Hurricanes and Health

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Summary

Hurricanes, also referred to as tropical cyclones or typhoons, are powerful storms that originate over warm ocean waters. Throughout history, these storms have had lasting impacts on societies around the world. High winds, rain, storm surges, and floods affect lives, land, and livelihoods and have a variety of effects on human health.

The direct health impacts of hurricanes include drowning due to flooding and trauma resulting from storm surges, blown debris, and structural collapse. Systems for detection, forecasting, early warning, and communications can give populations time to make preparations before hurricane landfall. Evacuation, shelter use, and other preparedness efforts have reduced mortality from hurricanes in many parts of Asia and the Americas. Engineered defenses such as sea walls, flood barriers, and raised structures provide added protection in some settings. While effective in the medium term, such approaches are costly and require dedicated resources, and therefore they have not been implemented in many at-risk sites around the world.

Indirect health impacts of hurricanes arise from damage to housing, electricity, water, and transportation infrastructure, and from effects on social supports, economies, and healthcare systems. Indirect health impacts can include infectious diseases, carbon monoxide poisoning, trauma sustained during cleanup, mental health effects, exacerbations of chronic disease, and increases in all-cause mortality. Indirect and long-term health consequences are poorly understood because dedicated study of specific impacts has occurred in only a handful of settings, and, given the diverse array of societies and geographies affected by hurricanes, it is unclear how generalizable the results of these studies may be.

Policy makers face three interlinked challenges in protecting human health from hurricanes. First, climate change is leading to increased hazards in many locations by altering hurricane dynamics and contributing to sea-level rise. Second, patterns of intensifying coastal settlement and development are expected to increase population exposure. Third, unequal patterns of exposure and impact on specific populations will continue to raise issues of climate and environmental injustice.

Situationally appropriate strategies to protect health from future storms will vary widely, as they must both address the locally relevant manifestations of hurricane hazards and adapt to the cultural and economic context of the affected population. In some areas, inexorable ocean encroachment may lead to consideration of managed retreat from high-risk coastlines; in

others, the presence of very large coastal urban populations that cannot feasibly evacuate may lead to design and use of vertical shelters for temporary protection during storms. New ideas and programs are urgently needed in many settings to address hazards associated with extreme rainfall, rising seas on floodplains and low-lying islands, landslide risk in areas undergoing rapid deforestation, and structurally unsound housing in some urban settings. Policies to reduce greenhouse gas emissions will help reduce long-term risk from hurricanes and sea-level rise.

Without concrete actions to address both hurricane hazards and population vulnerabiliy, the 21st century may be marked by increasingly dangerous hurricanes affecting growing coastal populations that will be left with few viable options for seeking safety.

Keywords: hurricane, cyclone, typhoon, tropical storm, health, mortality, climate change, sea level rise, adaptation

Subjects: Adaptation, Mitigation, Resilience, Health Impacts, Coastal Storm Surge, Exposed Populations

Hurricanes: A Complex Health Hazard

Hurricanes, known as cyclones in South Asia, typhoons in the western Pacific, and tropical cyclones in the scientific literature are powerful storms that originate over warm ocean waters. Hurricanes have shaped societies throughout history and are mentioned in narratives ranging from the cosmologies of the Taino people of the Caribbean to records of ancient Japan and India ("Kamikaze," 2016; Ladlow et al., 2019; Stefton, 2010; Woods Hole Oceanographic Institution, 2015). Hurricanes result in storm surges and heavy rainfall, flooding both coastal and inland communities. The accompanying high winds destroy infrastructure. Hurricanes frequently cause deaths from drownings and injuries. They also cause prolonged suffering from the ensuing disruption of healthcare, livelihoods, ecosystems, infrastructure, and in some cases breakdown of social and political functioning. The impact of these storms can be cataclysmic; the deadliest hurricanes of the past century have each resulted in more than 100,000 deaths (EM-DAT, CRED/UCLouvain, 2020).

The health impacts of hurricanes are shaped as much by human activity as they are by specific hurricane hazards. Upland deforestation, loss of coastal mangroves, and settlement of low-lying areas can result in adverse health outcomes when hurricanes strike (Das & Vincent, 2009; Shultz et al., 2016). There is also increasing evidence that anthropogenic changes in the earth's climate are exacerbating hurricane-related hazards. Rising sea levels and warming oceans may be contributing to higher hurricane wind intensity, coastal flooding, and rainfall (Marsooli et al., 2019; Ting et al., 2019).

The direct impact of hurricanes on human health has been extensively studied. The longer-term sequelae of hurricane-related impacts on the health and well-being of individuals and populations are receiving growing attention but are more difficult to study and address. The societal response to hurricanes and management of hurricane-related risks in the face of coastal settlement, population growth, and climate change are expected to dominate scientific inquiry and policy debates related to hurricanes in the 21st century.

This article presents information on the dynamics of hurricanes and their direct and indirect impacts on human health in the sections on “Hurricane Science” and “Research and Practice.” Approaches that have succeeded in mitigating harm, largely via early warning systems or infrastructure that reduce the impact of these storms on coastal populations, are described in “Historical Approaches to Risk Reduction.” Finally, the article explores the implications of climate change, human settlement, and development patterns in terms of the challenges and opportunities these create for managing health risks in “Twenty-First–Century Challenges” and “Meeting the Needs of the Twenty-First Century.”

Hurricane Science

Hurricanes arise from low pressure systems that form over warm ocean waters (National Hurricane Center [NHC], 2020b; National Weather Service [NWS], 2020). As the overlying air heats up, it begins to rise, creating a low-pressure area beneath it, which then draws in cool air. The incoming air warms and begins to rise, forming a rotating tower of clouds encircling a low pressure core that continues to feed the system of wind and clouds by drawing energy from the warm ocean waters (NWS, 2020). Hurricanes can reach hundreds of kilometers in diameter and achieve wind speeds in excess of 200 kph. Hurricane systems rotate counterclockwise around a central “eye” of calm air in the northern hemisphere, and they move clockwise in the southern hemisphere. They typically travel westward in their early phases due to prevailing trade winds (NHC, 2020b). The so-called hurricane belt in which most hurricanes have historically occurred lies between 8 and 20 degrees north and south of the equator. This risk zone may, however, be expanding into higher latitudes as a result of climate change (Kossin et al., 2014; NHC, 2020b).

The principle physical hazards related to hurricanes are high winds, storm surges, and heavy rain. High winds result from both the rotational movement of the storm and its movement across the earth’s surface (NHC, 2020b). Storm surges are rapid increases in local sea level caused by ocean water pushed forward by surface winds; these can be extremely destructive, reaching several meters high depending on storm dynamics and coastal geography (NHC, 2021). Heavy rain results from the large amount of moisture taken up from the warm ocean, which condenses into clouds as the air rises and cools. Total rainfall in a given location is a function of both water vapor dynamics within the storm system and the duration of exposure to the storm system. Large, slow-moving storms can result in hundreds of millimeters of rain, leading to extensive freshwater flooding (Emanuel, 2017). Other hazards documented in these storm systems include lightning strikes and tornadoes (Edwards et al., 2012).

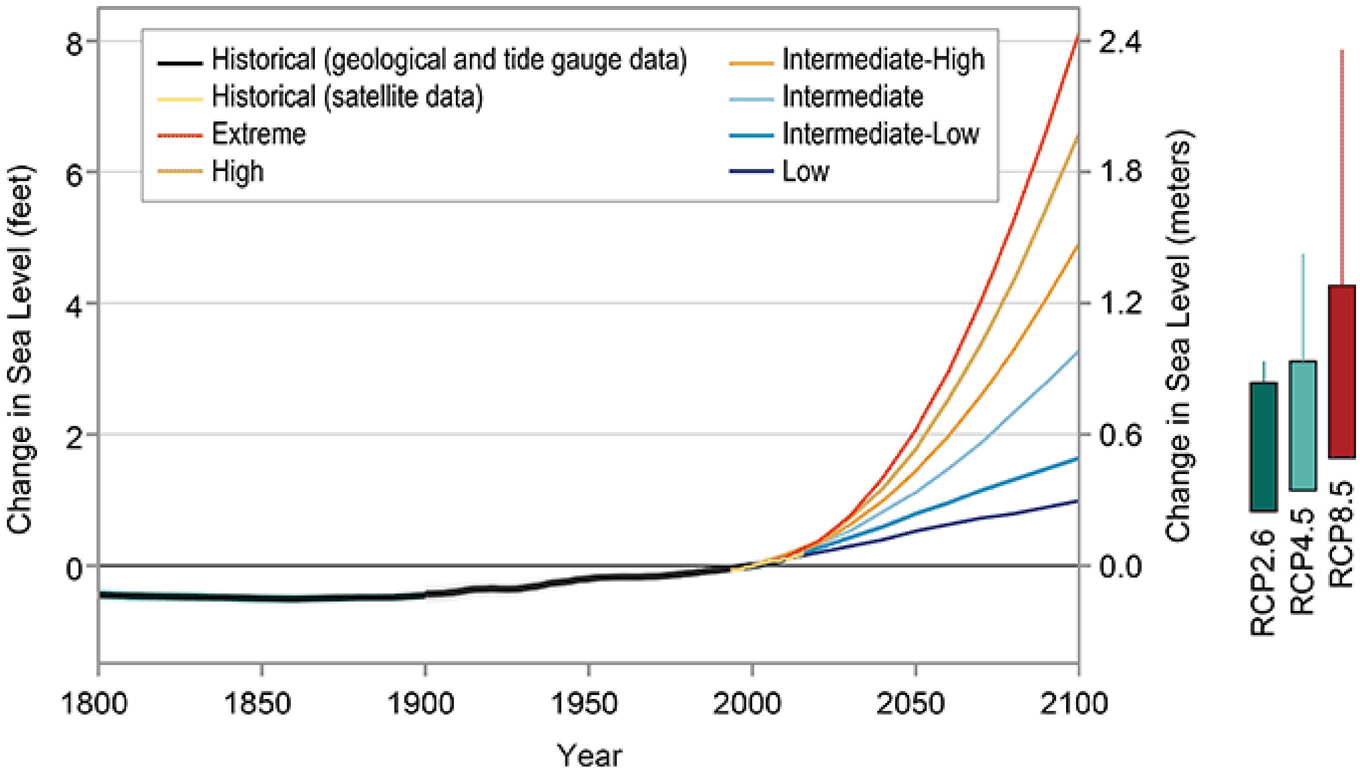

Figure 1. It is difficult to predict hazard changes related to climate change because of scientific complexity and uncertainties about future human behavior. For example, the amount of future sea level rise depends on both response to warming and future greenhouse gas emissions. The graph shows expected ranges of sea level rise by 2100 under different emissions scenarios (boxes at right) as well as higher projections based on new information about accelerated polar ice melt (vertical lines, right).

Source: Sweet et al. (2017).

Implications of Climate Change

Both anthropogenic climate change and cyclical multidecadal ocean oscillation patterns appear to affect hurricane dynamics (Balguru et al., 2018; Bhatia et al., 2019). Climate change, in particular, is of increasing concern because as the oceans and atmosphere warm, both the energy available to a storm and the moisture carrying capacity of the atmosphere increase, while altered atmospheric circulation patterns may affect storm formation and track (Knutson et al., 2020). Anticipated or observed effects include rapid intensification, increased risk of "stalling" leading to prolonged impacts, and extreme rainfall, all of which have detrimental impacts on affected populations (Balburu et al., 2018; Bhatia et al., 2019; Emanuel, 2017; Hall & Kossin, 2019; Shultz, Kossin et al., 2019; Ting et al., 2019). Recent evidence suggests that translocation speeds are slowing, most likely as a result of climate change, so that slow-moving, lingering storms may occur more frequently, resulting in extensive rainfall and flooding (Kossin, 2018). Climate change may also be contributing to an observed poleward migration of the hurricane belt, at the rate of about one degree of latitude per decade (Kossin et al., 2014). This trend may bring increased hurricane activity to populations that have historically been less exposed to this hazard (Haarsma, 2018; Ting et al., 2019). The implications of climate change for the total number of hurricanes in various ocean basins remain a subject of active research.

Alterations in hurricane dynamics are occurring in tandem with accelerating sea-level rise caused by continental ice melt and the thermal expansion of ocean waters, both of which are attributable to climate change (Figure 1). Global sea level is likely to rise substantially in future decades (Pörtner et al., 2019), but substantial uncertainty about the rate of sea-level rise remains, thanks to unanswered questions about the response of complex earth systems and uncertainties about the future trajectory of greenhouse gas emissions related to human activities (Sweet et al., 2017). Estimates of average sea-level rise range from 50 centimeters to 2 meters or more by the late 21st century (Pörtner et al., 2019); local changes in sea level will also vary as a result of changes in ocean currents and variations in coastal geologic subsidence or uplift (Boon et al., 2018). Even relatively small increases in local sea level have the potential to affect coastal communities and low-lying river deltas through storm surges and saltwater flooding that may substantially exceed the expectations that guided design of many coastal flood defenses in the 20th century (Marsooli et al., 2019).

Research and Practice

Efforts to understand and minimize the impact of hurricanes on human health combine well-established approaches to mitigating risk such as evacuation with more recent endeavors to address the health needs of socially or medically vulnerable populations before, during, and after these storms (Table 1). Vulnerable populations include historically marginalized communities; persons with specific resource limitations, language barriers, or access and functional needs; and those who depend on home-based or institutional care, electricity-dependent medical equipment, dialysis, cancer treatment, or other ongoing complex medical supports.

Direct Impacts on Health

While media portrayals of hurricanes often focus on high winds and flying debris, drowning from storm surges and freshwater flooding is actually the leading cause of immediate mortality from hurricanes (Bern et al., 1993; Rappaport, 2014). Settlements near sea level or adjacent to large bodies of inland water are at high risk of flood-related health imapacts, as occurred in New Orleans during Hurricane Katrina (Brunkard, 2008; Jonkman et al., 2009). Populations living in river deltas such as the Ayeyarwady in Myanmar and the Ganges in India and Bangladesh are particularly vulnerable and have historically suffered from high mortality (Figure 2) because there is no adjacent higher ground available for a safe retreat (Bern et al., 1993). Early warning systems and elevated cyclone shelters can dramatically reduce health impacts in these settings; mortality in major cyclones affecting Bangladesh decreased by an order of magnitude after widespread implementation of early warning and sheltering systems (Haque et al., 2012). Hurricanes also result in maritime drowning. For example, 791 lives were lost when a ferry capsized in the Philippines during Typhoon Fengshen (2008; Elinder & Erixson, 2012), and 1,430 died in a series of ferry accidents in Japan during Typhoon Marie (1954; Matsuo, 1986).

Trauma is the second leading cause of death during hurricanes, and it can also result from associated efforts to evacuate or secure structures before, during, or immediately after hurricanes. Direct impacts from blown debris and collapsing structures and falls sustained while escaping wreckage or securing sites result in lacerations and orthopedic trauma (Frasqueri-Quintana et al., 2020; Rotheray et al., 2012). Injuries, myocardial infarction and electrocution have been reported while boarding up homes or securing belongings in all phases of warning and response (Brackbill et al., 2014; Curran et al., 2018; Fayard, 2009; Gagnon et al., 2005). Persons in houses near the coastlines are particularly at risk, as these structures bear the direct impact of high winds (Shen et al., 2009).

Table 1. Immediate and Direct Health Impacts

Health impact	Causal hazard	Vulnerabilities	Risk reduction
Drowning	Storm surge, freshwater flooding, maritime disasters	Coastal settlements, floodplains	Elevated shelters, sea walls, evacuation of at-risk locations, early warning for vessels at sea, natural barriers (e.g., mangroves)
Trauma	Storm surge, freshwater flooding	Coastal settlements, floodplains	Elevated shelters, sea walls, evacuation of at-risk locations, natural barriers (e.g., mangroves)
Trauma	Building collapse (wind, storm surge, or flooding)	Coastal settlements, floodplains, wind-exposed areas, poorly constructed housing	Hardened hurricane shelters, evacuation of at-risk locations and structures
Trauma	Blown debris (wind)	Forested areas, urban areas, lack of shelter	Hardened hurricane shelters or dwellings
Trauma/ Suffocation	Landslides (rainfall)	Deforested hillsides, mountainous areas	Reforestation, land use changes, evacuation of at-risk locations
Electrocution	Preparations for impact or attempts to secure sites during storm impact	Unregulated power grids; aging infrastructure; lack of training	Power grid regulation and maintenance; training programs; access to skilled workers
Minor trauma	Preparations for impact or attempts to secure sites during storm impact	Poorly constructed housing or other buildings	Improved construction; safe work practices

Health impact	Causal hazard	Vulnerabilities	Risk reduction
Myocardial infarction	Preparations for impact or attempts to secure sites during/ after impact	Preexisting cardiovascular risk in persons securing sites or homes	Early warning to allow preparations by fit individuals; public health awareness

Delayed, Prolonged, and Indirect Impacts on Health

Infrastructure damage and societal disruptions following hurricanes result in negative health impacts through interrupted healthcare access, power outages, and evacuations. This section examines how these results can affect human health and reviews the existing body of research on prolonged health impacts beyond the immediate disaster event. Concerns include infectious diseases, women's health, mental health, prolonged impacts on patients living with noncommunicable diseases, and impacts on overall mortality.

Interrupted Healthcare Access

Road closures, building damage, power outages, and evacuations often result in interrupted or delayed access to healthcare due to competing demands on time and finances, loss of wages or livelihoods, loss of physical access, or breakdown in normal societal functioning. In the absence of insurance and social safety sets, hurricanes inflict a disproportionately heavy cost on the poor, and those on the brink of poverty may be pushed into long-term impoverishment after cataclysmic disasters (Doran et al., 2016; Loebach, 2019; Saha, 2017). Community-based health services including home visits, vaccination programs, maternal and child care, and other screening programs are often the first to be interrupted when healthcare facilities are destroyed or community health workers are unable to access affected communities (Ekperi et al., 2018; Gay et al., 2019; Gotanda et al., 2015; Lin et al., 2014; Loehn et al., 2011; Lurie et al., 2015; Mendez-Figueroa et al., 2019).

Some populations are at particularly high risk of loss of access to healthcare following hurricanes. During Hurricane Harvey, floodwaters precluded access to low-lying neighborhoods where several patients died at home while awaiting ambulances that could not reach them (Fink, 2018). Patients with chronic and ongoing care needs, including patients receiving chemotherapy or dialysis treatment and people dependent on visiting nurse services, home health aides, or on home-delivered meals, experience interruptions in services whose long-term impact is not fully understood (Gay et al., 2019; Kelman et al., 2015; Kleinpeter, 2009; Loehn et al., 2011; Lurie et al., 2015). Patients on hemodialysis are a particularly vulnerable subgroup, as they need frequent and regular access to dialysis services; prolonged intrruptions can be fatal, and in recent disasters in the United States, patients on dialysis have sought care by simply going to emergency departments that have had to improvise protocols to accommodate them (Kelman et al., 2015; Lin et al., 2014).

Power Outages

Existing literature suggests that power outages can have substantial health consequences including morbidity, increased hospitalizations, and death (Casey et al., 2020). Power outages frequently occur as a result of hurricane impacts and can have substantial health consequences in the days, weeks, or months following hurricane disasters. Carbon monoxide poisoning has been widely reported following hurricanes in the United States when households switch to indoor generators. These deaths typically occur within a few days of hurricane impact (Chen et al., 2013; Schnall et al., 2017). Patients dependent on electricity-powered equipment such as ventilators, left ventricular assist devices (LVADs), and critical drug infusions cannot survive for extended periods in the absence of backup power (Issa et al., 2018). Health facility damage or utility disruptions can result in patients and providers being trapped in hospitals that are suddenly rendered nonfunctional for prolonged periods (Bernard & Mathews, 2008; Ramme et al., 2015). In highly developed healthcare systems, loss of power may also result in loss of access to electronic medical records, rendering transitions of care to other facilities or systems more difficult. In the community, many patients depend on power to run oxygen concentrators and other equipment and to refrigerate medications; communications systems including cellular telephones can also fail during protracted power outages.

Evacuations

Evacuations before and during hurricanes, while necessary to flee from imminent danger, have also resulted in health harms (Dosa et al., 2012). During Hurricane Rita (2005), most of the fatalities attributed to the storm resulted from accidents during evacuation (Baker, 2018). The disorientation that stems from loss of familiar surroundings among the elderly and those with dementia coupled with complications of care transitions appear to contribute to increased 30- and 90-day mortality rates among elderly evacuees (Brown et al., 2012). Those with greater functional impairment have been found to have higher hospitalization rates in the months following hurricane impact (Thomas et al., 2012). Evacuations frequently result in avoidable interruptions to medical care and many evacuees do not have access to a complete list of their daily medications. In the United States, shelters invest significant resources trying to reconstruct medication lists (Jenkins et al., 2009). A review of more than 31,000 medical encounter forms from shelters after Hurricane Katrina revealed that the need for primary care services and for prescription medications were the principle immediate health concerns (Jenkins et al., 2009).

Population displacement disrupts jobs in the affected neighborhoods as well as in the communities that move. Families may be reluctant to evacuate or migrate when their livelihood is closely related to their land or community (Elder et al., 2007). The displaced are sometimes compelled to seek new work through kinship networks and other informal arrangements that are not readily visible to policy makers and the media. These new arrangements have been observed to have a wide range of effects, often placing the migrants in precarious positions with detrimental impacts on physical and mental health (Saha, 2017). However, recent evidence has shown that over time, migrants' health outcomes following disasters may mirror existing patterns in host regions. Eight-year survival in a Medicare cohort of Hurricane Katrina survivors improved by 2.07 percentage points, largely because of increased survivial in evacuees who migrated to regions with lower population mortality, healthier behaviors, and higher incomes (Deryugina & Molitor, 2018).

Infectious Diseases

Disease outbreaks following hurricanes are often related to flooding, water stagnation, and contamination of potable water (Campanella, 1999; Kang et al., 2015). Malaria and leptospirosis outbreaks have followed heavy rains, storms, and flooding in South Asia (Kouadio et al., 2012; Marinova-Petkova et al., 2019; Mendoza et al., 2013). Cholera outbreaks have also followed storms, including the 1985 cyclone in Sandwip, Bangladesh, Cyclone Idai (2019) in Mozambique, and Hurricane Matthew (2016) in Haiti (Bhunia & Ghosh, 2011; Cambaza et al., 2019; Chen & Azman, 2019; Hulland et al., 2019; Siddique, 1989). Presentations for respiratory illnesses including pneumonia have been observed to increase in the immediate aftermath of hurricanes and cyclones (Chang et al., 2016). Large numbers of skin and soft tissue infections are seen after hurriicanes, likely from a combination of direct contact with floodwaters, foreign bodies, limited access to sanitation facilities, and delays in accessing care (Kim et al., 2016; Lin et al., 2013; Tam & Nayak, 2012).

Women's Health

Access to women's health and reproductive healthcare services, including sites that screen for infectious diseases and family planning clinics, has often been disrupted after hurricanes (Kissinger et al., 2007; Leyser-Whalen et al., 2011). Maternal, fetal, neonatal, and infant morbidity and mortality have been observed to increase after disasters, which is likely related to some combination of increased stressors and decreased access to medical care (Mendez-Figueroa et al., 2019; Zahran et al., 2014). Rates of intimate partner violence, nonaccidental trauma in children, and other forms of interpersonal violence have been found to go up in the aftermath of hurricanes and other natural disasters (Anastario et al., 2009; Keenan et al., 2004; Picardo et al., 2010).

Mental Health

Several studies have shown increased rates of anxiety and depression in the aftermath of hurricanes, particularly among the elderly, young people, those who were injured, and those who lost employment as a result of the storm (Hirth et al., 2013; Mamun et al., 2019; McLaughlin et al., 2011; Orengo-Aguayo et al., 2019). The impact of hurricanes on mental health has been attributed to both the trauma of the event itself as well as destabilization of social functioning and supports in the aftermath of major storms (Chan et al., 2015; Shultz, Rechkemmer, et al., 2019). Long-term studies evaluating the persistence of psychiatric symptoms demonstrate elevated rates of depression, anxiety, posttraumatic stress syndrome, and other mental health problems for years after hurricane impact (Mamun et al., 2019; McLaughlin et al., 2011; Moscona et al., 2019; Orengo-Aguayo et al., 2019).

All-Cause Mortality

Official death tolls after disasters typically rely on vital registration data (birth and death counts maintained by the state). Populations most vulnerable to disasters live in areas of the world with weak registration systems. In general, these official registration systems only attribute deaths directly to hurricanes that have been so identified on the official death certificate, resulting in gross undercounting of even direct deaths, a problem that has been identified in a variety of disasters (Kiang et al., 2020). The counting of indirect and delayed deaths is even harder and increasingly relies on the calculation of excess mortality estimated by comparing all-cause mortality to predisaster annual and seasonal averages in the same population when such data are available (Acosta & Irrizary, 2020; Kim et al., 2017). After Hurricane Maria, for example, the initial official death toll of less than 100 was challenged by researchers who subsequently concluded that the excess mortality, based on a survey of over 4,000 households across Puerto Rico, was likely in the thousands. On further examination of all death certificates in the months following Hurricane Maria, the official count was revised to nearly 2,000 (Kishore et al., 2018; Santos-Burgoa et al., 2018). Retrospective analyses have identified increased mortality rates in other hurricane-affected regions including in New Jersey after Hurricane Sandy and in Hawaii after Hurricane Iniki (Hendrickson & Vogt, 1996; Kim et al., 2017).

Figure 2. Historical death toll from hurricanes in the late 20th and early 21st centuries. Data have been logarithmically transformed to facilitate comparison of death tolls in less affected nations. The vast majority of all deaths occurred in coastal regions of Asia, principally in nations with densely populated, low-lying river deltas. Of note, the data set includes all cyclonic storms, including events in Eurasia that were not tropical in origin.

Sources: Map by the authors. Data from EM-DAT, CRED/UCLouvain (2020).

Historical Approaches to Risk Reduction

Prior to the early 20th century, hurricanes were difficult to predict or track and populations usually learned of their arrival from direct observation of local weather changes just before landfall. In many cases, religious or supernatural significance was attached to hurricanes. The word *hurricane* itself originates from the Taino *hurakan*—a destructive deity at "the center of the wind" (Zimmer, 2020, p. 1). Across cultures, hurricanes were often considered a form of divine intervention. The two typhoons that foiled Mongol invasions of Japan in the 13th century were referred to as "divine winds" (Ladlow et al., 2019); and a 1780 hurricane in the Caribbean that served to sink or scatter naval forces and otherwise damage British assets during the American Revolution was described by one observer as "a visitation . . . to chastise the imprudence and arrogance of men" (Dolin, 2020, p. 2).

Scientific advances in the 19th and 20th centuries changed how human populations perceived, prepared for, and responded to hurricanes. The impact of hurricanes increasingly depended on the capacity to get people out of harm's way and to build engineered defenses against high winds and floods. Now, in the early 21st century, escaping from hurricanes entails either safely sheltering in place or physically moving (evacuating) to a more secure location elsewhere—both of which require effective early warning systems that are able to reliably predict, track, and communicate the risk of approaching hurricanes. It is important to note that a vast number of social, economic, political, and structural determinants shape the the efficacy and availability of both communication systems and sheltering options.

For much of the 20th century, advances in hurricane preparedness and their subsequent protective effect on population health were a product of improvements in early warning systems and communications capabilities, approaches to managing evacuation, and engineered defenses against storms and floods. Each of the these approaches, and their capacity to protect health, are described in the following sections and case study.

Early Warning

Technical assessments of hurricanes emerged in the era of extensive sea travel, supported by the development of the barometer and the collation of shipboard observations of waves and wind. By the 1920s, ships and weather bureaus were no longer dependent on the telegraph and were using wireless radio technology to transmit and receive maritime reports to follow storm paths in real time (Scotti, 2004). World War II ushered in aircraft-based hurricane reconnaissance, which further advanced in the 1950s under the auspices of the NHC in Florida. The combination of aircraft-based reconnaissance and centralized analysis of data by the NHC meant that for projections of hurricane paths in most of the North Atlantic basin were finally available for a few days into the future, making it feasible to prepare for evacuations and shelters in advance. By the 1960s, weather satellites capable of continuous observation of weather conditions over the world's oceans permitted hurricane scientists to follow storms across their entire lifecycle. These satellites greatly improved surveillance of remote ocean areas and of coastal regions where aircraft-based reconnaissance was not active. Aircraft surveillance, however, continues to provide extended intrastorm surveillance and measurement of barometric pressures, giving meteorologists information that cannot be measured by satellite and supports more comprehensive forecasts (Donegan, 2016), but intra-storm surveillance is not available in all regions (Sharma, 2011). While improved computing and data science capabilities have improved the accuracy of short-term storm track predictions, the fundamentally chaotic nature of weather systems means that long-term forecasts are inherently challenging (Orrell, 2007).

Communication

Advances in mass communication accompanied the growth of forecasting capabilities. In the 1950s, when the United States began to produce useful hurricane forecasts, radio and television supplied routine communication of warnings to the general public. By the end of the 20th century, coastal populations in East, South, and Southeast Asia also benefited from public address systems and radio broadcasts, and by 2020 Short Message Service (SMS) alerts warning of impending cyclones were commonplace (AFP, 2009; World Meteorological Organization, 2015).

The timing, tone, and content of disaster warnings are important, as are drills and practice. Research has repeatedly shown that the source of the information must be authoritative and trustworthy, the content must be clear and specific, and instructions to the population must be reasonable and feasible (Eisenman et al., 2007; Petrun Sayers et al., 2019). The effectiveness of early warning systems was demonstrated during Cyclone Phailin in eastern India in 2013, in which robust communication systems and shelter availability were credited with a much lower death toll (46 fatalities) than that experienced only 20 years earlier in the 1999 Odisha Super Cyclone, which led to more than 9,000 deaths (Jha et al., 2016).

Individuals face complex risk–benefit decisions when contemplating evacuation, as they may have to leave behind homes, belongings, land, and livestock. Large portions of a population may choose not to evacuate, relying on perceived stability of their shelter and what they may consider prior false alarms (Elder et al., 2007; Karaye et al., 2019). Memory of recent disasters has played an influential role in community response around the world (Brown et al., 2018; Monteil et al., 2020). The ablity to safely shelter in place or move is highly variable, particularly among older people, individuals with limited mobility, and those who lack access to transportation or resources to leave home for an extended period.

Case Study: The Hurricane of 1938

Lessons learned from the Hurricane of 1938 and other tragedies have shaped modern-day hurricane monitoring and preparedness. In September 1938, a large hurricane approached the southeast United States, prompting hurricane warnings. However, the storm turned north and warnings were canceled. Scattered reports suggested that the storm was tracking northward parallel to the coast, but the U.S. Weather Bureau lacked the technical capacity to assess the size or trajectory of the storm. As a result, warnings went out to New York and New England only as landfall was imminent; most people in the path of the storm were unaware of its arrival (Cappucci, 2018). On the afternoon of September 21, a Category 3 hurricane moving northward at more than 60 kilometers per hour made landfall on vacation beaches, causing extensive damage before moving inland. Survivors described a pleasant fall day that suddenly turned dark, with rapid onset of hurricane force winds and a storm surge that exceeded 4 meters in some locations. Many were stranded on beaches and barrier islands, unable to flee due to extensive flooding on coastal roads (Scotti, 2004). More than 600 people were killed by drowning or building collapses and thousands of homes were destroyed. Little, however, is known about the long-term health effects of the storm (NHC, 2020a).

Several factors contributed to the disastrous consequences of the 1938 hurricane. Forecasters needed good information and the ability to interpret it. In this instance, data were limited to a few wireless radio reports from ships at sea and forecast offices did not put these together into a useful, timely prediction, in part because they lacked formal modeling capabilities (Scotti, 2004). Populations in high-risk locations needed to evacuate but lack of warning meant homes closely facing the Atlantic waters were still occupied when the hurricane made landfall (Cappucci, 2018). Water, in the form of storm-surge flooding, caused the vast majority of immediate deaths, in part because the hurricane struck populated low-lying coastal areas without high ground to which people could flee. Well-built structures were protective: one couple survived by taking refuge in an abandoned stone fort on a sandbar, while the inhabitants of nearby wooden structures were killed or blown across miles of open water clinging to debris after buildings collapsed around them (Scotti, 2004). There is little record of the long-term health effects, but reconstruction took many years, with physical evidence of the storm visible more than a decade later.

These themes and observations have recurred worldwide. The story of hurricanes and health over the 21st century is largely one of improvements in detection and forecasting, implementation of early warning systems, evacuation of at-risk populations, and use of resilient structures and other engineering solutions to reduce the immediate health impacts of wind and water. This history is also replete with records of lethal outcomes when these approaches failed or were not in place.

Shelter in Place and Self-Sufficiency

Large populations at risk of being flooded during hurricanes live in low-lying or coastal areas, ranging from Bangladesh to the Gulf Coast of the United States. In the 1970s and 1980s, mortality from cyclones in Bangaldesh was dramatically reduced by improving early hurricane warning, developing communication systems able to reach populations in danger, and providing vertical sheltering options into which people were able to retreat, in some cases with ramps for their livestock (Figure 3). Cylcone Bhola in 1970 resulted in 500,000 deaths because people were caught off guard and were unable to retreat to higher ground since the terrain is mostly flat and at sea level for many hundreds of kilometers inland. Advances in early warning and vertical sheltering options have resulted in dramatic mortality reductions over the decades. Postdisaster mortality analysis of the 1991 Bangladesh Cyclone revealed that only those who had reached shelters on time survived the storm (Bern et al., 1993). These solutions remain imperfect, and as we see in subsequent sections, differentially impact members of the same community. Cyclone Sidr in 2007 resulted in 15,000 deaths, and although this was just a fraction of the 140,000 deaths estimated for the 1991 cyclone, the toll is staggeringly high for a predictable disaster in the 21st century (Haque et al., 2012).

Figure 3. Cyclone shelter in southeastern Bangladesh. Note the elevated shelter structure and the use of columns that allow floodwaters to pass without damaging the structure.

Source: U.S. Embassy, Dhaka, Bangladesh.

In dense urban centers such as Hong Kong and New York, vertical sheltering-in-place is commonplace, although accompanying power outages may result in elevator closures, making it difficult for older people to access services, as was observed in New York after Hurricane Sandy (Williams, 2013). Sheltering-in-place requires a level of self-sufficiency. In most settings, if the immediate habitat is not threatened by wind or floods, sheltering-in-place allows interdependence within familiar communities, provided people have access to food, potable water, meducations, and reliable communication.

Evacuation

Sheltering-in-place is often not an option in low-lying areas where there are insufficient vertical sheltering options in place and access to critical services may be lost from road closures, landslides, or widespread infrastructure and electrical disruption. Evacuation as an option has in the past mainly followed storms and floods, but advances in hurricane predictions have allowed for preemptive evacuation in recent decades.

Extensive research across cultures and over time has demonstrated that evacuation decisions are complex and multidimensional. In the western Indian state of Kerala in India, population literacy is high and there have been robust mechanisms for participatory local self-government. A study of the evacuation response to the 2018 Kerala floods demonstrated that communities were most likely to evacuate if so advised by local government representatives (Harvard South Asia Institute, 2020). This finding does not hold true in many other settings, likely due to varying levels of trust in government. In New Orleans, distrust of local government stemming from long-standing and pervasive structural injustices influenced community decisions to not evacuate during Hurricane Katrina (Elder et al., 2007). In addition, simply providing information does not guarantee that the recipients are able or willing to bear the costs of evacuating (Eisenman et al., 2007). Some success has been achieved by including community members in the planning and organization of evacuations and by leveraging trusted community organizations to convey risk and urgency (Ricchetti-Masterson & Horney, 2013).

Research has shown that beyond willingness to heed evacuation warnings, the ablity to evacuate is largely dependnent on the household’s socioeconomic context. There are several reasons people are unable to evacuate. They may not have access to a vehicle or alternate means of transportation (Eisenman et al., 2007; Lim et al., 2016) or they are responsible for others, such as those with disabilities or advanced age (Ricchetti-Masterson & Horney, 2013). They may be immobile themselves, may not have access to or knowledge of another location, or they may lack safe options for storing goods that must be left behind (Roy et al., 2015).

In the United States, where hurricanes are an annual occurance in the Gulf states, only 35% of U.S. emergency managers believe they are adequately prepared to handle large-scale evacuations (Federal Emergency Management Agency, 2019). Persistent challenges include traffic jams, risk of health impacts on evacuated populations, and problems with shelter and temporary housing. Evacuation of hospitalized patients carries the risk of care interruptions from transport delays or mishaps, loss of medical records, errors in transitions of care, and even loss of revenue. While hospitals prefer to retain their patients and have them shelter in place, the U.S. experience has shown that backup systems fail. Large hospitals have had to evacuate patients in both Hurricane Katrina (2005) and Hurricane Sandy (2012; Gallagher et al., 2006; McGinty et al., 2017). Long-term nursing facilties are less equipped to withstand prolonged infrastructure disruptions (power, water, road access), yet they are often home to some of the most medically vulnerable populations (Dosa et al., 2012).

Engineered Defenses

Well-engineered defenses constructed in the 20th century sought to provide physical barriers against floods, storm surges, and high winds. As experience over the past century has shown, these barriers require iterative expansion and renovation to accommodate urban expansion and climate-related changes, such as rising sea levels. The ancient sea wall of Shanghai was breached by Typhoon Gloria in 1949, flooding parts of the city and causing substantial loss of life. The sea wall was raised, and mortality in the 1956 typhoon was substantially lower. Shanghai continued to fortify the wall and build an extensive system of dams and dikes to mitigate the impact of frequent typhoons (Coutaz, 2018). Having survived a 1997 typhoon in part because of its sea wall, Shanghai is now extending and reinforcing its defenses against sea-level rise and future storms (Liu, 2011).

Limits of Current Approaches

A series of tragedies during the first two decades of the 21st century prompted a proliferation of research on the health impacts of hurricanes. The findings exposed some of the limitations of the health protection strategies that had been implemented during the 20th century. The failure of levees to protect low-lying communities from heavy flooding during Hurricane Katrina (2005) and drownings that occurred when evacuation shelters and other supposedly safe locations were flooded by storm surges during Typhoon Haiyan (2013) emphasized the importance of planning for extreme hazard profiles and the dangers of over-reliance on engineered solutions (Ehrenfreund, 2013; Jonkman et al., 2009; Lagmay et al., 2015). Hurricanes Katrina and Rita (2005) called into question the effectiveness of policies that focused primarily on evacuation, albiet for different reasons. During Hurricane Katrina, a disproportionate number of deaths occurred among the poor, the ill, and those otherwise unable to evacuate (Brunkard et al., 2008). Planners had unaccountably not recognized that hundreds of thousands of people in New Orleans and other low-lying communities in Louisiana and Texas had no cars, no knowledge of where to go, impaired physical mobility due to chronic illness, or caretaker responsibilities (Elder et al., 2007; Petrun Sayers et al., 2019). In contrast, during Hurricane Rita, more deaths were attributable to the evacuation process than to wind or water impacts from the storm (Baker, 2018). Power failures in hospitals and nursing homes resulted in deaths and evacuations during Katrina (2005), Sandy (2012), and other storms.

Studies following Hurricanes Katrina (2005), Sandy (2012), and Maria (2017) have shown persistently high levels of morbidity and mortality in the vulnerable subsections of the affected populations (Burton et al., 2009; Kishore et al., 2018; Swerdel et al., 2014). Individual and population health is undermined by long power outages, displacement, loss of livelihoods, food insecurity, and interrupted access to healthcare. An increasing number of studies have documented high levels of posttraumatic stress disorder, depression, and other mental health disorders following major hurricanes (Mamun et al., 2019; McLaughlin et al., 2011; Moscona et al., 2019; Orengo-Aguayo et al., 2019). Studies examining race, gender, age, and income effects have documented disproportionate health impacts and mortality among persons of color, older people, children, and the poor (Becquart et al., 2018; Bern et al., 1993; Toldson et al., 2011).

Twenty-First–Century Challenges

Climate change, unplanned urbanization, and population growth in at-risk locations present substantial challenges to those charged with developing comprehensive plans for hurricane mitigation and response. Current trends portend a future of increased population vulnerability and exposure to hurricane health hazards. Addressing these challenges in an equitable and effective manner will require immediate solutions to ameliorate current suffering and bolder approaches to change the calamitous path we seem to be on. This section summarizes the known risks to population health posed by progressive climate change, by continued development of coastal areas, and by unplanned urbanization in low-lying areas—all three of which are expected to intensify without local and global measures to change course.

Climate Change

Slow-moving hurricanes including Harvey (2017) and Florence (2018) resulted in substantial rain and extensive flooding (Kossin, 2018; NWS, 2020). Rising sea levels have similar effects due to risk of saltwater and storm surge flooding, with particularly dire implications for communities at or near sea level. More powerful storms appear to be associated with higher fatality rates and have historically been associated with widespread destruction of critical infrastructure (Dresser et al., 2016). From the standpoint of early warning, evacuation, and preparedness, more frequent and abrupt rapid intensification of storms prior to landfall presents a substantial planning and political challenge. These observed storm behaviors may leave scant time in which to take appropriate sheltering and evacuation measures.

The possible poleward shift in the locus of maximum intensity is also concerning, as this trend suggests that populations with less historical experience of hurricanes, and thus less cultural and institutional preparedness, may face an increasing risk of impacts in the future. While most models do not suggest an increase in absolute frequency, the frequency of severe storms is expected to increase (Knutson et al., 2021). Communities in settings that face recurrent or exceptionally severe hurricane disasters may be unable to recover fully between events and may be forced to endure impoverishment, population out-migration, and possibly abandonment, as occurred in Barbuda following Hurricane Irma (Wright et al., 2020).

Coastal Populations

Historically, the populations at greatest risk of health impacts from hurricanes have been inhabitants of the western coastlines of the Atlantic, Indian, and Pacific oceans, the Caribbean and South China seas, the Bay of Bengal, and certain islands in major ocean basins (Ting et al., 2019). Densely settled populations living at sea level or on low-lying flood plains in Bangladesh, Myanmar, India, and parts of Southeast Asia are at risk of experiencing both fresh- and saltwater flooding (Haque et al., 2012; Pörtner et al., 2019). Rising population density in these coastal zones presents a major challenge to governments seeking to protect their people from harm; 10% of the global population lives in areas that are at risk from sea-level rise by 2100 (Oliver-Smith, 2009), and a substantial portion resides in locations at risk from hurricanes.

Urbanization

An increasing proportion of those affected by future hurricanes reside in urban settings, presenting both obstacles and opportunities for protecting human health. Rapidly expanding megacities, including Chennai, Dhaka, Guangzou, and Manila lie in hurricane belts (National Ocean Service, 2020). Urbanization presents a particularly complex and important context for the consideration of future health impacts of hurricanes. While the urban environment, in theory, is planned and controlled, the reality is that many cities grow organically and contain a mix of land-use types. Construction of parking lots, roads, buildings, and other impermeable surfaces has reduced the flood protections afforded by vegetation and soil absorption, ranging from loss of mangroves along deltas and coasts to destruction of wetlands that have historically served to moderate inland flooding (Dasgupta et al., 2019; Del Valle et al., 2020; Zhang et al., 2018).

Even in hyperurban Hong Kong, major cyclones result in landslides and flooding, disrupting utilities and transport and destroying homes (Chan et al., 2016; Shang et al., 2020). Informal settlements in rapidly expanding cities may be at particularly high risk, as they are often constructed in marginal terrain susceptible to either surface flooding or landslides during heavy rainfall. Across Central America and parts of the Caribbean, deforestation of steep terrain for agricultural purposes has led to reduced moisture absorption capacity and soil stability, increasing the risk of both flash flooding and landslides—the lethality of which have been demonstrated during Hurricane Mitch and subsequent storms (Das & Vincent, 2009; Myers, 2012). Evacuation, a mainstay of efforts to protect health during hurricanes in many locations, may prove impossible in the context of very densely settled urban populations numbering in the millions.

While occupants of high-rise buildings may take advantage of vertical sheltering with proper preparations, doing so depends on the existence of appropriately engineered buildings capable of withstanding both high winds and soil saturation without experiencing catastrophic failure. At the same time, high-density settlement in urban environments may allow for more efficient distribution of supplies and better accessibility of healthcare institutions or deployed health assets in the immediate postdisaster setting. Some urban environments may allow for protection through engineered defenses such as levies, pumping systems, and sea walls. Yet sole reliance on engineered defenses has been observed to be catastrophic when those in charge unduly rely on them as the primary means of protecting populations from harm, as occurred during Hurricane Katrina (Narayanan et al., 2020).

Inequality and Justice

The health impacts of hurricanes are unevenly distributed among affected populations. This observation, increasingly supported by 21st-century events, raises critical questions of justice and inequality in any response strategy aimed at population protection. During Hurricane Katrina, the mortality rate was 1.7 to 4 times higher in the Black population than in the White population of Orleans Parish (Brunkard et al., 2008). There is growing evidence that intersecting demographic, socioeconomic and political determinants result in higher mortality among racial and ethnic minorities and among older people and those who are medically vulnerable (Cruz-Cano & Mead, 2019; Kim et al., 2017; Kishore et al., 2018; Roman et al., 2019; Santos-Burgoa et al., 2018). Disaggregated data can illuminate vulnerability and strategy gaps that need to be addressed for more equitable preparedness, mitigation, and response. There is concern that without effective safety nets, the poor often fall into poverty traps following major disasters, and that on a global scale, impacts related to climate change will be disproportionately borne by populations who have in general contributed minimally to historical greenhouse gas emissions (Samson et al., 2011).

Displaced and migrant populations require special consideration. By 2020, there were nearly 80 million forcibly displaced persons in the world. The one million Rohingya refugees from Myanmar, for example, who reside in densely populated refugee camps in and around coastal Cox's Bazaar in Bangladesh, are highly vulnerable to cyclone impacts. Although improved early warning systems will be beneficial, the intrinsic vulnerability of these settlements remains high (Alam et al., 2020). Similarly, migrants on the U.S.–Mexico border have limited early warning and few places to which they can flee; other solutions, such as engineered defenses or elevated shelters are not typically constructed in camps that are intended to be temporary (Harrison-Cripps, 2020).

Opportunities for Improved Outcomes

While the challenges related to climate change, demographics, and inequality are substantial, there are also some reasons to hope that the health needs of affected populations can be met during and after future hurricanes. Improvements in forecasting and communication, particularly in less wealthy settings, could allow an increasing proportion of those affected by hurricanes to make preparations before landfall. Increased awareness of the implications of climate change may motivate governments and communities to invest in long-term adaptation. And there is an opportunity to avoid the worst impacts of climate change on hurricanes and sea-level rise if aggressive reductions in global greenhouse emissions are implemented immediately (Pörtner et al., 2019). Increased appreciation of the long-term impacts of hurricanes on health and the limited effectiveness of a purely response-oriented strategy means that greater investment in preparedness may be forthcoming. Such investment will be particularly important for healthcare facilities, which in emergencies are very difficult to replace once incapacitated. Although a strategy of warning, evacuation, and engineered defenses may not be sufficient to protect all people in all places (Bukvic & Owen, 2017; Burger & Gochfeld, 2014; Doran et al., 2016; Seil et al., 2016), this approach will continue to offer substantial health protection benefits in appropriately selected settings and should be implemented when suitable. Community-led initiatives hold promise as a means to improve health protection from hurricanes in settings and among subpopulations that have historically proved to be disproportionately vulnerable to hurricane impacts.

Meeting the Needs of the 21st Century

Tropical cyclones will remain a potentially lethal hazard throughout much of the world for the foreseeable future. Improvements in weather observation, modeling, forecasting, communication, evacuation, and use of storm-resistant structures and engineered defenses during the past century demonstrate that investment in these activities can reduce direct health impacts. However, implementation of these approaches varies widely, and large-scale loss of life continues to occur in less wealthy or highly marginalized settings where such investments have not been made. In addition, climate change modeling, demographic and development trends, and lessons learned from tropical cyclone disasters in the first decades of the 21st century all point to a future of increasing complexity in which new approaches to risk reduction will be necessary. Novel dimensions of this hazard must be addressed, such as the effects of sea-level rise, and a broader range of vulnerable populations and health impacts must be considered; for example, those at risk of adverse health outcomes due to interruptions in electricity or continuity of medical care. Approaches suitable to coastal megacities must also be developed. Current strategies will need to be adapted to meet the needs of specific communities and extended into communities that do not yet benefit from policies and programs with well-demonstrated effectiveness. In addition, new strategies will be needed to address changing patterns of hazards and vulnerabilities across the world.

Research

Research on the health implications of tropical cyclones is most needed in settings that have been historically less studied and on hazards and vulnerabilities that are expected to intensify during the 21st century. Such research is necessary at both national and subnational scales; the implications for infectious disease, nutrition, mental health, and other secondary effects remain poorly understood in many populations despite reccuring evidence that long-term mortality is high. There is need for better understanding of the effects of cyclones on health impacts mediated through loss of electricity and loss of access to care; these downstream ramifications may only be appreciable after several years and will be difficult (and expensive) to ascertain. Given the urgency of addressing these issues, partnerships with key decision makers or participatory community-based research designs may facilitate translation of results by ensuring that research is valued by and addresses the needs of stakeholders, and that the research is actionable and sustainable from social, financial, and political perspectives.

Policy

Policy makers seeking to address the health impacts of hurricanes face several competing goals. First, storms must be tracked and expected hurricane impacts must be communicated. Second, populations must be protected from the direct health impacts of storms. Third, steps must be taken to reduce the long-term impacts of hurricane disasters. Finally, policies to reduce the intensity and impacts of climate change are needed to reduce the severity of health consequences arising from future storms. Reliance on response does not appear effective from the perspective of health protection; the disruption resulting from modern storms is on such a scale that outside help may be delayed beyond usefulness, be unable to reach those most in need, or be diminished by simultaneous crises (Willison et al., 2019).

The first two objectives—storm tracking and population protection from direct impacts—can be accomplished though a variety of proven approaches that have been implemented worldwide in numerous settings. The principal policy decisions to achieve effective tracking, prediction, and communication capabilties involve allocation of stable funding to meteorological services, investment in communication systems, and consideration of community-based programs in some high-risk settings. Protection from direct impacts is more challenging and may involve investment in large-scale infrastructure, hurricane shelters, and evacuation capabilities, as well as adaption of existing infrastructure to meet the needs of expanding populations and intensifying hurricane hazard profiles due to climate change.

Addressing the long-term health impacts of hurricanes presents a more complex policy challenge, as health impacts are diverse, solutions vary by location, and some impacts and solutions are incompletely evaluated. Strategies ranging from planting mangroves to hardening hospitals against flooding may be appropriate in specific contexts. Housing policy, in particular, presents opportunities for high-impact interventions that can address both immediate and delayed health consequences. An important new focus must be on communities with fragile economic structures, limited political influence, and high poverty rates that are located in settings frequently exposed to hurricane hazards. These communities are often unable to afford storm-resistant structures and should become an important focus area for political efforts to promote construction of hurricane-resilient housing (O'Connor, 2017; World Bank, 2019). While hurricane-resilient designs now exist, a combination of expense and resistance to enacting more stringent building codes has limited effective implementation. Financial security is also an essential component of recovery from disasters, with substantial implications for the long-term health of populations. Novel applications of digital cash transfers and expanded micro-insurance programs may have a role in improving postdisaster recovery (Cetinoglu & Yilmaz, 2020; Pega et al., 2015). In the health sector, facilities in at-risk communities need to be examined in terms of their capacity to withstand—both physically and operationally—increasingly damaging storms in order to continue to meet the needs of the populations they serve.

Conclusion

Tropical cyclones are a persistent and increasing threat to human health. Altered human settlement patterns, population growth, and climate change mean that increasing numbers of people will face these hazards over the course of the 21st century. Advances in detection, forecasting, and evacuation have led to dramatic reductions in mortality in some settings. However, much more is now needed, particularly in low-resource settings and regions that will be disproportionately affected by climate change.

Future efforts must focus on both increased implementation of proven approaches and devopment of novel health protection strategies. Integration of effective policies where they exist, extension of these approaches to populations that are not yet protected, and consideration of novel research and risk reduction strategies will be needed. New approaches must include investments in long-term changes in patterns of habitation and building practices, analyses of population vulnerabilities in the context of accelerating climate change, and efforts to curb greenhouse gas emissions.

Policy makers and politicians must develop and implement strategies that will reduce exposure to cyclone hazards while allowing people to prosper and thrive. Moving human settlements and key civil and industrial facilities away from coastal areas could reduce the exposure of human populations to worsening sea-level rise, storm surges, and hurricane intensification. Such approaches carry significant short-term economic and political costs, but they may have even greater long-term benefits. Effective implementation will likely depend on engagement of affected communities in the decision-making process. Achieving long-term health protection from hurricanes also demands collective efforts to reduce consumption and shift to sustainable sources of energy; reductions in greenhouse gas emissions sufficient to mitigate the extent of future climate change are essential.

These interventions will be challenging to design and implement. Sucessful action demands a groundswell of public concern, collaborative engagement between affected communities, researchers, and policy makers, and unprecedented national and international cooperation.

Further Reading

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