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Epidemiology of Tropical Cyclones: The Dynamics of Disaster, Disease, and Development

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Abbreviations: CDC, Centers for Disease Control and Prevention; EM-DAT, Emergency Disasters Database; PTSD, post-traumatic stress disorder.

INTRODUCTION

Tropical cyclones—variously defined as hurricanes, typhoons, and cyclones—regularly impact human populations and periodically produce devastating weather-related natural disasters. The epidemiology of tropical cyclones is fundamentally determined by the physical forces of massive cyclonic systems intersecting with patterns of human behavior. The destructive forces of cyclonic winds, inundating rains, and storm surge are frequently accompanied by floods, tornadoes, and landslides (1, 2). Human factors include land use and settlement patterns, building design and construction, forecasting and warning systems, risk perception, evacuation, and sheltering. Preparedness and mitigation strategies for minimizing harm include family disaster planning, stocking of hurricane supplies, protection of home sites, timely response to public warnings, and alertness to poststorm hazards.

Public health consequences associated with tropical cyclones include storm-related mortality, injury, infectious disease, psychosocial effects, displacement and homelessness, damage to the health-care infrastructure, disruption of public health services, transformation of ecosystems, social dislocation, loss of jobs and livelihood, and economic crisis. These outcomes disproportionately befall developing nations, and human factors strongly influence the observed disparities (3).

We conducted a review of the epidemiologic literature on the public health consequences of tropical cyclones. For the purpose of this review, we performed a keyword search on the Internet using a variety of academic search engines and websites, including MEDLINE, PubMed, the National Center for PTSD PILOTS database, the National Hazards Center database, and the National Oceanic and Atmospheric Administration/National Hurricane Center website, using combinations of the terms "tropical cyclone," "cyclone," "hurricane," "typhoon," "natural disasters," and "epidemiology." We also conducted keyword searches directly on the websites of *Morbidity and Mortality Weekly Report* and major medical and emergency medicine journals. Checks of the bibliographies of key references in the psychosocial and sociologic literature expanded the search. We conducted analyses of windstorm data using the Emergency Disasters Database (EM-DAT) of the Center for Research on the Epidemiology of Disasters (Brussels, Belgium) (4).

TROPICAL CYCLONES: CHARACTERISTICS AND FORMATION

Tropical cyclones are low-pressure weather systems that develop over the warm waters of the oceans, typically between the latitudes of 30° N and 30° S (1, 2, 5, 6). Cyclonic systems rotate counterclockwise in the Northern Hemisphere and clockwise in the Southern Hemisphere. Tropical systems evolve through a life cycle that includes the successive stages of tropical wave, tropical disturbance, tropical depression, and tropical storm (table 1). Depending upon geographic locale, tropical cyclones with wind speeds surpassing 74 miles/hour (118 km/hour) are termed "hurricanes" in the North Atlantic, the Caribbean, the Gulf of

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TABLE 1. Stages of development of a tropical cyclone*

Stage	Description
Tropical wave	A trough of low pressure in the trade-wind easterlies
Tropical disturbance	A moving area of thunderstorms in the tropics that maintains its identity for 24 hours or more
Tropical depression	A tropical cyclone in which the maximum sustained surface wind is ≤38 miles/hour (≤61 km/hour; ≤33 knots†)
Tropical storm	A tropical cyclone in which the maximum sustained surface wind ranges from 39 miles/hour (62 km/hour; >33 knots) to 73 miles/hour (117 km/hour; <64 knots)
Hurricane/ typhoon/ cyclone	A tropical cyclone in which maximum sustained surface wind is ≥74 miles/hour (≥118 km/hour; ≥64 knots)

* Source: National Weather Service, National Oceanic and Atmospheric Administration (8).

† A knot is 1 nautical mile/hour; a nautical mile is approximately equal to 1.15 statute miles (1.84 km).

Mexico, the eastern North Pacific, and the west coast of Mexico; ''typhoons'' in the western Pacific; and ''cyclones'' in the Indian Ocean and Australasia (1).

Tropical cyclone formation—cyclogenesis—requires six concurrent conditions: 1) warm ocean waters of at least 26.5°C to a minimum depth of 50 m (165 feet); 2) an atmosphere that cools rapidly with vertical height, transforming stored heat energy from warm ocean waters into thunderstorm activity that fuels the developing tropical system; 3) moist layers at mid-troposphere elevations (5 km (3 miles)) to enhance thunderstorm formation; 4) significant Coriolis forces to rotate the cyclone; 5) the presence of a near-surface, organized, rotating system characterized by spin (vorticity) and low-level inflow (convergence); and 6) minimal vertical wind shear—strong crosswinds at varying altitudes that can slice apart the towering vortex of cloud mass (7–11).

EXPOSURE TO THE FORCES OF TROPICAL CYCLONES: IMPLICATIONS FOR EPIDEMIOLOGY

Essential conditions for cyclogenesis dictate the descriptive epidemiologic parameters of place, force, time, and harm (table 2). Since warm ocean water is the generative element, only the planet's midsection can conceive tropical cyclones. Moreover, the pole-seeking, centrifugal Coriolis force is necessary to ''spin'' clusters of thunderstorms into a revolving, closed circulation. In consequence, tropical cyclones cannot form within 500 km (312.5 miles) of the Equator, where weather systems align with the direction of the Earth's rotation. Tropical cyclones are thus constrained to form within two tropical belts: above the Equator, where two thirds of storms develop, and below the Equator. Within these regions are seven tropical cyclone ''basins,'' each with its distinctive annual season (table 3) (12). While formation is restricted to tropical latitudes, damage and harm from tropical cyclones can extend far into extratropical areas, as is clearly evidenced by the Federal Emergency Management Agency map of federal disaster declarations for hurricanes affecting the United States in 2004 (http://www.gismaps.fema.gov/2004graphics/storms/ivan/county_map_all_storms.pdf).

The rigorous set of simultaneous conditions necessary for cyclogenesis limits the number of storms that form annually. For the period 1968–2003, an average of 88 tropical storms developed each year, of which 48 attained tropical cyclone intensity and 21 became major tropical cyclones (table 4) (13). Several metrics are used to categorize the destructive potential of cyclones, based on a combination of pressure, wind speed, storm surge, and structural damage. The Saffir-Simpson Hurricane Scale (14) classifies Atlantic and North Pacific hurricanes (table 5). Annual storm frequency also varies over protracted cycles spanning multiple decades (15–17).

While analyzing disaster risk for 1980–2000 using EM-DAT data (4), researchers with the United Nations Development Programme identified four developed nations (the United States, Japan, Australia, and New Zealand) and 29 developing nations with significant exposure to tropical cyclones (3). The average number of cyclone impacts on individual nations was 46 per year, with many cyclones affecting multiple nations. Conversely, each year, several nations experience multiple storms. For example, in 2004, the United States was struck by five hurricanes, four of which made landfall in the state of Florida.

PUBLIC HEALTH RESPONSE AND EPIDEMIOLOGIC INVESTIGATION OF TROPICAL CYCLONES

Tropical cyclones cause a range of public health consequences, including mortality, injury, and infectious diseases (1, 5, 18). Massive property destruction creates population displacement and economic hardship (19). In the immediate aftermath of major tropical cyclones, public health professionals conduct rapid health assessments, typically documenting widespread destruction, homelessness and displacement, severe damage to the infrastructure, loss of electrical power, lack of access to usual health-care services, and food shortages (20–29). With destruction of a broad area, cluster sampling methods are employed to representatively survey large populations affected by the storm (30).

Investigation of storm-associated mortality is one focus for epidemiologic study (18, 31–44). Researchers also examine patterns of storm-related morbidity, including injuries, respiratory and gastrointestinal diseases, dermal conditions, animal bites, and insect stings (20–26, 40, 45–71). Epidemiologic studies distinguish differential patterns of morbidity depending upon the type of natural disaster (72, 73) and inform decision-making regarding the mobilization and utilization of resources (27–29).

To prevent disease and monitor injury patterns, active epidemiologic surveillance is initiated (27–29, 58, 59, 74). Morbidity surveillance, including studies conducted at hospital emergency departments, commonly shows an early peak of storm-associated injuries (21, 40, 45, 46, 49, 55, 56) and may reveal sporadic outbreaks of infectious diseases (21, 24, 40, 46, 49–51). Both early and ongoing surveillance are necessary to detect increases in infectious diseases, including those with prolonged incubation periods (hepatitis, tuberculosis) and those characterized by later emergence due to delayed vector proliferation (1, 40, 47, 60, 61, 74).

Epidemiologic investigation is conducted in tandem with applied public health measures—treating cases of disease, managing solid waste, disinfecting drinking water, implementing vector control, identifying environmental hazards, and immunizing survivors (64, 75). Educating displaced survivors on hygienic practices, reactivating preventive public health services, restoring the health-care infrastructure, and eliminating crowded conditions are keys to preventing an increase in infectious diseases. Prevention and mitigation must emphasize awareness of local hazards and vulnerabilities, compliance with warning and evacuation procedures, awareness of inland flooding risks, and attentiveness to post-impact hazards (76).

PUBLIC HEALTH OUTCOMES

Mortality

Cumulative mortality. A publication of the United Nations Development Programme asserts that in disasters, ''human deaths are the most reliable measure of human loss'' (3, p. 13). Tropical cyclones have caused an estimated 1.9 million deaths worldwide during the past two centuries (77) and between 300,000 and 500,000 deaths in North America and the Caribbean since the ''discovery'' of the Americas in 1492, of which 75,000 occurred during the 20th century (78). During 1980–2000, an average of 11,800 deaths per year were attributed to cyclones (3).

Investigation of mortality. Epidemiologic studies categorize causes of death (35–40, 41, 44, 79), often employing medical examiner data to elucidate storm-attributable mortality (35, 36, 41, 44). Mortality is frequently categorized by disaster phase (pre-impact, impact, post-impact) (32, 35, 38). Some studies examine specific types of mortality such as electrocutions among response personnel (33, 34) or drowning deaths from floods (37, 79).

Centers for Disease Control and Prevention (CDC) investigations of mortality from tropical cyclones routinely differentiate directly related mortality from indirectly related mortality (36, 38, 39, 41–43). CDC epidemiologists created a classification matrix that separates directly related deaths, caused by the physical forces of the disaster, from indirectly related deaths, caused by unsafe or unhealthy conditions associated with predisaster preparations or the actual occurrence of the disaster (43). This matrix was used with high fidelity to categorize 46 Hurricane Andrew (1992) deaths (43). Deaths sustained during Hurricane Charley's (2004) javelin-like trajectory across the state of Florida were classified as directly related deaths from environmental forces, indirectly related deaths from circumstances caused by the storm, or deaths from natural causes in which the physical stress of the storm exacerbated a preexisting medical condition (41).

Mortality trends. Prior to the implementation of warning, evacuation, and shelter systems, drowning from storm surge accounted for an estimated 90 percent of cyclone-attributable mortality (1, 6, 80, 81). High-density settlement in low-lying areas with poor housing construction amplifies risks in nations such as Bangladesh and the Philippines, where storm surge remains the major direct cause of mortality following tropical cyclones (82, 83). Likewise, before 1990, the majority of deaths due to land-falling hurricanes striking the United States occurred at the time of impact and were attributed to drowning in storm surges (38). When Hurricane Camille (1969) crashed into the Gulf of Mexico, pushing 25-foot (7.7-m) storm tides onshore, most of the 256 storm-associated deaths were drowning deaths due to tidal surges (84).

Quantum improvements in hurricane forecasting and well-devised evacuation and shelter procedures have shifted hurricane mortality trends in two ways (32). First, storm-surge drowning deaths have decreased markedly, and by default, the majority of impact phase deaths are now due to high-velocity winds (36). Second, most of the storm-related mortality and much of the morbidity now occurs during the post-impact period. Prominent causes of death and injury are now electrocutions from downed power lines, chain-saw injuries, blunt trauma from falling trees, and motor vehicle fatalities occurring during the early post-impact period (33, 85). Observation of hurricane mortality patterns in developed nations suggests the need to provide specific guidance to the public regarding post-impact hazards such as live power lines and falling trees (38).

Mortality and development. Historically, developing nations of the Asia-Pacific region have experienced the greatest absolute and proportionate mortality from tropical cyclones (3). During the past two centuries, 42 percent of tropical cyclone-associated deaths have occurred in Bangladesh, and 27 percent have occurred in India (77). Developing nations in the Caribbean have also experienced major loss of life from hurricanes.

Analysis of EM-DAT data for the period 1900–2004 identified 77 tropical storms and cyclones causing a minimum of 1,000 deaths each. Fifty of these high-fatality storms occurred in developing nations of the Asia-Pacific region, and 16 occurred in the Caribbean and Central America (table 6). The three deadliest cyclones produced catastrophic loss of life: 300,000 deaths and 138,000 deaths in the Bangladesh cyclones of 1970 and 1991, respectively, and 100,000 deaths in the Chinese typhoon of 1922. The 18 deadliest tropical cyclones—16 storms in the Asia-Pacific region and two in Central America—all occurred in developing nations. In the developing world, the majority of these high-fatality storms and deaths occurred after 1959, while no developed nation has sustained 1,000 deaths from any storm since 1959 (table 6).

Two developed nations, the United States and Japan, have experienced cyclones associated with more than 1,000 deaths. Japan ranks second in the world in terms of ''physical exposure to cyclones in percentage of population'' (3). While Japan experienced nine typhoons resulting in at least 1,000 deaths between 1900 and 1959, no subsequent typhoon,

TABLE 2. Relation of tropical cyclone properties to epidemiologic parameters

Tropical cyclone property	Epidemiologic parameter			
	Place	Force	Time	Harm
Formation over warm waters	Greatest danger of a cyclone encounter is in and along the coasts of tropical oceans. There are seven defined tropical cyclone basins worldwide (see table 3).	Cyclone intensities are greatest over warm waters.		
Coriolis forces necessary	Cyclones do not form within 500 km (312.5 miles) of the Equator.			
Earth's rotation	Movement is predominantly westward and poleward. The implication is that western shores of major tropical oceans—and eastern coasts of major continents—frequently encounter cyclones. Western coasts of major continents are spared.			
Length of trajectory: up to 12,000 km (7,500 miles)	Length of the tropical cyclone path relates to the total geographic area at potential risk.			
Annual fluctuation of ocean temperatures			Cyclones most often occur during peak seasons in all seven basins. In the North Pacific basin, hurricanes can occur year-round; in the other six basins, hurricane occurrence is restricted to 6–7 months of the year.	
Multidecade cycles			Cyclone frequency varies over 25- to 40-year cycles.	
Duration: up to 31 days			Longevity of the tropical cyclone relates to period of potential risk.	
Size of storm: diameter of tropical-storm-force winds—50–1,000 km (31–625 miles)			Duration of storm impact is related to the diameter of the storm passing over the locale.	A large hurricane circulates more than 1 million cubic miles of atmosphere per second (1.6 million km^3/second) (see Williams (2)).
Forward speed			Duration of storm impact is related to the forward speed.	Forward speed adds to or subtracts from the rotating wind speed depending upon the portion of the storm encountered.

Table continues

among hundreds encountered in the past 45 years, has produced 1,000 fatalities.

The United States ranks first in the number of annual tropical cyclone impacts (an average of 12 tropical cyclones per year strike the continental United States, Puerto Rico, the US Virgin Islands, and Pacific jurisdictions) (3). While cumulative hurricane mortality for the United States for the period 1900–2004 was approximately 15,000, *half* of these deaths occurred in 1900 when the deadliest hurricane (and the deadliest natural disaster) in US history killed 7,200 citizens in Galveston, Texas (86). In 1928, 1,836 people perished in a hurricane that pummeled Florida's Lake Okeechobee region. The death toll was 408 in the Florida Keys following the most intense hurricane ever recorded for the United States, the 1935 Labor Day hurricane (reputedly the ''Storm of the Century'') (87). US hurricane mortality per decade has trended downward during the past century: 1,400 deaths per decade for the period 1910–1939; 700 deaths per decade for 1940–1969; and 250 deaths per decade for the period 1970–1999.

Examining the record of tropical cyclones, the salient disparity between developing nations and developed nations emerges. In developing nations, cyclone mortality continues to be periodically catastrophic, with deaths occurring primarily during the impact phase and being predominantly due to storm surge. In contrast, for developed nations, tropical cyclone mortality has declined markedly, and the majority of deaths now occur in the post-impact period.

Injuries

Storm-associated injury. For tropical cyclones, physical injury represents the major cause of death and the primary cause of morbidity (6). Minor trauma is common, including lacerations, abrasions, contusions, puncture wounds, sprains,

TABLE 2. Continued

Tropical cyclone property	Epidemiologic parameter			
	Place	Force	Time	Harm
Force and energy		Tropical cyclones possess immense size and energy and a range of intensities that can cause widespread destruction. A mature hurricane generates about 1.5×10^{12} W/day of kinetic energy specifically to maintain the flow of the cyclonic winds—equivalent to 50% of the current electrical generating capacity worldwide! Total energy generated daily is 400 times greater—6.0×10^{14} W!		
Wind speed	For a Northern Hemisphere storm—	*Right side of storm*: Total wind force = wind speed + forward speed. *Left side of storm*: Total wind force = wind speed – forward speed.		Risk of harm and damage increases exponentially with wind speed. Wind speed is maximal in the eye wall of the storm and decreases as the distance from the eye increases. Higher wind speeds produce higher storm surges.
Storm surge				Storm surge represents the major cause of death in areas that are coastal or low-lying and lack warning systems. Storm surge height increases with increasing cyclone intensity, wind speed, and forward speed.
Tornadoes	Tornadoes are most often generated from the upper right quadrant of the storm.			Extreme wind speeds and pressure gradients tend to cause extreme focal damage.
Rain and flooding				Rains cause direct damage to exposed housing stock and contribute to flooding, landslides/mudslides, and downed trees and power lines.
Landslides/ mudslides				Landslides represent a major cause of mortality when cyclones pass over steep or mountainous terrain.
Multiple necessary climatic conditions	Limited by the rigorous conditions necessary for formation.		Limited by the rigorous conditions necessary for formation.	Limited by the rigorous conditions necessary for formation.

and fractures (21, 40, 45, 46, 49, 55, 56). The top three cyclone-related injuries are lacerations, blunt trauma, and puncture wounds, with 80 percent of these injuries being confined to the feet and lower extremities (57). The United States has organized regional Disaster Medical Assistance Teams to provide rapid, mobile medical assistance to survivors injured in hurricanes and natural disasters (88).

Injury by disaster phase. Prior to storm impact, injuries such as falls, blunt trauma, lacerations, and muscle strains may occur during storm preparation as citizens install plywood and metal shutters and make preparations to secure homes, businesses, and potential projectiles. Injuries occur during mass evacuation, including a notable increase in motor vehicle crashes. Frail elderly citizens are particularly vulnerable to injury during transport and sheltering. Structural collapse, wind-borne debris, falling trees, and downed power lines are potentially injurious hazards during impact and after the storm. Some victims are directly exposed to the harmful forces of wind, rain, flood, or storm surge as a consequence of damage to their shelter or desperate attempts to drive to safety while the storm is raging. Occupancy of a mobile home during the impact phase poses an extremely high risk for injury or death (36). Injuries abound during the post-impact phase, including puncture wounds, lacerations, falls from roof structures, and chainsaw mishaps. Burn injuries may occur from the use of candles, open fires, portable stoves, or gas-powered generators during power outages.

Injury and development. The frequency and severity of injuries incurred during a tropical cyclone are inversely related to the degree of physical protection from the storm; therefore, understandably, developing nations bear the major burden of cyclone-attributable injury. Unfortunately, no international standard exists for classification of disaster-related injuries, which limits comparison across studies (6, 57).

Infectious diseases

Conditions following a cyclone that increase the likelihood of infectious diseases include 1) disruption of public health services and the health-care infrastructure, 2) damage to water and sanitation networks, 3) changes in population

TABLE 3. Tropical cyclone season, by basin

Basin	Complete season	Peak season
Atlantic	June 1–November 30	August–October, with a sharp peak in late August/early September
Northeast Pacific	May–November	Late August–early September
Northwest Pacific	Year-round	July–November, with a major peak in late August/early September
North Indian	April–December	Double peak: April–June (May peak) Late September–early December (November peak)
Southwest Indian	Late October–May	Double peak: 1) Mid-January 2) Mid-February–early March
Australian/Southeast Indian	Late October–May	Double peak: 1) Mid-January 2) Mid-February–early March
Australian/Southwest Pacific	Late October–early May	Late February–early March

density (especially in crowded shelters), 4) population displacement and migration, 5) increased environmental exposure due to damage to dwellings, and 6) ecologic changes (3, 62).

Infectious diseases and development. Outbreaks of infectious diseases following tropical cyclones are rare in developed countries but more common in the developing world (22, 26, 61, 64). In developed nations, posthurricane infectious disease surveillance has occasionally detected increases in self-limiting gastrointestinal disease and respiratory infections (23, 40, 54), but more typically, no increase in communicable disease is found (46, 61). Conversely, while some studies in developing nations demonstrate no increase in infectious disease rates following tropical cyclones (61), in other instances, infectious disease outbreaks have been documented (46, 60, 61, 63–66). Outbreaks of balantidiasis on the Pacific island of Truk after the 1971 typhoon, typhoid fever in Mauritius following the 1980 cyclone, and acute respiratory infections in Puerto Rico following the 1989 hurricane provide examples (61). An outbreak of leptospirosis followed the 1996 hurricane in Puerto Rico (67). Increases in both acute respiratory infection and self-limiting gastrointestinal disease were noted in the Dominican Republic following Hurricane

TABLE 4. Numbers of tropical storms and cyclones per storm season, by basin and hemisphere, 1968–2003

	Tropical storms			Hurricanes/typhoons/ tropical cyclones			Intense* tropical cyclones		
	Most	Least	Average	Most	Least	Average	Most	Least	Average
Basin									
Atlantic	19	4	10.6	12	2	5.9	6	0	2.0
Northeast Pacific	27	8	16.3	16	4	9.0	10	0	4.1
Northwest Pacific	35	17	26.7	24	9	16.9	14	3	8.5
North Indian	11	2	5.4	5	0	2.2	3	0	0.4
Southwest Indian	18	7	13.3	11	2	6.7	6	0	2.7
Australian/Southeast Indian	13	1	7.3	8	0	3.6	5	0	1.6
Australian/Southwest Pacific	18	4	10.6	12	0	4.8	6	0	1.9
Hemisphere									
Northern	76	39	58.7	47	24	33.7	23	5	15.1
Southern	38	19	29.0	22	7	14.5	11	0	5.9
Global total	106	68	87.7	64	36	48.3	34	7	21.0

* Category 3 and above (see table 5).

TABLE 5. The Saffir-Simpson scale of hurricane intensity*

Category	Wind speed			Storm surge		Central pressure (mbar)	PD‡ value	Expected damage
	miles/hour	km/hour	knots†	feet above normal	m above normal			
1	174–95	119–153	64–82	4–5	1.2–1.8	≥980	1	No real damage to building structures. Damage primarily to unanchored mobile homes, shrubbery, and trees. Some coastal road flooding and minor pier damage.
2	96–110	154–177	83–95	6–8	1.9–2.7	965–979	4	Some roofing material, door, and window damage to buildings. Considerable damage to vegetation, mobile homes, and piers. Coastal and low-lying escape routes flood 2–4 hours before arrival of center. Small craft in unprotected anchorages break moorings.
3	111–130	178–209	96–113	9–12	2.8–3.9	945–964	9	Some structural damage to small residences and utility buildings, with a minor amount of curtainwall failures. Mobile homes are destroyed. Flooding near the coast destroys smaller structures; larger structures are damaged by floating debris. Terrain continuously lower than 5 feet (1.5 m) above sea level may be flooded inland for 8 miles (13 km) or more.
4	131–155	210–249	114–135	13–18	4.0–5.5	920–944	16	More extensive curtainwall failures, with some complete roof structure failures on small residences. Major erosion of beach. Major damage to lower floors of structures near the shore. Terrain continuously lower than 10 feet (3.1 m) above sea level may be flooded, requiring massive evacuation of residential areas as far as 6 miles (10 km) inland.
5	>155	>249	>135	>18	>5.5	<920	25	Complete roof failure on many residences and industrial buildings. Some complete building failures, with small utility buildings being blown over or away. Major damage to lower floors of all structures located less than 15 feet (4.6 m) above sea level and within 500 yards (457 m) of the shoreline. Massive evacuation of residential areas on low ground within 5–10 miles (8–16 km) of the shoreline may be required.

* Source: Simpson and Riehl (14).

† A knot is 1 nautical mile/hour; a nautical mile is approximately equal to 1.15 statute miles (1.84 km).

‡ PD, property damage.

Georges in 1998 (22). In the aftermath of Hurricane Mitch (1998), a possible increase in cholera was documented in Guatemala, Nicaragua, and Belize, along with outbreaks of leptospirosis in Nicaragua and gastrointestinal disease in Honduras (64).

Factors unique to developing nations that are more likely to favor the emergence of disease include high endemic rates of disease, low immunization rates, poor access to clean water (71), poor sanitation, prolonged crowding in shelters, and inadequate nutrition. Prolonged disruption of routine public health-care services is more likely to occur in developing countries and contributes to an increase in disease. During the 1970 cyclone in Bangladesh, damage to the health-care infrastructure and interruption of ambulatory treatment of patients with active tuberculosis may have led to an increase in the transmission rate of this disease (60).

Malaria and vector control. Interruption of both public health-care services and antimalaria spraying may have contributed to an outbreak of more than 75,000 cases of *Plasmodium falciparum* malaria in Haiti following Hurricane Flora (1963) (60, 63). Following Hurricane Mitch (1998), rates of dengue fever increased in Guatemala and Honduras and numbers of malaria cases increased in Guatemala and Nicaragua (64). The increased incidence may have been due to a lack of preventive measures, alterations in mosquito

TABLE 6. Locations of 77 tropical cyclones causing more than 1,000 deaths each, 1900–2004*

Country	1900–1959		1960–2004		1900–2004	
	No. of storms	No. of deaths	No. of storms	No. of deaths	No. of storms	No. of deaths
Developing nations						
Asia/Pacific						
Bangladesh	2	66,000	13	522,015	15	588,015
China	5	158,064	1	1,174	6	159,238
India	6	108,742	5	37,576	11	146,318
Vietnam	2	3,330	2	10,682	4	13,982
Philippines	1	1,000	5	11,604	6	12,604
Honk Kong	1	10,000	0		1	10,000
Pakistan	0		1	10,000	1	10,000
Myanmar	1	2,700	1	1,070	2	3,770
Taiwan	3	3,046	0		3	3,046
Republic of Korea	1	1,104	0		1	1,104
Atlantic						
Honduras	1	1,500	2	22,600	3	24,100
Haiti	2	3,750	3	8,876	5	12,626
Dominican Republic	1	2,000	1	1,400	2	3,400
Nicaragua	0		1	3,332	1	3,332
Cuba	1	2,500	0		1	2,500
Dominica	1	2,000	0		1	2,000
El Salvador	1	2,000	0		1	2,000
Guadeloupe	1	2,000	0		1	2,000
Belize	1	1,500	0		1	1,500
Developed nations						
Japan	9	24,716	0		9	24,716
United States	2	7,836	0		2	7,836

* Source: Emergency Disasters Database (4).

breeding sites, and increased environmental exposure among survivors. The CDC recently investigated transmission of malaria in resort areas of the Dominican Republic following Hurricane Jeanne (2004) (48).

Delayed-onset infectious disease. A significant but delayed increase in infectious disease, including typhoid and paratyphoid fever, infectious hepatitis, gastroenteritis, and measles, was reported 5 months after Hurricanes David and Fredrick in the Dominican Republic in 1979 (60). Delayed onset is partially explained by extended stays in crowded shelters with insufficient sanitary facilities, disruption and contamination of food and water supplies, and low immunization rates—conditions that are more prevalent in developing nations (60).

Infectious disease myths. Contrary to popular belief, the presence of a large number of corpses following catastrophic natural disasters is not associated with epidemic infectious diseases (68, 69). These deaths are caused by the traumatic force of a natural disaster, not by disease, and therefore do not lead to epidemics.

Animal bites and arthropod bites and stings

An increased incidence of animal and arthropod bites following tropical cyclones has been noted (21, 40, 45, 60, 63, 64, 70). Contributing factors include 1) increased environmental exposure due to forced evacuation or destruction of dwellings, 2) transformation of natural habitats by the storm or subsequent clean-up efforts, and 3) proliferation of mosquitoes due to disruption of breeding sites or temporary suspension of vector control measures in the immediate aftermath of the storm.

A significant increase in bee stings was noted following Hurricane Gloria (1985) (45). Insect stings accounted for 21 percent of all hurricane-related inland emergency department visits in South Carolina following Hurricane Hugo (70). The proportion of emergency department visits for insect bites significantly increased after both Hurricane Opal (1995) (21) and Hurricane Floyd (1999) (40). In the same study, an increase in dog bites occurred up to 1 week after impact (40).

Psychosocial consequences

Behavioral health effects are among the most long-term and debilitating outcomes of natural disasters, including tropical cyclones (89–91). While many people experience fear and distress at the time of disaster impact, the majority return to normal functioning (92, 93). However, some persons experience persistent distress that affects behavioral and functional capability, and a subset progress to post-traumatic stress disorder (PTSD), major depression, or other psychiatric outcomes. Rates of suicide (94) and child abuse (95) appear to rise following natural disasters. Integration of behavioral health components into triage and emergency medical services has been proposed (96).

Risk and protective factors. Risk factors for adverse psychological outcomes in natural disasters are 1) the severity of individual exposure, including such features as bereavement, injury to oneself or a family member, the perception of threat to life, separation from family, extensive loss of property, and displacement; 2) female gender; 3) age, such that both children and older adults are at greater risk; 4) lower socioeconomic status; 5) predisaster functioning, particularly previous psychiatric history; and 6) the presence and degree of secondary stressors (90). Social support, self-efficacy, and positive coping strategies buffer the severity of behavioral health consequences (90, 97).

Adult PTSD. In the United States, increases in rates of psychological disorders were noted throughout 5 years of surveillance following the extensive flooding that accompanied Hurricane Agnes (1972) (98). When psychiatric morbidity was investigated in previously non-ill subjects from the neighborhoods most damaged by Hurricane Andrew (1992), 51 percent met criteria for a new-onset disorder, including 36 percent with PTSD, 30 percent with major depression, and 20 percent with anxiety disorders. Sustaining ''severe damage'' was the salient risk factor (99). In the aftermath of Hurricane Andrew, four hurricane experience variables—damage, loss, life threat, and injury—predicted both PTSD symptoms and immune suppression (100). Among Hurricane Andrew shelter residents surveyed 1 month after impact, losses of home and property were strongly related to depression and distress (101).

Ethnic differences. Ethnic differences in PTSD prevalence were noted following Hurricane Andrew, with the highest rates being found in Spanish-preferring Latinos (38 percent), intermediate levels in African Americans (23 percent), and the lowest rates in Caucasians (15 percent) (102). The same investigative team analyzed changes in PTSD symptomatology over a period of 30 months postimpact; intrusion and arousal symptoms declined, depressive symptoms remained stable, and avoidance/numbing symptoms actually increased (103).

Children and adolescents. Garrison et al. (104, 105) studied adolescents who developed PTSD after Hurricanes Hugo and Andrew and elucidated four major risk factors: intensive exposure, prior history of violent trauma, Caucasian ethnicity, and female gender. After Hurricane Andrew, Shaw et al. (106–108) examined the prevalence and progression of posttraumatic symptomatology in elementary school students and assessed the effectiveness of school-based interventions using crisis intervention specialists in schools most affected by the storm. LaGreca et al. (109–111) explored children's posttraumatic stress symptoms following Hurricane Andrew in relation to prehurricane functioning.

Pacific basin studies. In studies from other international hurricane basins, adverse psychological outcomes were documented in survivors after Cyclone Tracy struck Darwin, Australia, in 1974 (112), and persistent PTSD was documented in New Zealand after Cyclone Bola (1988) (113). When a succession of five typhoons struck Guam in 1992, a sample of persons who had been assessed for acute stress disorder after the first typhoon and subsequently experienced four additional storms was reassessed after the typhoon season subsided (114). Persons who had acute stress disorder following the initial typhoon were significantly more likely to have progressed to PTSD or depression after the full series of typhoons.

Behavioral health and development. Behavioral health consequences are increasingly salient following tropical cyclones that affect developed nations, particularly when effective mitigation strategies successfully limit the extent of storm-related mortality, injury, and illness. However, psychosocial consequences are more severe in developing nations, partly because of exposure to massive death and harm.

The monumental devastation of the December 2004 Southeast Asian tsunami prompted a meta-analysis of the psychosocial consequences of natural disasters in developing countries versus developed countries (90). Generally, during a natural disaster, a much higher proportion of the population in developing nations sustains severe loss and extreme trauma and experiences ''clinically significant distress or criterion-level psychopathology'' (77). An elevated prevalence of PTSD was specifically apparent in all three studies of hurricane survivors in developing nations (115–117).

Economic impact

Tropical cyclones are among the costliest of weather-related natural disasters. A National Oceanic and Atmospheric Administration report lists all of the ''billion-dollar'' weather-related disasters occurring in the United States during the period 1980–2004 (118). Hurricanes accounted for the largest proportion of these costly disasters, with Hurricane Andrew being clearly distinguished as the most expensive disaster event to date, at $35.6 billion (table 7).

PREVENTION AND CONTROL OF PUBLIC HEALTH CONSEQUENCES OF TROPICAL CYCLONES

Among natural disasters, tropical cyclones are uniquely amenable to risk reduction through a combination of planning, technology, and behavioral change (6, 14) with public health interventions. Effective forecasting, warning, evacuation, and sheltering are primary approaches to reducing hurricane-related mortality and morbidity for persons who reside in high-risk locales. The marked reduction in cyclone fatalities and injuries and the near-absence of infectious disease outbreaks found in developed nations is a data-based testament to the preventive potential of cyclone preparedness, mitigation, and response strategies.

Forecasting

Tropical cyclones can be detected at formation and are being tracked with increasing precision in terms of location, trajectory, central pressure, wind speed, storm surge, point of landfall, wind fields, and rainfall production—thus facilitating timely and targeted warnings. Attesting to the accuracy of forecasts, the US National Hurricane Center reports that the mean error for their 24-hour storm track is less than 100 miles (<160 km), and the mean error for storm intensity is 10 miles/hour (16 km/hour) (119).

Warning

The technology of warning systems has been a major dimension of research on natural hazards mitigation (120–123). Typically, tropical cyclones are detected multiple days to weeks prior to landfall, providing time for serial public warnings. News media are able to carefully, repetitively provide updated guidance regarding preparation, protection, evacuation, and sheltering. Citizens especially turn to mass media to manage information about hazards with long lead times (124). Advisories issued by authoritative sources such as the National Weather Service effectively cue protective action (124, 125). The National Hurricane Center has developed SLOSH (Sea, Lake, and Overland Surges from Hurricanes), a computerized model for estimating storm surge heights (122)—an important forecasting capability, given the prominence of storm surge fatalities. To enhance public understanding and response to warnings, proposals have been formulated for an ''All-Hazard Warning Network'' (126).

Hurricane warnings must be coupled with accurate risk perception to produce a timely response by the public (127–130). For example, an early warning system was implemented in Bangladesh after the 1970 cyclone (300,000 deaths); nevertheless, 138,000 people perished in the subsequent 1991 cyclone when most failed to respond to warnings (31, 131). Among those who failed to heed the warnings, 45 percent reported that they did not anticipate the storm to be severe, 16 percent did not understand the warnings, and 16 percent did not seek shelter because of the force of the storm (31). Failure to heed warnings, coupled with diversion of preparedness resources and a lack of shelters, contributed to the death toll during the 1999 cyclone in Orissa, India (132, 133).

Evacuation

Developed nations have devised strategies for sequenced evacuation (129, 134), starting with keys and barrier islands and progressing to coastal areas, including low-elevation inland areas. The scope and scale of evacuation is matched to the intensity of the approaching storm. Successful evacuation of 500,000 South Floridians occurred prior to Hurricane Andrew (1992) (135). Three million persons were evacuated from the path of Hurricane Floyd (1999) (136).

TABLE 7. Hurricanes generating economic costs of at least 1 billion dollars (''billion-dollar storms''), United States, 1980–2004

Year	Storm	No. of deaths	Cost (billions of $US)
1983	Alicia	21	5.9
1985	Elena	4	2.4
	Juan	63	2.8
1989	Hugo	89	13.9
1991	Bob	18	2.1
1992	Andrew	61	35.6
	Iniki	7	2.4
1994	TS* Alberto	32	1.2
1995	Marilyn	13	2.5
	Opal	27	3.6
1996	Fran	37	5.8
	Georges	16	6.5
1998	Bonnie	3	1.1
1999	Floyd	77	6.5
2001	TS Allison	43	5.1
2003	Isabel	55	5.0
2004	Charley	34	14.0
	Frances	38	7.0
	Ivan	52	12.0
	Jeanne	28	6.5

* TS, Tropical Storm.

Assessment of personal and property risk is critical for compliance with evacuation orders (128–131, 137–139). Citizens seek information primarily from radio and television and make independent judgments regarding evacuation (128, 129, 140, 141). Many citizens living in coastal areas in the major hurricane basins improvise evacuation arrangements, often sheltering in the homes of family members and friends (135).

Shelter

Safe shelter is critical for survival. In the high-fatality 1991 Bangladesh cyclone, deaths were negligible among those who reached official shelters (31, 131, 142). Forty percent of family members were killed in an area without shelter access, in contrast to 3.4 percent in an area with available shelters (142).

Land-use planning

Community cyclone preparedness, including land-use planning, is facilitated when citizens correctly perceive the risks posed by cyclones and support hazard mitigation planning and policy (121, 127). Hazard assessment is the first step toward development of an effective land-use hazard mitigation policy (127). Consistency between public risk perceptions and expert risk assessment is essential for successful land-use planning.

Building design and construction

Designing and constructing new structures—and retrofitting existing structures—to withstand natural disasters is an important preventive measure. Upgrading and enforcing building codes decreases the risk of injury associated with hurricanes. Persons in poverty are more vulnerable, living in less fortified housing in more dangerous locales with diminished economic means to protect the dwelling or recover damages. Structural preventive measures are especially important in developing countries with hazardous living conditions, limited resources, inadequate infrastructure, and compromised recovery potential (26).

Preparedness behaviors

Preparedness behaviors for disasters have been conceptualized into the categories of provisions, protection, planning, and skills (143). Specific to tropical cyclones, preparedness includes stocking ample hurricane supplies, protecting the homestead with hurricane shutters or protective window glass, developing family disaster plans, training with community disaster response teams, and seeking information for action when a storm is approaching.

Vulnerable populations

As the Hurricane Andrew (1992) experience attests, the elderly, recent immigrants, women-headed households, persons in poverty, and persons with special medical needs are more vulnerable throughout all phases of the disaster response process (144).

Risk perception

Accurate risk perception is a necessary stimulus for responding to warnings, engaging in protective activities such as installing hurricane wind protection, and evacuating when advised (127, 143, 145–147). Public risk perception is related to previous experience with hazard events (148, 149). Paradoxically, previous experience may actually reduce perceived risk, especially when the public has experienced a ‘‘miss’’ rather than a hit following energetic preparation (127). The sense of invulnerability that comes from a close but minimal encounter with a previous hurricane was a frequently cited reason for failure to evacuate along Florida’s Gulf Coast during Hurricane Eloise (1975) (150). Persons with hurricane ‘‘experience’’ may believe that they are better equipped to deal with future cyclones (151). In contrast, experiencing significant hurricane *damage* is associated with realistic risk perception (152).

EPIDEMIOLOGIC METHODS IN TROPICAL CYCLONE INVESTIGATION

Epidemiologic investigations of tropical cyclones typically involve rapid health-needs assessments conducted in the early post-impact period, classification and investigation of storm-related mortality, and surveillance of patterns of injury and the possible emergence of infectious diseases related to displacement and disruption of the public health infrastructure. Most studies to date have been proficient, brief, descriptive epidemiologic investigations conducted shortly after impact and close to the points of initial landfall or maximum destruction.

Epidemiologic investigations benefit from the seasonal predictability and long warning period of tropical cyclones, the placement of epidemiologists in health departments throughout hurricane zones, the increasing standardization of sampling methods and definitions of disaster-associated outcomes, advancing field investigation technologies, and experienced investigational support from professionals in federal government agencies such as the CDC. These factors facilitate timely deployment and conduct of investigations that directly inform response efforts. Despite these advances, study designs for epidemiologic assessment of tropical cyclones have not improved remarkably since the classic studies of the East Bengal cyclone of 1970 were conducted more than three decades ago (18).

Opportunities for advancement of the field abound. Comparative epidemiologic studies investigating the differential risks and hazards in developing nations are largely lacking. Well-designed analytical studies using case-control methods to determine storm exposures leading to death, injury, or illness and cohort studies designed to track and monitor storm-affected populations throughout the response and recovery periods are notably absent from the literature. Epidemiologic studies have not typically integrated objective estimates of the physical forces of exposure to better characterize the patterning of health outcomes. Epidemiologic studies have generally omitted or provided only cursory inclusion of psychosocial consequences. Epidemiologic studies have not consistently assessed and integrated human preparedness behaviors. Moreover, special-needs populations have been understudied.

The cyclical nature of tropical cyclones, which repeatedly strike well-identified coastal and island populations, creates the intriguing prospect of conducting continuous surveillance of populations in high-frequency impact zones, thus overcoming one of the major limitations of disaster epidemiology studies—the post-impact-only investigation. Prospective, longitudinal investigations could thoughtfully integrate the disciplines of epidemiology, emergency medicine, behavioral health, sociology, emergency management, climatology, and development studies. Such studies would also permit exploration of the effects of multiple encounters with tropical cyclones over time.

CONCLUSION

Tropical cyclones are formidable storm systems that have produced some of the world’s most catastrophic natural disasters. Recent advances in construction, forecasting, warning systems, evacuation, and sheltering have sharply reduced tropical cyclone-associated mortality and morbidity in developed nations. Lacking this complement of mitigation technologies, developing nations remain vulnerable to devastating harm and loss, but the prevention potential is apparent. Behavioral health consequences are prominent regardless of level of development but are understudied in epidemiologic investigations. Among natural disasters, tropical cyclones are uniquely amenable to multidisciplinary, analytical epidemiologic investigation using prospective study designs, with the potential for significant advancement of the science of disaster epidemiology.

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