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Projecting the Impacts of a Changing Climate: Tropical Cyclones and Flooding

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Abstract

Purpose of Review There is clear evidence that the earth's climate is changing, largely from anthropogenic causes. Flooding and tropical cyclones have clear impacts on human health in the United States at present, and projections of their health impacts in the future will help inform climate policy, yet to date there have been few quantitative climate health impact projections.

Recent Findings Despite a wealth of studies characterizing health impacts of floods and tropical cyclones, many are better suited for qualitative, rather than quantitative, projections of climate change health impacts. However, a growing number have features that will facilitate their use in quantitative projections, features we highlight here. Further, while it can be difficult to project how exposures to flood and tropical cyclone hazards will change in the future, climate science continues to advance in its capabilities to capture changes in these exposures, including capturing regional variation.

Summary Developments in climate epidemiology and climate science are opening new possibilities in projecting the health impacts of floods and tropical cyclones under a changing climate.

Keywords Tropical cyclones · Flooding · Climate · Human health · Climate health impact projections

Introduction

There is clear evidence that the earth's climate has changed over the past decades, largely from anthropogenic causes [1–3]. The climate will continue to change in the coming century; how much will depend in part on our policy choices in the near future and our commitments to achieve those policy goals [3]. In the United States (US), a key report in policy decisions is the US Climate and Health Assessment [4]. This report is mandated by the US Congress and created by the US Global Change Research Program, which brings together thirteen government agencies. The most recent assessment includes a chapter on climate-related disasters [5], which highlights how little evidence is available that quantitatively projects the expected health impacts of disasters like floods and tropical cyclones, noting:

> Many qualitative studies have been published about the potential or expected health hazards from these events, but few draw strong or definitive conclusions that exposure to health hazards will increase due to climate change. ... There is no quantitative information

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> on which to base probability estimates of the likelihood of increasing exposure to health hazards associated with extreme precipitation, hurricanes, coastal inundation, drought, and wildfires [5].

In this review, we assess why quantitative health projections are so rare for flooding and tropical cyclones, even while they are available for other types of climate-related exposures like extreme temperatures (e.g., [6–8]). We aim to highlight opportunities and challenges when projecting potential health impacts of flooding and tropical cyclones under scenarios of climate change. While these projections are valuable for any part of the world, we focus on the US.

Quantitative Climate Health Impact Projections

The construction of computer models that simulate the Earth system and enable scientists to predict, from fundamental physical principles, how the weather and climate will evolve, is one of the great scientific achievements of the last 50 years. This has allowed society to look into the future and recognize the implications of a warming world. Indeed, climate and Earth system models, and the predictions made for different emission scenarios, form much of the bedrock of the evidence base for mitigation and adaptation [9].

Output from these models can be used to project health impacts. Vicedo and coauthors [10] define one framework for doing so, in combination with results from epidemiology and projections of baseline health. While not the only approach for conducting such projections, it has proven a powerful framework for climate epidemiology—particularly for temperature-related impacts—and offers a promising direction for similar projections of health impacts of tropical cyclones and flooding. Figure 1 sketches how this framework combines evidence from epidemiology, climate modeling, and demographics [4], illustrating with a simple hypothetical example for tropical cyclone exposure.

There are, of course, challenges and opportunities for these quantitative climate health impact projections. Some are common, regardless of the climate exposure being investigated. One example is in characterizing uncertainty around central impact estimates—a question that is challenging but for which tools are quickly advancing. Climate models are continuously being improved, and they now incorporate uncertainty from a number of sources, including internal variability introduced by uncertainty in the exact future timing of recurrent phases like the El Nino-Southern Oscillation. Many modeling efforts also address uncertainty introduced by the climate model itself, by using output from models developed by several of the large climate modeling groups worldwide. Further, demographers have done work to project future changes in population size in different communities, as well as changes in characteristics of those populations—like aging—that might affect baseline rates of health outcomes in the future (e.g., [11]).

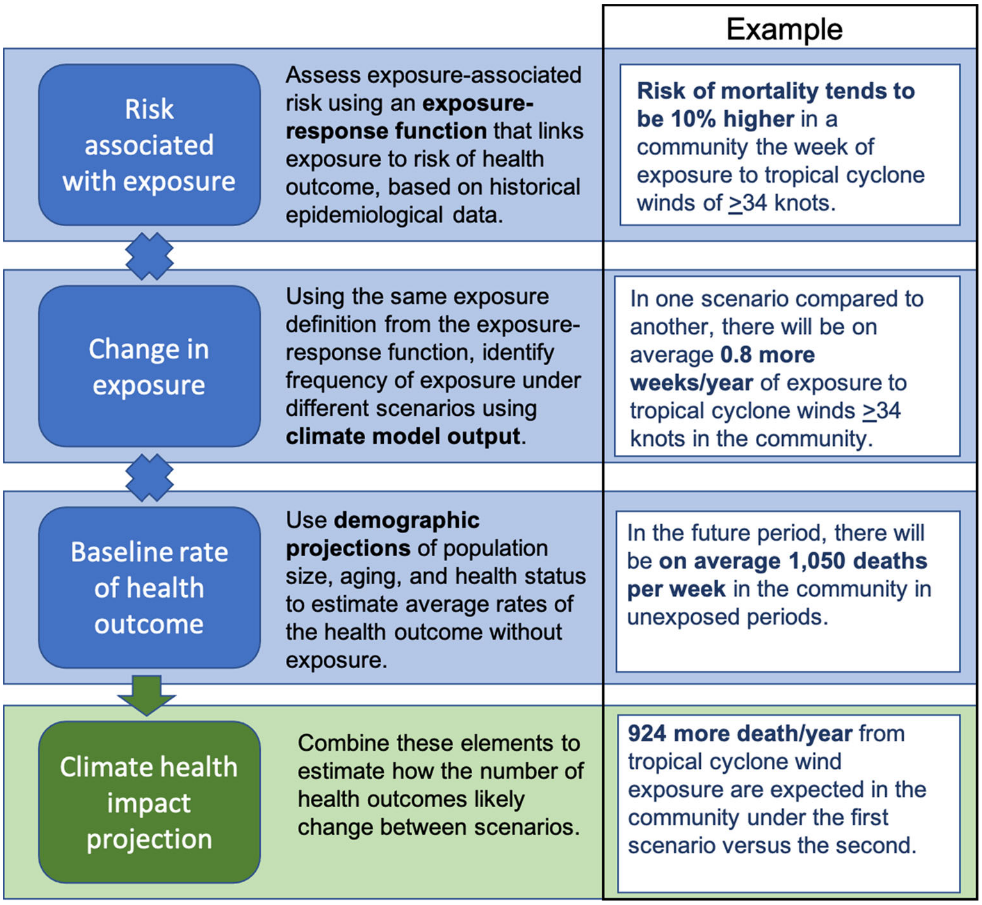
Other challenges, however, are more distinctive to floods and tropical cyclones, raising more barriers compared to projections for other exposures. We will review these challenges—and promising work toward overcoming them—in the following sections. We use separate sections to discuss flooding (including that from tropical cyclones) versus other hazards of tropical cyclones. When a study has focused on a tropical cyclone as a whole, rather than specific hazards, we have generally included it in the section on tropical cyclones, excepting a few tropical cyclones notable for flooding (e.g., Hurricanes Katrina, Harvey, Florence, Floyd).

Floods

Flooding, broadly defined, happens when there is water where there should not be, “water overflowing onto land which is typically dry” [12]. There are two broad types of floods. The first, inland flooding, occurs on a variety of spatial and temporal scales. Flash floods happen quickly and over a relatively localized area. They are often caused by extreme precipitation and can be amplified by surface factors like topography, soil type, and the size of the drainage basin [12]. River floods occur over longer time periods—from days to weeks depending on catchment properties—and typically over a much larger spatial scale than flash floods [12]. Large-scale, slower river flooding can itself cause more localized, faster flash floods, for example when river flooding causes the failure of a dam [12].

The second type is coastal flooding. A common source of coastal flooding is storm surge, which is defined as an abnormal rise in sea level accompanying a tropical cyclone or other intense storm. Storm surge can extend up to a mile inland [13], depending on local bathymetry and topography. Coastal flooding can also result from tides, high waves, heavy rains, and their compounding effects. Even lakes can experience their own surge-type flooding from pressure difference–driven waves called seiches [12].

Several weather systems are associated with flooding. Flash floods can be caused by “training” thunderstorms (several in a row that pass over the same area), orographic precipitation (when moisture-heavy air masses move over mountains), and slow moving or stalled tropical cyclones [12]. Larger systems of organized thunderstorms can bring heavy rain on a more regional scale, causing river flooding, and tropical cyclones can cause river flooding well inland from landfall [14]. Sudden increases in temperature or rain-on-snow at higher elevations with snowpack can also



Assess exposure-associated risk using an **exposure-response function** that links exposure to risk of health outcome, based on historical epidemiological data.

Risk of mortality tends to be 10% higher in a community the week of exposure to tropical cyclone winds of ≥34 knots.

Using the same exposure definition from the exposure-response function, identify frequency of exposure under different scenarios using **climate model output**.

In one scenario compared to another, there will be on average **0.8 more weeks/year** of exposure to tropical cyclone winds ≥34 knots in the community.

Use **demographic projections** of population size, aging, and health status to estimate average rates of the health outcome without exposure.

In the future period, there will be **on average 1,050 deaths per week** in the community in unexposed periods.

Combine these elements to estimate how the number of health outcomes likely change between scenarios.

924 more death/year from tropical cyclone wind exposure are expected in the community under the first scenario versus the second.

Fig. 1 Key components in conducting a quantitative climate health impact projection following the framework of Vicedo et al. [10], as well as a simple hypothetical example of collecting and combining these components to project the potential mortality impact of a specific tropical cyclone–associated exposure when comparing two future scenarios

cause downstream river flooding. For storm surge, severity is influenced by storm characteristics, including track, intensity (primarily wind speed, but also surface pressure), size and forward speed [15]. At a larger scale, atmospheric rivers can lead to multi-day, widespread rainfall events that, when coupled with mountainous terrain, can cause flash flooding on a longer time scales, and seasonal shifts in atmospheric conditions, such as monsoons, lead to months-long wet seasons that can bring devastating flooding.

Weather systems are not the only drivers of flooding, however, and the same weather conditions can result in different likelihood of flooding depending on other factors. Local factors that influence risk include flood management strategies, land surface cover, and soil saturation [12, 16, 17]. Topography also plays a role, with particularly high flood risk in certain regions (e.g., the Balcones Escarpment in Texas [18, 19]) and areas with certain topographic features (e.g., canyons [20]).

Historical and Current Impacts on Human Health

Each year, on average, flooding directly causes several dozen deaths in the United States—estimates range from 60/year to 100/year depending on the decades considered [18, 21]. Most are from drowning [18, 20], although some result from other causes, including physical trauma and automobile accidents [18, 22, 23]. When flood waters are cold, hypothermia can also cause direct health impacts [24, 25].

Wounds, electrocutions, poisonings, and other indirect injuries can also follow floods. About a 40% increase in pediatric emergency room visits for trauma complaints, for example, was identified in Houston following Hurricane Harvey, and visits for toxocological emergencies more than doubled [26]. Improper use of generators and gasoline-powered power washers can lead to deaths and hospitalization for carbon monoxide poisoning [25, 27, 28]. Contaminants in flood waters can cause blood infections—including leptospirosis, which is otherwise very rare [29, 30]—as well as skin infections and other dermatological issues [31], as observed during Hurricanes Floyd [25] and Harvey [26]. Exposure to chemical irritants can also be a problem, as during floods industrial sites sometimes release dangerous chemicals into surface water [24, 31, 32]. Hurricane Harvey, for example, resulted in flooding or damage to over a dozen Superfund sites [31].

Floods also raise concerns about vector-borne disease. The mechanism is clear, as flooding could increase vector populations, change vector behavior, and increase people's chance of being bitten [25, 27, 31]. However, post-flood vector surveillance has often found minimal risk for vector-borne diseases (e.g., [33, 34]), and campaigns like aerial pesticide spraying after some major floods (e.g., Hurricane Harvey) also limit risk [35]. Ultimately, there has been little evidence that major floods in the US have caused outbreaks of vector-borne disease in humans (e.g., [33, 36]). Exceptions include one study that found that rates of West Nile virus increased after Hurricane Katrina in affected areas of Louisiana and Mississippi [37], as well as a national, multi-year study found that heavy rainfall (one driver of flood risk) tended to increase West Nile incidence over the next two weeks [38].

Another case where plausible pathways are clear but realized human impacts are variable is gastrointestinal disease. Flooding can expose people to pathogens associated with gastrointestinal illness [24, 32] through recreational water (e.g., [39]) or contact with flood waters (e.g., [40]). Flooding—and conditions that strongly increase the risk of flooding, like extreme precipitation events—can also contaminant drinking water sources through sewer overflow in the many US communities that still use combined sewer systems [41], as observed during Hurricane Harvey [42]. Gastrointestinal disease can also spread in shelters when people are displaced by floods; gastrointestinal outbreaks were identified in shelters following Hurricanes Floyd [25], Katrina [43], and Harvey [44]. However, despite plausible causal links between extreme rainfall, flooding, and gastrointestinal disease [45], epidemiological results can vary [46]. For example, studies have linked extreme precipitation events to salmonellosis [47], shigellosis [48], and *Campylobacter* infection [49], as well as to more general gastrointestinal symptoms or medical visits (e.g., [50–52]). However, some of these studies found these connections only in coastal areas [49] or only in areas served by drinking water from surface sources [50] or with combined sewer systems [51]. Other studies found no association at all [39]. Similarly, several floods have been associated with increased risk of gastrointestinal symptoms or medical visits or waterborne disease [25, 53], but others have not [27, 54], or only for mild symptoms [40].

There is clearer evidence of a link between flood exposure and respiratory health outcomes. One large multi-year study found a small but statistically significant increase in risk of respiratory hospitalization among older adults in association with tropical cyclone–associated flood events [55], and substantial respiratory impacts have been identified for specific floods (e.g., Hurricanes Floyd [25] and Katrina [56]). Some respiratory risk may be related to evacuation. Respiratory outbreaks occurred in evacuation shelters following Hurricanes Harvey [57] and Floyd [25], and pneumonia and upper respiratory infections were identified in evacuees following Hurricane Katrina [43]. Flooding can also trigger mold growth in homes (e.g., [58–61]), which creates a longer-term threat to respiratory health (e.g., [62]), although these increased exposures do not always translate to health impacts [59]. Floods can also create increased risk of fatal and non-fatal cardiovascular outcomes (e.g., [56, 63, 64]), as severe disasters can create emotional and physicals triggers for acute cardiovascular events [65, 66].

Flood exposure among pregnant women has been associated with adverse birth outcomes and later health of the child. Risk of low birth weight, preterm birth, and fetal death have all been linked to specific floods (e.g., [67–73]), although one study conversely found that risk of preterm birth was reduced following Hurricane Katrina [74]. Prenatal flood exposure has also been linked to later risk of autism [75] and obesity [76]. One pathway for these risks is through prenatal stress, which can directly affect fetal growth and also increase risk of prenatal smoking and alcohol use in the mother [77], as well as increase rates of maternal risk factors like preeclampsia [67]. Extreme weather is also associated more broadly with mental health outcomes [78, 79], and floods have been linked with psychological depression, anxiety, and post-traumatic stress disorder (e.g., [27, 80–85]), including specifically among children [86–89]. Floods can also increase risk of suicide and violence [24, 25].

Anticipated Future Changes

Globally, extreme precipitation is expected to intensify with climate change, in part because rising temperatures will increase the amount of moisture that air can hold when saturated [90]. In recent decades, extreme precipitation has indeed increased in the US [91, 92], with the largest trends over the eastern half of the country. Extreme precipitation events are projected to continue to become more frequent and intense across the US [91, 93–95]; under one scenario, there could be 2–3 times as many by the end of the century [92].

Some of this change may be driven by changing patterns in the specific weather systems in specific regions. For example, mesoscale convective systems are key drivers of extreme precipitation events in parts of the Southwestern, Central and Eastern US. Large and intense storms of this type are projected to occur more than three times as often under a future climate scenario compared to present, with about an 80% increase in precipitation volume [95]. Climate change may also result in changes to extratropical cyclones inland over the US East Coast, causing them to produce heavier precipitation in this area (although these systems may also become less frequent) [93, 94]. Atmospheric rivers are a significant driver of extreme precipitation, particularly along the US West Coast [96], with notable recent examples in the winter and fall of 2021 [97, 98]. Strong atmospheric rivers are expected to occur more frequently under scenarios of climate change [94].

While extreme precipitation can be a primary driver of flood, increases in extreme precipitation do not necessarily result in increases in the hydrologic response [99, 100]. Consequently, while the US National Climate Assessment can project an increase in heavy downpours in the US with high confidence, an increase in the frequency of flooding can only be projected with medium confidence and only in some regions [91]. There is some evidence of an increasing trend in flood magnitude in some, but not all, regions of the US [101], but these changes have not been clearly attributed to anthropogenic climate change [91], and their associations with large-scale climate systems have been found in some studies to be weak (e.g., [101]). Yet some studies find a clear signal of changing extreme precipitation in changing flood risk and severity in parts of the US (e.g., [91]) and also in changing flood damage [102].

Disentangling changes in flooding patterns between hazard drivers and changes in property at risk is challenging [94]. Firstly, flooding can depend on non-precipitation aspects of a changing climate. For example, some of the flooding in mountainous areas of the US West is caused by rapid snow-melt or by rain falling on snow. In coastal areas, flood risk will be influenced not only by extreme precipitation but also by sea levels. Climate change is expected in raise sea levels, and as a result worsens coastal flooding from storm surge and tides [103–106]. Warming temperatures can also affect the flood response by increasing surface evaporation and drying out soils, or by changing rain-snow ratios of falling precipitation [107]. Secondly, other important factors are outside the climate system, for example, land use, topography, and impervious surface coverage [14, 94]. Some of these will change only slowly with time (e.g., topography), but some, like land use and flood management practices, could change substantially on a faster time scale.

Projecting Future Health Impacts

Techniques and Challenges for Projections of Changing Exposure When trying to project the future health impacts of floods, one challenge comes from the difficulty projecting change in exposure, especially compared to other exposures, like temperature. Global climate models are a key source of climate model output for health impact projections. However, while these models include precipitation measures in their output, precipitation is not perfectly tied to flood risk, and so further steps are required to project changes in flood frequency and characteristics under climate scenarios (or precipitation metrics can be used within health projections of flood impacts, but with the caveat that they do not perfectly capture changes in flood exposure). Further, flood risk is influenced by different weather systems in different parts of the country, including tropical cyclones, mesoscale convective systems–organized convective storms, and atmospheric rivers. Some of the contributing processes for these weather systems are not well-captured by global climate models, nor are some of the extreme magnitudes, and therefore require a higher geographic resolution [95, 106].

Extra steps beyond global climate modeling—or alternative approaches—are therefore needed to project future flood risk. One approach is to use statistical modeling of flood risk. Statistical models are developed to model the association between factors like precipitation and flood risk based on historical data [108, 109]. These models can then be applied to global climate model projections of factors like precipitation under a future scenario to estimate flood risk. A second approach is to pair climate model output with hydrological models [106, 108–110]. Hydrological models may incorporate physics and topography of land and the sea floor near the coast to model flooding that might result from forcings, including precipitation. Finally, there are approaches that focus on generating projections of flood events or the storms that can drive them—for example, historical flood event data can be sampled in a way that is weighted to reflect future risks (e.g., based on projected future temperatures) and storm-tracking algorithms can be applied to climate model output to track contributing weather systems such as mesoscale convective systems (e.g., [95]).

Many of these approaches require high-resolution output (e.g., [95, 106]). Supercomputing power limits climate change simulations to relatively coarse grids (e.g., 50–100 km resolution). This resolution cannot resolve the detailed structure and lifecycles of intense weather systems such as tropical cyclones and mesoscale convective systems. Better simulations of such systems are critical for predicting changes in flood triggering precipitation. Despite great progress in improving the representation of these processes in climate models, and in downscaling techniques that add detail to climate model output, there remain gaps in our understanding of future changes in high-impact events, especially at regional and local levels [111]. A new generation of high-resolution climate models could therefore revolutionize the quality of information available regarding risks of unprecedented extreme weather and dangerous climate change [112]. A massive leap to kilometer-scale global models is now realistic—prototypes are now being built to simulate limited time periods, and their level of realism is ground-breaking [113, 114].

When exposure is projected with global climate models, there are a number of sources of uncertainty, including from internal climate variability, climate model uncertainty, and uncertainty surrounding future policies to reduce emissions. Further uncertainty is added in moving from climate model output to projections of flood risk. Flood risk is affected by measures like deforestation, land-cover change, urbanization, wetland reclamation, and flood management systems [91, 94]. The risk to humans from flooding also depends on where people choose to live. At a large scale, population growth near coastal regions can increase the potential for high health impacts from coastal flooding, while more local choices about defining flood plains and restricting residential development in flood-prone areas can influence human impacts of a flood in that community. Swain et al. [110] combined climate model projections with a flood model and demographic projections to show a 30–127% increase in population vulnerable to flooding in the latter half of this century. Population exposure may also be changed by urbanization [115], as urbanized areas are more likely to flood due to loss of vegetation and extent of impervious surfaces.

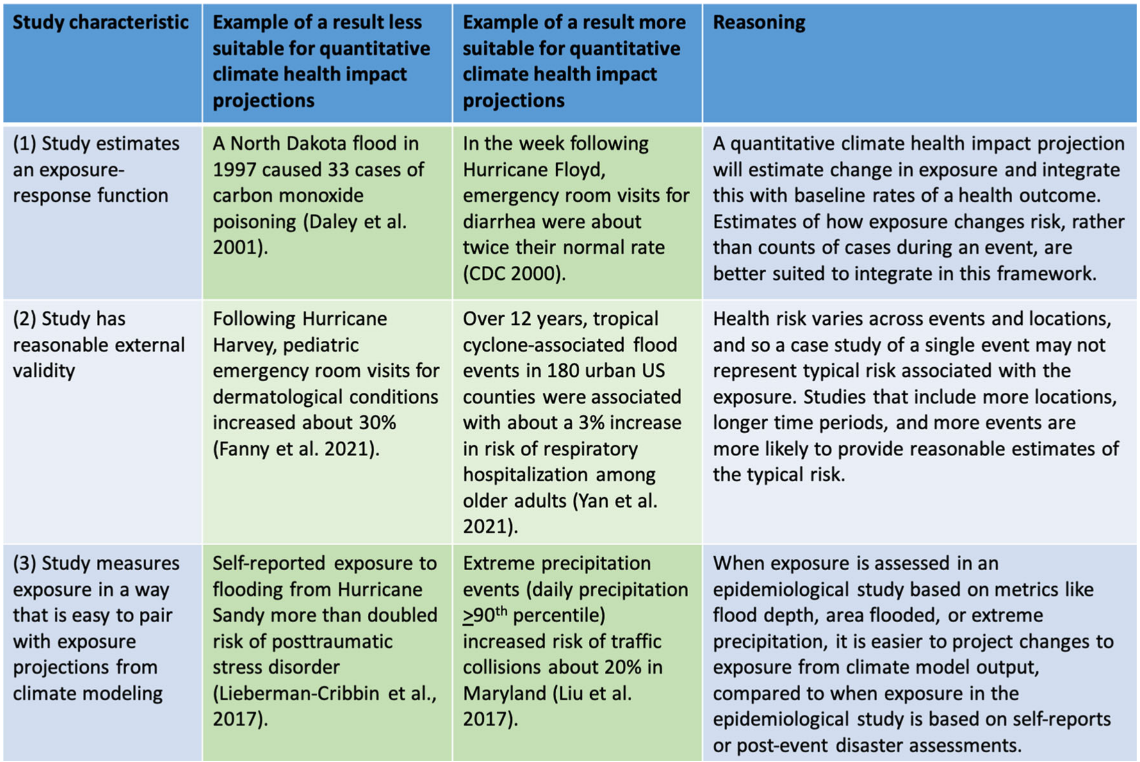
Techniques and Challenges for Incorporating Health Impacts into Projections Another challenge when trying to project the health impacts of flooding is that many available epidemiological results are not well-suited to use with the projection framework illustrated in Fig. 1. This is because epidemiological studies of disasters serve diverse needs, including rapid identification of and response to public health needs following a disaster. However, this challenge is rapidly being addressed by a growing body of epidemiological literature on floods. In this section, we highlight three characteristics (Fig. 2) that help make epidemiological results well-suited to apply in projecting the health impacts of floods under scenarios of climate change.

The first characteristic is that the study should estimate an exposure-response function. Many flood epidemiology studies instead enumerate flood-related health outcomes (e.g., [18, 21, 27–30]). For example, a study may provide counts of deaths from certain outcomes that were attributed to floods. While these studies help qualitatively assess how changing flood exposures may impact health, their results are difficult to apply in the framework of quantitative health impact projections, which requires an exposure-response function. Such functions link a well-defined exposure to risk of a health outcome, as compared to baseline risk. They can be simple functions: for example, an estimate of the relative risk of a health outcome during a flood compared to an unexposed period. More complex exposure-response functions are also possible, including ones that estimate varying health risk as a continuous metric of changing levels of exposure. A growing number of studies are estimating these exposure-response functions for flooding or for extreme precipitation events, which strongly increase flood risk. These include estimates of how flood-related exposures have changed the risk of cardiovascular and respiratory medical visits [55, 116–118], mental health outcomes [80], traffic collisions [119], and gastrointestinal infections [47, 49] (Table 1).

The second characteristic is that the study should have reasonable external validity—that is, the exposure-response function should generalize fairly well to events outside of those used to fit the function [120]. For flood epidemiology, a study that estimates average health risks based on data from many floods (including floods of different severity), many communities, and a wide range of years will be more likely to have good external validity than a case study of a single flood in a single location. Many flood epidemiology studies, however, have focused on a single event, including flooding from Hurricanes Katrina [63, 82, 83], Harvey [26, 81], Florence [121], Sandy [54, 80], and Floyd [25], or specific floods in Iowa [27], North Dakota [67], and the Midwest [40]. While their estimates may reflect the risk of that flood well, they may provide a biased estimate of typical flood-associated risk.

Unfortunately, there are few examples of flood epidemiology studies that have used the same analytical framework to estimate the common health risks from multiple floods, although there are a number of studies that have done so measuring a proxy, exposure to extreme rainfall events (e.g., [39, 47, 49–52, 116, 119]), and in fact one study has extended such results to project future health impacts [122]. One reason is that, traditionally, flooding has been hard to track in a systematic and comparable way across time and space, although there is ongoing work to create unified databases of flood events (e.g., [123]). By comparison, there are numerous such epidemiological studies of other climate-related exposures, like heat waves and temperature (e.g., [124–128]), and this type of multi-year, multi-community estimation of exposure-response functions is often used in climate health impact projections for these exposures (e.g., [6–8]).

The final characteristic is that the study should define exposure in a way that can be easily integrated with climate model output. Exposure to flooding can be assessed for an epidemiological study in several ways, including indicators of severe damage (e.g., disaster declarations by the Federal Emergency Management Agency), self reports of exposure, flood height and/or location (e.g., [40, 80]), and proxies based on extreme precipitation (e.g., [39, 47, 49–52, 116, 119]). The framework shown in Fig. 1 requires a projection of how exposure will change in the future, and this ideally should align with the way exposure is measured when generating the epidemiological exposure-response function. Table 1 provides examples of how exposure was assessed for a few flood-related epidemiological studies, as well as how the same metric of exposure might be linked with climate model output.



Study characteristic	Example of a result less suitable for quantitative climate health impact projections	Example of a result more suitable for quantitative climate health impact projections	Reasoning
(1) Study estimates an exposure-response function	A North Dakota flood in 1997 caused 33 cases of carbon monoxide poisoning (Daley et al. 2001).	In the week following Hurricane Floyd, emergency room visits for diarrhea were about twice their normal rate (CDC 2000).	A quantitative climate health impact projection will estimate change in exposure and integrate this with baseline rates of a health outcome. Estimates of how exposure changes risk, rather than counts of cases during an event, are better suited to integrate in this framework.
(2) Study has reasonable external validity	Following Hurricane Harvey, pediatric emergency room visits for dermatological conditions increased about 30% (Fanny et al. 2021).	Over 12 years, tropical cyclone-associated flood events in 180 urban US counties were associated with about a 3% increase in risk of respiratory hospitalization among older adults (Yan et al. 2021).	Health risk varies across events and locations, and so a case study of a single event may not represent typical risk associated with the exposure. Studies that include more locations, longer time periods, and more events are more likely to provide reasonable estimates of the typical risk.
(3) Study measures exposure in a way that is easy to pair with exposure projections from climate modeling	Self-reported exposure to flooding from Hurricane Sandy more than doubled risk of posttraumatic stress disorder (Lieberman-Cribbin et al., 2017).	Extreme precipitation events (daily precipitation ≥90th percentile) increased risk of traffic collisions about 20% in Maryland (Liu et al. 2017).	When exposure is assessed in an epidemiological study based on metrics like flood depth, area flooded, or extreme precipitation, it is easier to project changes to exposure from climate model output, compared to when exposure in the epidemiological study is based on self-reports or post-event disaster assessments.

Fig. 2 Characteristics of climate epidemiology studies that make results more suitable to use within quantitative climate health impact projections. For each characteristic, examples are provided from the epidemiological literature that illustrates a finding that is more versus less suited for projecting health impacts. The less suited examples may come from studies with other results that are better suited, or from studies that were framed to fill other epidemiological research needs, including rapid needs assessment following a disaster

Some metrics related to flood exposure are straightforward to extract from climate model output—extreme precipitation, for example, can be directly calculated from model projections. Other metrics of exposure require additional hydrological modeling driven by climate model projections (e.g., flood water height, reports of a flood event in the community or at the subject's residence). There is, however, a trade-off in these exposure assessment choices. As the exposure assessment for an epidemiological study moves further from the etiologic cause of the health risk, the more likely it becomes that exposure measurement error will introduce bias in the estimated exposure-risk function, with bias toward the null (i.e., an underestimation or failure to detect health risk) a particular concern [129]. For example, exposure assessment that is based on flooding rather than extreme precipitation may be more powerful in identifying a signal for health risk, even if it is harder to integrate with climate model output.

Hurricanes and Other Tropical Cyclones

Tropical cyclones are systems of strong circulating air that originate over tropical or subtropical waters. They form only in specific "basins" of the ocean, and the vocabulary for severe tropical cyclones varies by basin. Therefore, while the most severe tropical cyclones (peak wind speeds exceeding 118 km/h) in the North Atlantic and Northeast Pacific basins are called "hurricanes", similar severe tropical cyclones in other basins of the world are called "typhoons" or "cyclones". In the mainland US tropical cyclones make landfall along the Atlantic or Gulf of Mexico coasts, from storms formed in the North Atlantic basin, although occasionally Pacific tropical cyclones can affect parts of the US, including the Southwestern US (mainly through precipitation) and Hawaii [130].

Mature tropical cyclones are characterized by a well-defined center (the eye), surrounded by an organized ring of thunderstorms and violent circulating winds (the eye wall). The eye wall is typically within 5–100 km of the eye; outside this, wind speeds decay with distance [131]. The size of the tropical storm force wind field, and hence the extent of dangerous winds, typically extend from tens to hundreds of kilometers from the eye, even among storms with the same intensity at the storm's core. Take the case of Hurricanes Ivan and Dennis, which made landfall in similar locations one year apart, both as category 3 storms [132]. Ivan was far more damaging than Dennis, partly attributed to Ivan's hurricane wind field extending over an area 5 times larger than for Dennis.

Table 1 Examples of how results from epidemiological studies could be combined with climate model output by using the exposure metric from the epidemiological study in estimating change in exposure from climate modeling. In some cases, the example only highlights one way exposure was assessed in an epidemiological study, while the study considered several approaches. This table aims to illustrate a few examples of opportunities and challenges when combining epidemiological evidence with exposure projections

Study	Health outcome	Exposure metric	How change in exposure could be projected
Flooding			
Smith et al. [117]	Influenza emergency room visits	Daily precipitation ≥99th for location	Calculated directly from climate percentile model projections
Schinasi et al. [118]	Asthma exacerbations	Categorical levels of relative daily precipitation	Calculated directly from climate model projections
Soneja et al. [116]	Asthma hospitalization	Daily precipitation ≥90th percentile for location	Calculated directly from climate model projections
Liu et al. [119]	Traffic collisions	Daily precipitation ≥90th percentile for location	Calculated directly from climate model projections
Lee et al. [47]	Salmonellosis infection	Daily precipitation ≥90th percentile for location	Calculated directly from climate model projections
Soneja et al. [49]	*Campylobacter* infection	Daily precipitation ≥90th percentile for location	Calculated directly from climate model projections
Lieberman-Cribbin et al. [80]	Mental health outcomes	Flood water height	Local flood height model driven by climate model projections
Yan et al. [55]	Cardiorespiratory hospitalization	Flood event in the county, based on disaster report database	Local flood extent model driven by climate model projections
Wade et al. [40]	Gastrointestinal symptoms	Mississippi River over 15-foot flood stage	Hydrology model driven by climate model projections
Tropical cyclones			
Parks et al. [133]	Hospitalization	Local (county) wind from a tropical cyclone of ≥34 knots	Tropical cyclone wind risk model run within climate model projections
Yan et al. [55]	Cardiorespiratory hospitalization	Local (county) wind from a tropical cyclone of ≥41 knots	Tropical cyclone wind risk model run within climate model projections
Grabich et al. [134]	Birth rates	Local (county) wind from a tropical cyclone of ≥64 knots	Tropical cyclone wind risk models run within climate model projections
Grabich et al. [134]	Birth rates	County ≤60 km from storm track	Tropical cyclones tracked directly from climate model projections
Currie and Rossin-Slater [135]	Birth outcomes and labor complications	Residence ≤30 km from storm track	Tropical cyclones tracked directly from climate model projections
Yan et al. [55]	Cardiorespiratory hospitalization	Local (county) cumulative precipitation from a tropical cyclone of ≥125 mm	Simplified physics tropical cyclone rainfall model run within climate model projections
Czajkowski et al. [136]	Fatalities	Categorical division of local (county) cumulative precipitation from a tropical cyclone	Simplified physics tropical cyclone rainfall model run within climate model projections
Grabich et al. [137]	Birth outcomes	County given FEMA disaster declaration	No clear current approach

Tropical cyclones move forward at speeds between 0 and 60 km/h and, like corks in a stream, speed and direction depend on the prevailing environmental winds. Their forward motion raises surface wind speeds on the right side of the storm in the Northern Hemisphere and on the left side of the storm in the Southern Hemisphere. Other hazards of the storm can extend far from its center. Rain fields and bands often extend well beyond the inner core, and severe flooding can occur both at the coast and well inland [14]. For example, flooding was caused by Hurricane Odile in western Texas [138] and by Tropical Storm Lowell followed by Hurricane Ike in Missouri, Illinois, and Indiana [139], while Hurricane Sandy's impacts stretched as far inland as the Appalachian Mountains, producing heavy snow and blizzard conditions from western North Carolina northeastward through southwestern Pennsylvania [140].

The types and severity of tropical cyclone hazards vary greatly from storm to storm. Some storms are most notable for dangerous winds, but bring lower risk of flooding. Hurricane Andrew, for example, hit the Miami area as a Category 5, the highest rating on the Saffir-Simpson hurricane wind scale [141]. It destroyed more than 25,000 homes in Dade County, caused widespread power outages in the area (with 2.5 million out of power), and required many to leave their homes at least temporarily [142, 143]. Other storms have lower winds but bring dangerous levels of precipitation or flooding. A recent example is Hurricane Harvey in 2017, which was the most significant tropical cyclone rainfall event in US history in both scope and peak rainfall amounts [144], with storm total rainfall amounts exceeding 60 inches at multiple stations.

Historical and Current Impacts on Human Health

In recent decades, there have been, on average, about 50 direct tropical cyclone–associated deaths per year in the US [145]. There is substantial variation in this number from year to year, since some storms account for large numbers of direct deaths while many caused few or no deaths; in fact, about two-thirds of all of the direct tropical cyclone–associated deaths between 1963 and 2012 were caused by only six storms [145]. Drowning causes over half of these direct deaths, from both coastal and inland flooding [136, 145].

Indirect deaths—although harder to track and characterize than direct deaths [146]—form a substantial part of the total mortality impact from tropical cyclones. One study of several dozen US tropical cyclones found that there were almost as many indirect fatalities as direct fatalities from the storms [147], and several studies have found that traditional surveillance methods might miss a large number of tropical cyclone–associated deaths, especially indirect ones [148–150]. A number of these storm-associated indirect deaths are from cardiovascular causes [147, 148, 151]. These cardiovascular deaths follow pathways that include physical exertion during preparation before the storm or clean-up after, evacuation, and heat exposure following the storm [147]. Tropical cyclones can also cause indirect accidental deaths, including from automobile accidents, injuries during storm preparation and clean-up, and carbon monoxide poisoning [94, 147, 152]. Some evidence suggests that other indirect tropical cyclone–associated deaths come from increased risk of death from cancer, diabetes, and stillbirth [70, 148].

There can also be substantial health impacts from nonfatal injuries and accidents [153]. Storm preparations and clean-up are one pathway. Between 2001 and 2017, there were over 300 reported injuries in the US related to putting up and taking down storm shutters for hurricanes, including lacerations, sprains, strains, and fractures [154]. Those cleaning up after the storm can be at risk of carbon monoxide poisoning, heat stress, and sunburn [155]. Risk of poisoning—including bleach ingestion, which might be associated with trying to clean water for drinking—and wounds, burns, and other injuries can increase following a tropical cyclone [142, 143, 156]. As with flooding, these disasters can increase dangerous exposure to insects (e.g., [157]). While snakebites have been listed as health impacts of specific tropical cyclones, a multi-year study in Texas found no clear evidence that risk of snakebites increased in association with tropical cyclone exposure [158].

Tropical cyclones have been repeatedly linked to an increased risk of hospitalization among the elderly [55, 133, 159, 160]. These links are particularly clear for respiratory outcomes, including chronic obstructive pulmonary disease and asthma (e.g., [55, 156, 160]). One pathway might be widespread power outages following a storm, which causes problems using medically powered equipment and increases exposure to outdoor heat. Respiratory outcomes may also be linked to evacuation, which creates psychological stress (a trigger for a number of acute respiratory outcomes like asthma attacks), while crowding and poor sanitation in evacuation shelters can help spread respiratory infections. Respiratory risk might also in part result from mechanisms observed to increase asthma risk during thunderstorms and summertime extreme precipitation events (e.g., [116, 118]), plausibly from severe thunderstorms' effects on release and movement of fungal spores [116]. Tropical cyclone exposure may also elevate risk of non-fatal cardiovascular and renal outcomes—medical visits for both conditions have been observed to increase in association with tropical cyclone exposure (e.g., [151, 156]).

Tropical cyclones can also create conditions that are conducive to spreading gastrointestinal disease. Some of this risk comes from flooding, through mechanisms previously described. Tropical cyclones can also affect food and water access through other hazards of the storm. For example, power outages and other damage can prevent safe levels of water pressure, make it difficult to store food safely, and hamper garbage clean-up (e.g., [142, 157]). Evacuation shelters can struggle to maintain adequately sanitary conditions and also create crowded conditions conducive to the spread of highly contagious enteric viruses like norovirus. However, as with floods, epidemiological patterns in gastrointestinal disease are variable following tropical cyclones. For example, there was no evidence of significant outbreaks of gastrointestinal illness in south Dade County in the month following Hurricane Andrew [142] or in New York City following Hurricane Sandy [156]. Conversely, an increase in pediatric emergency department visits for gastroenteritis was observed the week following Hurricane Andrew at a South Florida children's hospital [143]. Tropical cyclone exposure can also elevate risk of infection to other body systems, including the skin, ear, nose, and throat [142, 156, 159]. Increased risk of skin infections and rashes, for example, were identified following Hurricane Andrew [142], Katrina [43], and Sandy [156].

Tropical cyclone exposure has also been associated with pregnancy and birth impacts, although findings are somewhat inconsistent regarding this risk. While some studies have found that specific storms were associated with an increased risk of preterm birth (e.g., [161]), this may be limited to severely affected areas [162]. A large-scale multi-year study found maternal exposure to tropical cyclones was linked to an increase in the risk of preterm birth, but the estimated increase was small and most noticable for the earliest preterm births [163]. Following Hurricane Sandy, hospitalizations increased in Long Island among the Medicare population for pregnancy, childbirth, and puerperium causes [159], and Hurricane Andrew was linked to increased risk of fetal distress [70]. Conversely, some studies found little association between tropical cyclone exposure and low birth weight or fetal death [135, 164]. Hurricane exposure can also increase risk for a number of mental health outcomes [165], including post-traumatic stress disorder, major depressive disorder, anxiety, and substance use [166] (e.g., [159, 167]), as well as risk of depression in disaster responders [155].

Anticipated Future Changes

The environments within which tropical cyclones evolve have already warmed and become more moisture laden. Consequently, some changes to tropical cyclones have already been detected. Kossin et al. [168] found a recent increase in global lifetime maximum wind speed. This intensity increase has not been uniform across all hurricane categories; rather, the most intense storms have intensified the fastest [169]. These are the storms that undergo rapid intensification [170], indicating that, should this trend continue, hurricane forecasting may become more difficult in the future [171]. Other observed changes include sea levels that are higher today than a few decades ago. Today's storm surges therefore ride on top of these higher seas. A global slowdown in the forward speed of tropical cyclones has been detected [172], including a rising trend in stalling storms over vulnerable coastal populations. But this has not yet been linked to climate change.

Significant future changes to tropical cyclones and their environments are expected. Whereas the balance of evidence suggests a future reduction in overall storm numbers globally [173], consensus is somewhat weak on this projected change, and changes for the North Atlantic basin are even less clear. The recent rise in storm numbers for the North Atlantic, while detected, have not been conclusively attributed to climate change due to the large climate variability in this region and limitations in the historical data available to test for trends [174–176]. This challenges our current ability to project future storm numbers at the basin scale. Recent research using high-resolution climate models projects a decrease in the frequency of Southern Hemisphere storms, but a less clear pattern in the Northern Hemisphere [176], and a study that downscaled global climate models to very high-resolution projects an increase, rather than decrease, in tropical cyclone frequency in the North Atlantic, particularly at higher latitudes most relevant to exposure in the US [177].

Several mechanisms of the climate system could allow future tropical cyclones to become, on average, more intense. Tropical cyclones get their energy from warm ocean temperatures and an unstable atmosphere. As the oceans and overlying atmosphere continue to warm the thermodynamic environment becomes more favorable for intense tropical cyclones [178]. However, changes in other environmental factors such as wind shear or Saharan dust can also influence future tropical cyclone activity [179]. Overall, there is evidence that tropical cyclone intensities are expected to, on average, increase in the future with climate change [173], including for tropical cyclones affecting the US [103]. There is also a projected increase in the number of very intense tropical cyclones (major hurricanes, which are category 3 or higher) in the North Atlantic basin under climate change [180]. Climate change may also increase the incidence of rapid intensification of tropical cyclones, which could increase the risk of a storm making landfall with much higher wind speeds than forecast [177], and decrease their rate of decay after landfall [181].

Human impacts depend not only on the frequency and intensity of tropical cyclones, but also on the paths of the storms [182] and how quickly they tend to move through populated areas [183–185]. Several studies have projected that tropical cyclones' translational speeds will continue to slow in the future, particularly in the midlatitudes (e.g., [177, 185]). Patterns in translational speed, however, can vary substantially by region. One study of Texas, for example, projects that climate change is likely to increase, rather than decrease, average tropical cyclone translational speeds around landfall in the state [183].

Storms in the future are also likely to have higher precipitation rates, and this anticipated change is assessed with an even higher level of confidence among tropical cyclone climatology experts than the anticipated increase in average tropical cyclone intensity [173]. Emanuel [186] found hurricane Harvey-like rainfall totals to already be six times more likely today than in the late twentieth century, with rising probabilities expected in the future. The increasing capacity for moisture in the air, as air temperature increases, is expected to change precipitation patterns from tropical cyclones [175]. Reduction in the forward speed of storms could also result in more precipitation in an area—particularly in the extreme case of a storm that stalls [187]. Finally, another changing hazard anticipated with climate change at a medium to high level of confidence is that, when a storm does make landfall, its storm surge will typically result in a higher inundation level because of anticipated sea level rise [173], especially when combined with an increasing intensity of the storms [188].

Projecting Future Health Impacts

Techniques and Challenges for Future Projections Earlier we described challenges in projecting flood exposure; many of these apply when projecting tropical cyclone exposures, as well. For example, the main tool to project climate is global climate models. However, capturing the structure of the strongest storms over periods of a hundred years requires a level of detail beyond the capacity of current computational resources [175–177]. Today's climate model projections are starting to explicitly represent tropical cyclones [189] that can be tracked, counted, and intensity bias-corrected [190]. They still, however, miss the strongest storms and are limited to a small number of projections or time windows. Downscaling can help, but is computationally expensive. To reduce computational costs, some projections focus detail only in the region or regions of interest, by embedding a regional climate model with the global climate model (e.g., [175, 191]) or with targeted variable-resolution meshes [192]. Even with these regional domains, computational costs can be prohibitive and therefore can only be run for a limited number of periods, regions, or projections.

Other approaches are possible. One is to infer tropical cyclone activity using empirical relationships between tropical cyclones and their large-scale environment, in line with the statistical modeling approach described for flood projections. So-called tropical cyclone genesis indices use combinations of sea surface temperature, atmospheric stability, spin and environmental winds to predict tropical cyclone frequency and sometimes also tropical cyclone intensity [193]. However, the metrics produced by this approach are often yearly, basin-wide measures (e.g., yearly tropical cyclone damage potential [194]), which may not be suitable for health impact projections.

Another approach uses statistically based tropical cyclone risk models, which have been developed using the historical record to model tropical cyclone genesis, track and intensity. These models are computationally efficient and can therefore be run to generate thousands of years of tropical cyclone activity (e.g., [184, 195]). This class of risk models has also been adapted to use historical environment data such as winds and humidity in addition to the historical tropical cyclone record to capture greater variability [196]. However, this approach can be limited when projecting future exposures, since its use of historical records may not adequately capture the large and significant expected future changes.

Another approach is to combine climate model data with simplified (and therefore computationally fast) physical models of tropical cyclones (e.g., [177]). These models can provide information on regional track shifts, and changes in the full tropical cyclone intensity distribution. They have been used successfully to model exposure and impacts [183, 197]. In addition to providing information on storm characteristics such as intensity, track location, and translation speed, they have also been used to drive storm surge [198]. Similar approaches have been used to project changes in tropical cyclone precipitation exceedances [186, 199]. Perhaps the key benefit of these physically based models is that they use physics to produce events outside historical ranges. For example, [200] were able to quantify the likelihood of extreme surge events far higher than anything in the historical record.

Regardless of the approach chosen, there are added complications because tropical cyclones are rare events. This makes it more difficult both to study trends and attribution of past events and also to develop modeling approaches to project future patterns [174, 176], especially when combined variability introduced by shifts in recurring large-scale atmospheric phases like the Atlantic Multidecadal Oscillation [182]. A compounding factor is that measurement technology has substantially improved over the last century, and so data prior to the mid-twentieth century is sometimes not comparable with more recent measurements [174], thereby challenging our understanding. Further, since tropical cyclones are rare in any time period, it is often necessary when projecting future risk to generate large sets of synthetic tracks, to address the inherent variation that results when characterizing patterns in rare events.

Incorporating Health Impacts into Projections As with flooding, for tropical cyclones there are some challenges in applying existing epidemiological evidence to when projecting future impacts. The characteristics that help make an epidemiological study suitable for quantitative climate health impact projections are the same for tropical cyclones as for flooding (Fig. 2): they should provide an estimated exposure-response function, have reasonable external validity, and define exposure in a way that can be easily integrated with climate model output.

Many tropical cyclone epidemiology studies do not estimate exposure-response functions. Often, rapid epidemiological and public health research is conducted following a tropical cyclone, to characterize immediate needs as well as the health impacts of the storm. For example, the US Centers for Disease Control and Prevention's Morbidity and Mortality Weekly Report has published reports soon after Hurricanes Floyd [25], Katrina [43], Harvey [201], Matthew [152], Irma [202], and Florence [121]. Most of these do not estimate exposure-response functions (although [25] is one exception).

A growing collection of tropical cyclone epidemiology studies, however, do estimate exposure-response functions; Table 1 gives a few examples. These studies estimate exposure-response functions through comparison to a counterfactual of the expected rates of the health outcome in the study population had the storm not occurred. Methods to make these comparisons range from simpler (e.g., comparison to a comparable control period in the same study area, as in [25], or unexposed geographic areas) to more complex methods developed to study repeated disasters like heat waves and wildfires (e.g., [127, 203]), which allow the estimation of exposure-response functions using data from multiple storms (as in [55, 133]).

The hazards of a tropical cyclone vary in severity from storm to storm and geographically within a storm, and health risk is associated with severity. For example, stronger winds are associated (non-linearly, rapidly increasing as wind speed increases) with increased damage to property and infrastructure [204], as is the duration of strong winds [205]. It would therefore be helpful to have epidemiological exposure-response functions that include exposure on a continuous, rather than binary scale. Such studies are, to date, very limited, although there are a few studies that have explored different thresholds or categories of exposure (e.g., [55, 133, 137, 162]). In the future, epidemiological research could also further improve tools for projections by estimating exposure-response functions that capture the mixtures of hazards within a storm, leveraging developing epidemiological approaches to study mixtures [206, 207]. Similar approaches could be used to fit exposure-response functions for the impacts of compound events (e.g., tropical cyclones followed by heat waves). These compound events could occur more frequently in the future [94], and changes in these exposures are an active area of climate science research (e.g., [208–210]).

In terms of external validity, tropical cyclone studies that focus on a single event are expected to have limited external validity, compared to studies that use data from multiple storms, locations, and years. Many tropical cyclone epidemiology studies focus on a single storm (e.g., [25, 54, 80, 85, 121, 142, 143, 149, 150, 152, 156, 157, 159–162]). Study that focuses on very severe events, like Hurricanes Katrina and Andrew, might be particularly limited in external validity since the health risk from these storms might be much higher than those expected under less severe, but much more frequent, exposures. Other studies are available that are multi-year and either national- or state-level, but do not estimate exposure-response functions (e.g., [136, 145, 147, 154, 158, 211]). However, multi-year studies that estimate exposure-response functions are becoming more common. For example, there are now multi-state, multi-year studies of how tropical cyclone exposures impact hospitalizations among older adults [55, 133]. Similarly, studies of birth outcomes have been conducted for multi-year periods in Texas [135] and Louisiana [75], as well as a national-scale study [163]. At a smaller scale, several studies have also incorporated several storms by investigating health risks during one severe storm season, such as 2004 in Florida [134, 137, 148, 164, 167] or 2005 in the Gulf Coast region [59, 70, 155].

In terms of exposure assessment, there are some studies of tropical cyclones that have used metrics of exposure that can be applied in a fairly straightforward way to climate model output. These include direct measures of storm hazards (e.g., wind intensity [55, 133, 134, 137, 163], reports of flooding [55], cumulative precipitation [55]), as well as measures of how close the storm's central track came to the community (e.g., [134, 135, 137]). Other studies have assessed exposure based on disaster caused by the storm, including disaster declarations and assessments made by the Federal Emergency Management Agency (e.g., [137, 159]) and a community hardship index that combined data from the Federal Emergency Management Agency with considerations like whether there were power outages and gasoline shortages [151], while other studies have assessed exposure based on personal impacts of the hurricane (e.g., need for evacuation, loss of personal property) [167]. Epidemiological research based on exposure assessed in these ways is difficult to pair with climate model output to use in health impact projections, as there is currently no clear way to identify exposures under future scenarios from climate model output.

As climate modeling techniques continue to advance, however, it may become easier to integrate exposure projections with epidemiological results based on damage–related exposure assessments. One promising area is the advent of Earth System Models (ESMs). ESMs offer an opportunity to move beyond physical descriptors of atmospheric and oceanic states to predictions of societally relevant quantities such as disease spread, habitat loss, water availability, wildfire risk, air quality, and crop, fishery, and timber yields [212]. In short, they provide the means not just to assess the potential for future global change stresses, but also to determine the outcome of those stresses on the biosphere. The untapped potential of ESMs is, accordingly, to bring dispersed research related to climate processes, vulnerability, impacts, and adaptation, and mitigation into a common, integrative framework. ESM capability could be extended to inform the management of disaster assistance. For the US, for example, new ESMs could project regional Federal Emergency Management Agency emergency declarations and major disaster declarations.

Conclusions

In this review, we have explored challenges and opportunities in projecting the health impacts of tropical cyclones and flooding under scenarios of climate change—an area where quantitative projections are currently very limited [5]. Despite a wealth of studies characterizing health impacts of floods and tropical cyclones, many are better suited for qualitative, rather than quantitative, descriptions of climate change health impacts. However, a growing number of studies have features that will facilitate their use in quantitative projections; specifically, estimation of an exposure-response function, reasonable external validity, and exposure assessment that allows easy integration with climate model output. Further, while it can be difficult to project how exposures to flood and tropical cyclone hazards will change in the future, climate science continues to advance in its capabilities to capture changes in these exposures, including capturing regional variation.

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Compliance with Ethical Standards

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