirect deaths (1,418) is almost as large as the number of direct deaths (1,803)*. That percentage is almost identical to what Doocy et al. (2013) reported for a much smaller subset of storms.

By far the largest number of indirect deaths was the more than 500 associated with Katrina (Table 1).

In about half of the storms, indirect deaths accounted for more casualties than direct deaths. The correlation coefficient between the number of indirect and direct deaths in storms is high—0.86—but is highly influenced by Katrina. Without that storm, the coefficient is only 0.32.

We extrapolated from the 59 storms to estimate for all storms during the 50-year period the number of direct deaths to be 2,170 and indirect deaths as 1,804 (by a process that results in slightly different percentages than noted above).⁴ The annual averages can then be estimated roughly as 43 direct and 36 indirect U.S. tropical cyclone fatalities, 79 in total.

MOST COMMON FATAL FACTORS. Four factors, each with multiple manifestations that sometimes occur in combination, were associated with a large

³ Our review of the LSOE database of 1,155 victims indicated 341 direct deaths, 507 indirect deaths, and the remaining 307 fatalities indeterminate for direct or indirect cause. For Juan, we found 53 more drowning fatalities associated with the storm's remnants far inland. Using the new Katrina and Juan counts, and R14's counts for direct deaths in the other 57 storms, we get a total of 1,803 direct deaths for the 59 storms.

⁴ To make these estimates, we started with R14's direct death count of 2,544 for the 50 years and adjusted it in three steps. First, we subtracted the number R14 used for direct deaths in Katrina (891) in Louisiana and added the number from LSOE (341), for a total of 1,994. Then, just for the purpose of obtaining a rough estimate for the 50 years, we proportioned the 307 indeterminate deaths in Katrina into direct (40%) and indirect (60%) parts, as would be consistent with the percentages observed for the other Louisiana casualties in that storm. This contributes another 123 people to the direct death count, or $1,994 + 123 = 2,117$. We also made a smaller upward adjustment of 53 for the new data from Juan (1985), giving an estimated total for the 50-year period for all storms of $2,117 + 53 = 2,170$ direct deaths. The number of direct deaths from the 59 storms is estimated to be $1,803 + 123 = 1,926$. This means the 59 storms were responsible for around 89% of the direct deaths ($1,926/2,170$).

To estimate roughly the total number of indirect deaths for the 50 years, we took the indirect death count of 1,418 for the 59 storms and added 60% of the 307 indeterminate Katrina deaths (184), giving 1,602. We then divided that subtotal by ~ 0.89 to estimate the number of indirect deaths for all storms over the 50 years: 1,804.

majority of indirect deaths. They are power problems, cardiovascular failure, evacuation, and vehicular incidents. Table 1 and Fig. 1 show the distribution of casualties across the most frequently noted concomitants for the 10 storms associated with the most indirect deaths, and for the aggregation of all 59 storms studied. Additional data can be found at www.nhc.noaa.gov/data/indirect_deaths.php.

Power problem. Power problems, usually in the form of loss of electricity for the public, triggered a variety of equipment failures or other actions that contributed to loss of life, in some cases in combination with other factors. We discuss now the most common of these occurrences.

CARBON MONOXIDE (CO) POISONING. The need to regulate air temperature in the home, especially to cool during the summer in the south and to warm

farther north later in the hurricane season, provides strong stimulus to use a temporary power supply when conventional commercial power sources fail. Portable generators provide a popular solution to the loss of home air conditioning (cooling) or heating, refrigeration of consumables, and lighting, as well as important creature comforts like television. Misuse of the generators, most often evident as inadequate ventilation, led to around 70 CO poisoning deaths, with one or more instances in about one-third of the storms. The most CO deaths in a single storm occurred during and in the unusually chilly aftermath of Hurricane Sandy in the northeastern states (e.g., Table 1). In New York City, the number of carbon monoxide cases during the week of Sandy was said to be more than 10 times larger than would have been expected without the storm; it was still 6 times as high during the following week (Fink 2012a). There were also many nonlethal CO cases.

TABLE 1. Distribution of casualties by frequently noted factors for the 10 storms associated with the most indirect deaths and for the aggregation of all 59 storms studied. Counts provided for direct deaths (D), indirect deaths (I), cardiovascular failure (Card), cardiovascular failure during evacuation (CaEv), evacuation without vehicle accident (Evac), vehicle accident during evacuation (VEv), vehicle accident not related to evacuation or striking a tree (Veh), vehicle striking a tree (VeTr), tree incident without vehicle (Tree), carbon monoxide poisoning (CO), electrocution (Elec), fall (Fall), and fire in residence from open flame (Fire).

					Cardio-vascular	Evacuation			Vehicle			Power			
Rank	Name	Year	D	I	Card	CaEv	Evac	VEv	Veh	VeTr	Tree	CO	Elec	Fire	Fall
1	Katrina*	2005	520	565	318	27	46	0	12	2	4	9	3	0	5
2	Rita	2005	7	101	0	0	37	46	4	0	0	9	2	0	1
3	Andrew	1992	23	90	3	1	5	1	12	0	4	4	5	2	6
4	Sandy	2012	73	82	2	1	0	0	15	2	6	15	2	3	10
5	Camille	1969	288	55	30	0	0	0	9	0	0	0	4	0	0
6	Frances	2004	6	49	3	0	1	2	18	5	3	2	4	1	6
7	Ike	2008	20	44	1	0	0	3	0	0	5	9	7	2	1
8	Isabel	2003	16	36	2	0	0	0	4	6	4	8	3	1	4
9	Charley	2004	10	29	3	0	1	0	5	1	1	2	2	1	4
10	Hugo	1989	17	27	7	0	0	0	0	0	2	0	4	13	0
All 59		1963–2012	1,803	1,418	430	38	98	63	163	38	39	69	68	45	49

* An additional 307 deaths in Katrina were indeterminate for direct or indirect cause

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

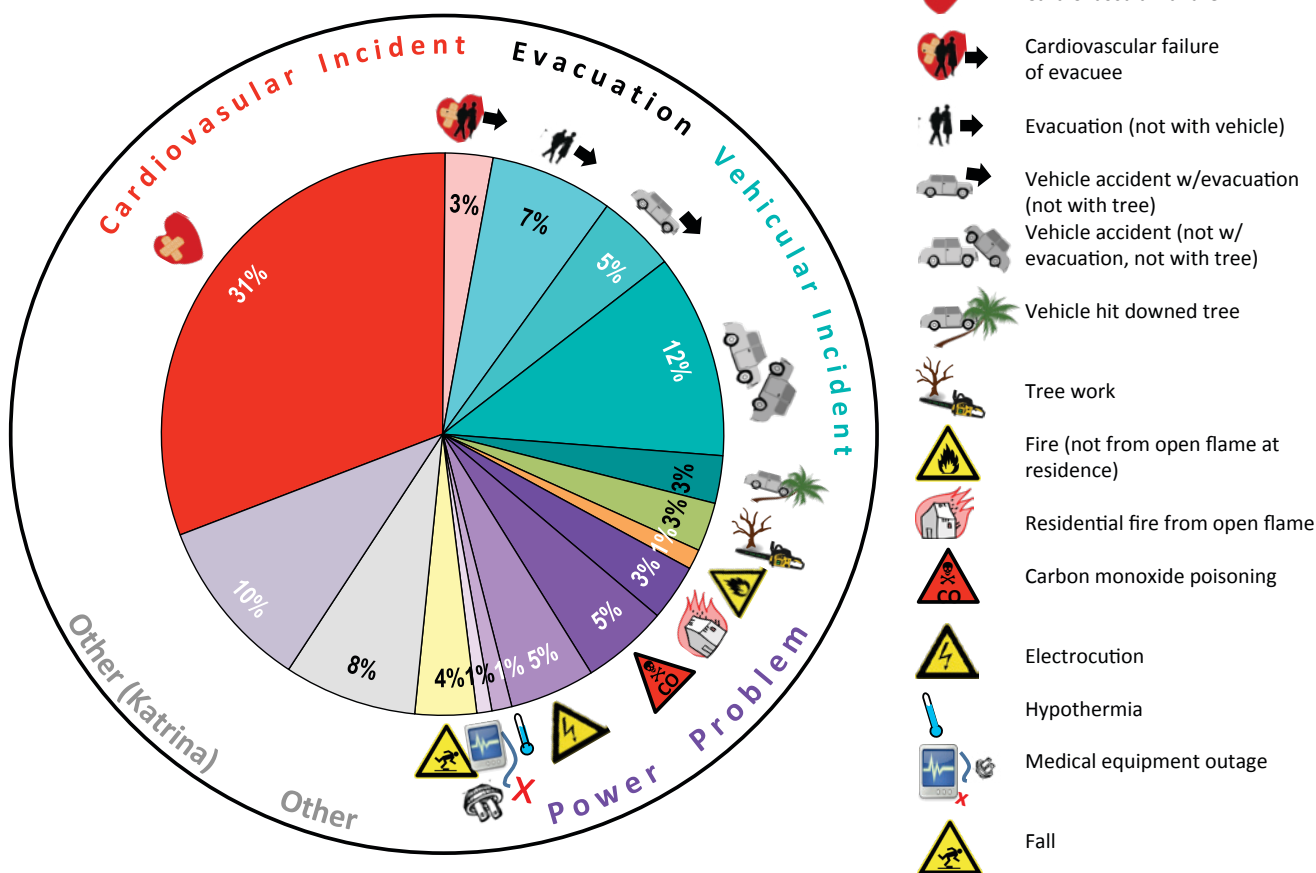


FIG. 1. 1963–2012 U.S. Atlantic tropical cyclone indirect deaths distributed by primary factor present. Note that power problems, beyond being the primary antecedent in the incidents having a purple shading, also occurred in another 2–3% of the other factors shown. Vehicle accidents where traffic lights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

HYPOTHERMIA. Tropical cyclones require the relatively warm water and air implied by their name to form and persist. While 80°F water can be warm enough to sustain the life of a hurricane, prolonged direct exposure of skin to water of that temperature can quickly become a threat to human life. The longer the exposure, greater the immersion, lower the temperature, and higher the wind speed, the greater the risk. Means to counter the chill, whether by properly run generator or another method, are not always available. Hypothermia is blamed for indirect deaths in five storms. Perhaps not surprisingly, Sandy and the weather that followed it resulted in most of the lives lost to hypothermia. We point out that when hypothermia occurs in the water it can also lead to drowning, and thus poses risks in both direct and indirect ways.

INOPERATIVE MEDICAL EQUIPMENT. In five storms, including four instances during Sandy and three in Hurricane Ike (2008)—both recent storms—the loss of commercial power proved fatal when medical equipment necessary to sustain life failed.

ELECTROCUTION. Storms led to the electrocution of around 65 people, mostly in singular incidents. One or more electrocutions occurred in association with about two-thirds of the storms, including nearly every hurricane. The latter observation is consistent with knowledge that the stronger the wind the greater the chance that electrical lines will be downed, with some still live. Electrocutions were almost evenly distributed between contacting live wires, power restoration activities, and miscellaneous causes. Of

the second group, we find especially troubling that about half (nine) of the electrocutions involved utility workers.

HOUSE FIRE FROM MISUSE OF OPEN FLAME. Admonition about the dangers of using an open flame for light or heat inside the home has been a standard component of hurricane outreach materials for decades. Still, 40 people lost their lives from residential fires attributed to a misused candle or similar source.

We point out that power problems, beyond being the primary antecedent in the incidents already described, were also present in another 2%–3% of the cases. Falls and vehicle accidents (discussed below) are two examples. To avoid double-counting these cases, they only contribute to the totals of those other factors in our tallies, including in the table and figure.

Almost 50 people fell to their deaths during the study period. Most occurred in or near their residences. At least 12 seniors died from falls in dark passages or stairwells where the storm had knocked out electricity for lights. The youngest of them was 73 years old while their *average* age was 83 years old. Other falls, not related to a power outage, took place from ladders preparing for the storm or from elevated locations around the home while people were clearing debris or attending to downed trees after the storm.

Cardiovascular failure. Heart attacks and other cardiovascular failures are the most pervasive elements in indirect deaths—occurring in about one third of them (Fig. 1). They also formed the most uncertain category of indirect death, as it comprised health-related incidents where no physical external contributor could be identified.

A staggering number of such deaths can be linked to Katrina. As noted above, the LSOE data suggest either direct or indeterminate causes for a little more than half of those deaths. Of the remainder, all indirect, LSOE listed a cardiovascular event as a primary contributing factor for death in more than half the cases (more than 300).⁵ The number of these cases exceeded 200 for Orleans Parish alone and is about 10 times greater than the average number of deaths per week there due to “diseases of the heart” over the previous three years (see Eavey and Ratard 2008). Both surprising and instructive, the

number of these cases roughly matches the number of drowning victims identified explicitly by LSOE in Katrina in that area—that is, about the same number as deaths caused for certain by storm surge. The Mississippi state coroner’s log listed another dozen victims of cardiovascular failure associated with Katrina.

Heart-related problems also stood out as common occurrences in other storms, though they made up a much smaller fraction of the losses in most of them. This difference could be related to Katrina’s disproportionately severe overall impact, including the extended period of duress and/or differences in attribution and reporting practices. Still, while the state of Mississippi recorded between 8 and 18 deaths associated with heart disease in each of the four days before Camille made landfall, nearly double that number (20–29) occurred in each of the 4 subsequent days. Lew and Welti (1996) noted for Hurricane Andrew (1992) an

...unexpected increase in cardiovascular deaths in the elderly for the week following the storm. The medical examiner case load [of bodies to examine] doubled (from an average of 10 cases per day to 20 or more per day [meaning an increase of at least 70 deaths above the norm]) during that one week, with the increase due predominantly to “natural” cardiovascular disease in the elderly. Although these deaths could not be attributed directly or indirectly [by their definition] to the storm, their collective demise in temporal proximity may represent the toll of Hurricane Andrew’s physical and psychosocial stress on those with limited cardiovascular reserve.

This risk persists. Swerdel et al. (2014) found a comparable increase in fatal cardiovascular events in New Jersey in the week following Hurricane Sandy’s arrival. (They also noted a smaller increase in the number of strokes, although our data for Katrina and Camille didn’t show an increase). The New Jersey medical examiner’s office reported more generally that during Hurricane Sandy nearly half of the fatal cases

...were certified as natural, including individuals with significant underlying chronic disease exacerbated by conditions created by the storm (i.e., loss of electricity affecting individuals requiring continuous home oxygen) or

⁵ This number is much larger than the still-sizable 100 or so such deaths reported by Brunkhard et al. (2008) for the smaller dataset they analyzed.

undesirable circumstances created by physical displacement. (Mitchell et al. 2013).

The impact of the stresses actually is even larger. According to Zahran et al. (2014), up to about half of the stillbirths that occurred during Hurricanes Katrina and Rita can be attributed to those storms.

Looking across the storms, the circumstances of cardiovascular cases varied. Cardiac arrests occurred before, during, and after storms. Physical (over) exertion was often apparent, with the physiological details and contributing factors numerous and often interdependent. Of the 52 instances where the individual's activity was known, 36 deaths occurred in association with strenuous physical labor in the preparation or clean-up phases of the storm, and 10 while being evacuated (or at the evacuation site). It stands out that 29 of the 30 (97%) casualties who were engaged in hard work related to the storm were male and only 1 was female (the gender of the other 6 is not known).

Examples from before the storm include putting up plywood (Irene, 2011), helping a neighbor with shutters (Frances, 2004), loading sandbags (Wilma, 2005), seeking shelter (Ivan, 2004), and securing the roof ahead of the storm (Jeanne, 2004).

Examples from during the storm are trying to ride out the storm in a vehicle (Charley, 2004) and securing a boat (Danny, 1997).

After storm conditions arrived and/or departed, examples of heart failures reported were associated with bailing out a flooded basement (Irene, 2011), helping pump out a basement (Frances, 2004), cleaning up debris (Wilma, Ivan), strenuous poststorm work (Wilma), using a chain-saw during clean-up in the heat (Charley, 2004), cutting down trees (Isabel, 2003), bailing water out of car (Floyd, 1999), repairing a fence (Opal, 1995), cleaning up debris (Opal, 1995), repairing a damaged home (Hugo, 1989), and one individual who "saw everything he had, totally demolished" (Hugo, 1989).

Also, exacerbating or independent of the risks from physical activity, there were instances of overexposure to the elements, especially to heat. Areas impacted by the worst storms can be without electricity for weeks. In Katrina, one million people remained without power in the summertime heat and humidity of early September in Louisiana and Mississippi a week after the storm's passage (DOE 2015). The most common ways in which a victim altered their actions in an ultimately deadly manner because of the loss of power

were discussed above (e.g., misuse of a generator). We must also realize that the risk is more than a lack of familiarity (e.g., with how to use a generator), as "physical and emotional stress can take a toll on all types of people, making even someone who normally knows what he's doing more prone to fatal error" (Marcus and Kestin 2005).

In addition, prolonged exposure to oppressive summer conditions in the absence of air conditioning contributed to indirect deaths by inducing physiological failures in unquantified, but possibly large numbers. While not noted often on death certificates, heat stress compromised the cardiovascular systems of some Katrina victims (Ratard 2014, personal communication).

Hurricane Rita struck the upper Texas and southwestern Louisiana coast in September 2005, just four weeks after Katrina came ashore farther to the east in Louisiana. There were at least 34 indirect deaths in Harris County, Texas, which contains heavily populated Houston. According to NWS (2011), "the majority of these fatalities occurred during the evacuation prior to Rita and were the result of excessive heat and transporting the elderly."

Heat also contributed to 9 of the 13 indirect deaths associated with Rita in Montgomery County, located immediately to the north of Harris County.

Evacuation. One way to prepare for a storm is to avoid it by relocating to a place outside of the storm's expected physical impacts. It has been long known that doing so, however, comes with its own risks that lead to difficult decisions for the public, public officials, healthcare providers, and others (e.g., Hans and Sell 1974; Quarantelli 1980; Heath et al. 2001; FHC 2008; HHS 2011; Fink 2012b).

The reports we examined explicitly identified around 200 cases in which a death occurred in association with evacuation. In arriving at this number we included ~75 deaths that occurred during Katrina in a parish other than the victim's residence—but not in a medical facility—or that occurred in their home parish but not in a residence or medical facility. The number of people who evacuated and died at someone else's residence in their home parish is not known, but perhaps significant. Also not counted were any of the more than 400 Louisiana residents who fled the storm to another state and died there, though some likely succumbed to an evacuation-related cause.

More than 80 evacuation-related fatalities occurred with Rita. A little more than half of that total and about one-third of the 200 cases perished due to vehicle accidents.

Around 40 people died away from home due to a heart disease issue.

Vehicular incidents. Vehicle accidents make up the fourth and final category of frequent events, accounting for more than 250 indirect deaths. Here we exclude instances where flood waters swept away a car or truck and drowned its occupant(s); those qualify as direct deaths. We assigned indirect deaths to cases where a vehicle hydroplaned on a wet roadway, was involved in an accident during an evacuation, collided with an object when crossing an intersection where street lights were not operating, and the like.

An unexpectedly large number of fatal accidents—more than 30—occurred where a vehicle struck a downed tree. We can add these cases to other tree-related indirect deaths (e.g., during poststorm cleanup) and the direct deaths attributed to trees falling onto victims (see R14). When we do that, we find that the total of tree-related fatalities, direct and indirect, approaches 100. This makes trees, especially large ones susceptible to toppling or fracture, a notable risk to safety in U.S. tropical cyclones.

OTHER STATISTICS. *Age.* The number of indirect fatalities increased generally with age. In fact, there were about 8 times as many victims who were more than 70 years old as there were victims under the age of 21. For the most part, this disparity comes from the large number of senior citizens who died from heart-related ailments.

Gender. More men than women succumbed from indirect causes by about 58% to 42%. The difference between genders is less than the difference observed for direct deaths (71% to 29%; cf. Rappaport 2000). Percentages for the subset of almost 400 victims of cardiovascular failure for which gender is known are very close to those overall for indirect deaths.

Timing. We didn't find enough information to establish a robust timeline of losses relative to the storm's passage, but the data do show that significant losses occurred ahead of the storm. As noted above, around 200 evacuation-related deaths were recorded, most of them known or presumed to have been from incidents taking place ahead of the storm.

A much larger number of indirect deaths—perhaps two or three times as many—took place during the response and recovery phase, or at least after the occurrence of a storm-triggered event like rain-slickened roads or where the wind downed power lines, interrupting the delivery of electricity.

Landfall intensity and size. The correlation coefficient between indirect deaths and landfall intensity was slightly positive—around 0.25—as it was for direct deaths and landfall intensity. However, as might be expected, with their stronger winds and attendant greater impact on the electrical infrastructure, hurricanes were responsible for a disproportionately large number of deaths related to power outages compared to tropical storms.

We wondered whether indirect deaths might be more strongly correlated with a metric that considers storm size, too. The “Integrated Kinetic Energy” (e.g., IKE_{10} in Powell and Reinhold 2007) attempts to account for the entire surface wind field rather than just the maximum intensity. Perhaps it is a little surprising that we found near-zero correlation between indirect deaths and the IKE at landfall of the 13 storms on our list that Powell and Reinhold analyzed.

ANOMALIES. While indirect deaths averaged around 36 per year, the number varied greatly from storm to storm and year to year. A clustering of losses by type of event occurred in some storms. In fact, the median for each of the causes across the 59 storms was 0 people, except for three causes where it was 1 person. We expect the medians would all be 0 if we expanded the database to include the other 69 (not as) deadly tropical cyclones. The averages behave similarly.

One such clustering was the large number of cardiovascular victims in Katrina. Those victims were also older on average than heart-related casualties in other storms: age 77 versus 66 years old. In fact, for Katrina there were around 150 victims of at least 80 years old, including almost 50 people who were 90 years old or older.

Hypothermia events occurred almost exclusively in Sandy. Sandy also had by a fair amount the most cases of carbon monoxide poisoning, with both of these impacts attributable to the loss of power and to cold weather associated with the storm and its aftermath.

A tragic bus fire during the evacuation of a nursing home in advance of Hurricane Rita in 2005 took the lives of more than 30 elderly passengers.

SUMMARY AND DISCUSSION. A review of storm-related reports and databases for 59 U.S. tropical cyclones from the past half-century tells us that the number of indirect deaths is almost as large as the number of direct deaths.

Indirect deaths occurred most often in association with loss of electricity, cardiovascular failure, evacuation, and vehicle accidents. The prestorm phase presented significant threats to safety mainly from accidents during home preparations (e.g., fall from a ladder or building) and in association with evacuations, mainly from vehicle accidents and/or incidents involving the elderly.

Most indirect fatalities, however, occurred after a triggering storm condition or after the storm had completely passed. The loss of electricity was noted in many of those cases. It was the antecedent to falls in the dark and/or down stairs, house fires, inoperative life-sustaining medical equipment, CO poisoning, hypothermia, electrocution during power restoration or from power lines that were unexpectedly live, and vehicle accidents associated with inoperative traffic lights.

The importance of electricity is likely greater than indicated because the available data exclude the count of those who evacuated at least partly out of concern that power would be lost, and then died during the evacuation process (e.g., the Hurricane Rita bus tragedy) or at their evacuation destination. It also doesn't include some who died from the exacerbating impacts of heat stress resulting from a sometimes-extended period without air conditioning.

Other incidents noted most often in the latter stages of the storm or after the storm's passage were recovery activities, vehicle accidents on slippery roads, and vehicle collisions with downed trees. We highlight further the involvement of trees in fatal incidents as, like loss of electricity, they appear in multiple types of fatalities. In addition to posing a deadly roadway obstacle, they were noted in storm clean-up accidents and heart attacks, some from physical overexertion. We recall that Rappaport (2000) noted toppling and fracturing trees were also causes of direct deaths.

Cardiovascular failures occurred with especially great frequency, in about one-third of the indirect deaths.

Evacuating and being evacuated also accounted for a significant number of indirect deaths. This observation supports the practice of care providers comparing the relative risk of conducting an evacu-

ation—especially of the frail and elderly—to the risk of not evacuating.

The data make clear that reducing the number of deaths associated with tropical cyclones in a significant way will require decreasing the occurrences of both indirect and direct deaths. Improvements in the hurricane forecast enterprise have led to a decrease in the number of direct deaths from what would have been expected otherwise (Willoughby et al. 2007). Among those life-saving advances over the study period has been a lengthening of the tropical cyclone forecast horizon from two days to five days. Paradoxically, the increase in lead time also provides opportunity for an increase in certain kinds of casualties, most notably indirect casualties during the lengthened preparation phase. It should then not be surprising that while the ratio of direct deaths to indirect deaths was more than two to one up through 1995, the ratio has reversed since approximately 2000—though changes in reporting procedures (i.e., recognizing and providing more information explicitly about indirect deaths) are likely also partly responsible for the change.

Minimizing indirect deaths will require focused outreach and education. We hope this study has identified the risks that can form the focus of those efforts to provide for greater public safety and the impetus to make significant progress quickly.

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