Risks of infectious disease hospitalisations in the aftermath of tropical cyclones: a multi-country time-series study

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Summary

Background The proportion of intense tropical cyclones is expected to increase in a changing climate. However, there is currently no consistent and comprehensive assessment of infectious disease risk following tropical cyclone exposure across countries and over decades. We aimed to explore the tropical cyclone-associated hospitalisation risks and burden for cause-specific infectious diseases on a multi-country scale.

Methods Hospitalisation records for infectious diseases were collected from six countries and territories (Canada, South Korea, New Zealand, Taiwan, Thailand, and Viet Nam) during various periods between 2000 and 2019. The days with tropical cyclone-associated maximum sustained windspeeds of 34 knots or higher derived from a parametric wind field model were considered as tropical cyclone exposure days. The association of monthly infectious diseases hospitalisations and tropical cyclone exposure days was first examined at location level using a distributed lag non-linear quasi-Poisson regression model, and then pooled using a random-effects meta-analysis. The tropical cyclone-attributable number and fraction of infectious disease hospitalisations were also calculated.

Findings Overall, 2·2 million people who were hospitalised for infectious diseases in 179 locations that had at least one tropical cyclone exposure day in the six countries and territories were included in the analysis. The elevated hospitalisation risks for infectious diseases associated with tropical cyclones tended to dissipate 2 months after the tropical cyclone exposure. Overall, each additional tropical cyclone day was associated with a 9% (cumulative relative risk 1·09 [95% CI 1·05–1·14]) increase in hospitalisations for all-cause infectious diseases, 13% (1·13 [1·05–1·21]) for intestinal infectious diseases, 14% (1·14 [1·05–1·23]) for sepsis, and 22% (1·22 [1·03–1·46]) for dengue during the 2 months after a tropical cyclone. Associations of tropical cyclones with hospitalisations for tuberculosis and malaria were not significant. In total, 0·72% (95% CI 0·40–1·01) of the hospitalisations for all-cause infectious diseases, 0·33% (0·15–0·49) for intestinal infectious diseases, 1·31% (0·57–1·95) for sepsis, and 0·63% (0·10–1·04) for dengue were attributable to tropical cyclone exposures. The attributable burdens were higher among young populations (aged ≤19 years) and male individuals compared with their counterparts, especially for intestinal infectious diseases. The heterogeneous spatiotemporal pattern was further revealed at the country and territory level—tropical cyclone-attributable fractions showed a decreasing trend in South Korea during the study period but an increasing trend in Viet Nam, Taiwan, and New Zealand.

Interpretation Tropical cyclones were associated with persistent elevated hospitalisation risks of infectious diseases (particularly sepsis and intestinal infectious diseases). Targeted interventions should be formulated for different populations, regions, and causes of infectious diseases based on evidence on tropical cyclone epidemiology to respond to the increasing risk and burden.

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Introduction

Tropical cyclones, also known as hurricanes and typhoons, are among the most frequent and destructive natural disasters.[1] Globally, an estimated 150 million people[2] are exposed to tropical cyclones, which cause billions of dollars in damages[3,4] each year. The impacts of tropical cyclones are likely to worsen due to increasing tropical cyclone risks as a result of climate change and the rapidly growing coastal population, indicating that tropical cyclones will remain a major public health concern.[5,6] Understanding the health effects of tropical cyclones has important implications for developing response strategies to mitigate the foreseen health burden.

After the passage of a tropical cyclone, infectious diseases are among the major health concerns and prominent focus of public health efforts due to the post-cyclone environment, which can cause increased risks of disease transmission (eg, via contaminated water, increased disease vectors, disrupted sanitation and hygiene, and overcrowded and displaced populations).[7,8] Relatively few studies, mainly from the USA and China, have investigated the risks of infectious diseases

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Research in context

Evidence before this study

Before this study, we did a systematic review to summarise the current evidence on the health effects of tropical cyclones. A systematic search was conducted in five electronic databases (MEDLINE, Embase, PubMed, Scopus, and Web of Science) between database inception and Dec 21, 2022 using a combination of search terms of tropical cyclone (eg, "cyclon*", "hurricane*", "typhoon*", and "tropical storm*") and diseases (eg, "diseas*", "morbid*", "hospital*", "incidence*", and "infect*). An updated search was conducted on Feb 10, 2024. We found that most previous studies mostly focused on a single tropical cyclone event within a specific region and period and exhibited great inconsistency in modelling approaches, study designs, and analytical strategies, hindering the comparability and generalisability of the results. Evidence involving a consistent quantitative assessment of tropical cyclone exposures and the attributable infectious disease risk was scarce. No studies had systematically and quantitatively evaluated the tropical cyclone-attributable infectious disease risks on a multi-tropical cyclone and multi-country scale.

Added value of this study

Our large-scale population-based study, including 124 tropical cyclones and 2·2 million hospitalisations for infectious diseases from six countries or territories during various periods between 2000 and 2019, estimated the tropical cyclone-attributable hospitalisation risks and burdens for different subtypes of infectious diseases (ie, all-cause infectious diseases, intestinal infectious diseases, dengue, tuberculosis, malaria, and sepsis) in different population subgroups (ie, age, sex, and country and territory of location). Overall, we found elevated hospitalisation risks for infectious diseases that tended to dissipate 2 months after the tropical cyclone exposure. Younger populations and males had high tropical cyclone-attributable risks and burdens, especially for intestinal infectious diseases. The tropical cyclone-attributable hospitalisation risk and burden of cause-specific infectious diseases varied greatly across countries and territories. The tropical cyclone-attributable proportion of infectious disease hospitalisations appears to have increased in Viet Nam, Taiwan, and New Zealand, and decreased in South Korea after 2000.

Implications of all the available evidence

The scientific evidence regarding the spatiotemporal pattern of infectious disease risks and burdens after tropical cyclones can help us better understand the health impact of tropical cyclones. The results highlight the need for evidence-based tropical cyclone preparedness and intervention strategies targeted for different populations that extend beyond the cyclones' immediate aftermath, and the urgency to integrate climate change mitigation efforts to respond to the increasing tropical cyclone health hazards in some countries and regions.

associated with tropical cyclones.[9] These studies reported mixed findings that are difficult to compare due to inconsistent modelling approaches and differing exposure and outcome definitions.[9] Additionally, these studies mostly focused on specific regions or single tropical cyclone events, which limits the generalisability and applicability.[9] A comprehensive and consistent assessment of infectious disease risks with multiple tropical cyclones over long timeframes across countries is needed to provide high-quality evidence for informing disaster management.

Tropical cyclone frequency and intensity varies greatly across regions. Tropical and subtropical regions generally experience more and stronger tropical cyclones (eg, Viet Nam, Taiwan, and Thailand), whereas those in higher latitudes (eg, Canada and New Zealand) often experience milder effects.[2] However, changes in the climate might be altering tropical cyclone patterns, leading to more intense storms at higher latitudes due to poleward migration.[10,11] For example, in 2023, Cyclone Gabrielle made landfall in New Zealand and caused more than US$8 billion in damages, making it the costliest tropical cyclone in the Southern Hemisphere.[12] However, very little evidence on tropical cyclone epidemiology is available from regions with fewer tropical cyclones, which could be more vulnerable to future stronger tropical cyclones than regions with more frequent cyclones.[9] Here, we integrated available data on infectious disease hospitalisations over two decades from six countries and territories (Viet Nam, South Korea, Taiwan, Thailand, Canada, and New Zealand) with different geographical and tropical cyclone characteristics, to estimate the attributable cause-specific, age-specific, and sex-specific infectious diseases risks and burden. We also investigated effect modifications by location characteristics and characterised the exposure–response and lag–response relationships, which had important implications for disaster preparedness.

Methods

Data collection and organisation

We conducted a multi-country time-series study to examine the associations between tropical cyclone exposure and hospitalisations for cause-specific infectious diseases. We obtained hospitalisation data (ie, age, sex, location of residence, admission date, and the ICD codes of the primary diagnoses) for infectious diseases from Canada (261 second-level administrative divisions [regions or districts within the provinces and territories] from the Hospital Morbidity Database;[13] 2005–19), New Zealand (66 territorial authorities from the National Minimum Dataset, Ministry of Health;[14] 2000–19), Taiwan (six special municipalities from the

National Health Insurance Research Database, Ministry of Health and Welfare of Taiwan;[15] 2000–18), South Korea (17 administrative divisions from the National Health Insurance Service National Sample Cohort;[16] 2002–19), Thailand (77 provinces from the Ministry of Public Health;[17] 2015–19), and Viet Nam (26 provinces from the provincial and city hospitals;[18] 2003–15). Only all-cause infectious disease hospitalisations were available from Viet Nam. The detailed clarifications of the data representativeness in each study country and territory are provided in the appendix (p 2). We aggregated the hospitalisation data by sex (female and male) and age (≤19, 20–59, and ≥60 years). According to the ICD-9 and ICD-10 codes, we gathered hospitalisation data for all infectious diseases (ICD-9: 001–139 or ICD-10: A00–A99, B00–B99), and five specific infectious diseases: intestinal infectious disease (ICD-9: 001–009 or ICD-10: A00–A09), malaria (ICD-9: 084 or ICD-10: B50–B54), sepsis (ICD-9: 038 or ICD-10: A40–A41), dengue (ICD-9: 061 or ICD-10: A90–A92), and tuberculosis (ICD-9: 010–018 or ICD-10: A15–A19). These subtypes constitute a major component of infectious diseases under the ICD and are among the most prevalent and impactful infectious diseases that might escalate after tropical cyclones.[7,9] Sepsis in particular, although not directly induced by tropical cyclones, can arise as a complication of various infectious diseases, particularly those aggravated by tropical cyclone-related conditions.[19,20] The aftermath of tropical cyclones often leads to inadequate health-care access and infrastructural damage, further amplifying the risk of sepsis development.[9,19] Consequently, an integrated multi-country dataset of monthly age-specific, sex-specific, and cause-specific hospitalisations for infectious diseases in 453 locations across six countries and territories was yielded for subsequent analysis. A flow diagram illustrating the procedure of data collection and organisation can be found in the appendix (p 7).

We obtained global gridded population data in 2010 at a spatial resolution of 1 km from the Gridded Population of the World (version 4) dataset from the Socioeconomic Data and Applications Center (SEDAC), which has been shown to be consistent with national census and population registers.[21] Based on the gridded population data and location boundaries, we estimated the total number of populations for each location. We obtained a gridded dataset of gross domestic product (GDP) to calculate the GDP per capita for each location, by dividing the total GDP by the estimated total population of the grid cell covered by that location.[22] We also acquired the global gridded relative deprivation index (RDI) from the SEDAC to estimate the RDI of each location. The RDI characterises the overall degree of deprivation and poverty based on multiple dimensions (eg, child dependency ratio, infant mortality rates, and human development index), with a higher value indicating a higher level of deprivation.[23] Finally, we extracted hourly observations of the global ground-level temperature at a resolution of 10 km to estimate the daily average temperatures for each location.[24]

Exposure assessment

We applied an improved wind field model[25] to estimate the global hourly wind fields associated with tropical cyclones, similar to previous studies.[6,26] The methodology of this model has been described in detail in our previous work.[1,2] Briefly, based on the global historical information on tropical cyclones from the International Best Track Archive for Climate Stewardship (IBTrACS),[27] we used a parametric wind model to generate gridded hourly wind fields (ie, daily maximum of 1 min sustained wind speeds associated with the tropical cyclone) for each tropical cyclone event in IBTrACS with a spatial resolution of 1/12° (~10 km). For our analysis, we aggregated the data to 1/2° (~55 km) spatial and daily temporal resolution, matching the local time zones of the hospitalisation datasets. To focus on tropical cyclones and avoid the decreased accuracy of parametric wind field models for extratropical cyclones (which is due to their relatively slow wind speeds[25]), events in IBTrACS were truncated once they had undergone extratropical transition. Grid cells with a tropical cyclone-related maximum sustained wind speed of at least 34 knots (ie, 17·5 m/s) were considered to be exposed.[28,29] For each location, a tropical cyclone exposure day was defined as a day for which the grid cell containing the location centre was tropical cyclone exposed.[1,30] Only locations with at least one tropical cyclone exposure day were included in the analyses.

See Online for appendix

Statistical analysis

Given the relatively small number of tropical cyclone days and cause-specific infectious disease hospitalisations, and in line with previous studies, we analysed the tropical cyclone–infectious diseases association at a monthly timescale.[28] A classical two-stage time-series analytical framework was used to characterise the association.[30,31] In the first stage, we implemented a quasi-Poisson regression model, accounting for potentially overdispersed outcomes, to estimate the association between monthly number of tropical cyclone days with age-specific, sex-specific, and cause-specific hospitalisation counts for infectious diseases for each location. To account for the potential delayed and cumulative effects, tropical cyclone exposure days were modelled with a distributed lag term up to 12 months after the tropical cyclone, using a natural cubic spline function with two internal knots placed at equally spaced values in the log scale of lag months.[28] Seasonality and long-term trends were controlled using natural cubic splines of calendar year and month with 3 df.[32,33] Monthly averages of temperature were adjusted using natural cubic splines with 4 df.[28,34,35]

In the second stage, we pooled the location-specific estimates by country and territory using a random-effect

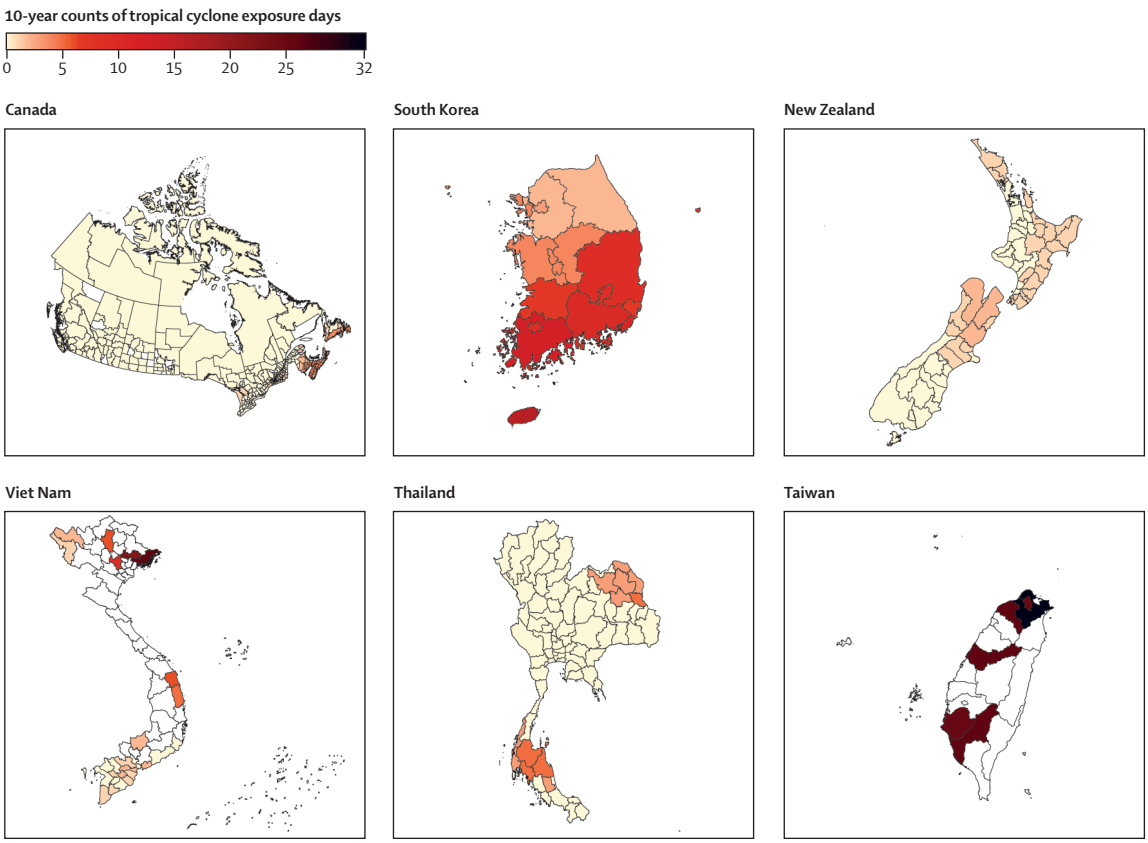

Figure 1: **Counts of tropical cyclone exposure days per decade in Canada, South Korea, New Zealand, Viet Nam, Thailand, and Taiwan during the study period**
Hospitalisation data were unavailable from the blank locations.

meta-analytical model. The pooled tropical cyclone–infectious diseases association was presented as cumulative relative risk (RR) with 95% CI of hospitalisation associated with each additional day of tropical cyclone exposure in a month. To characterise the exposure–response associations, we estimated the cumulative RR associated with each additional cyclone day defined with different thresholds (eg, maximum sustained wind speed of ≥40 knots instead of 34 knots) and modelled the trend of these risks using dose–response meta-analysis with natural cubic spline with three knots at fixed percentiles (25%, 50%, and 75%) of the exposure distribution.[36,37] We performed a series of sensitivity analyses to check the robustness of the results: placing different numbers of knots (2, 3, or 4) for the lag effects of the tropical cyclone; extending the maximum lag to 18 months after the tropical cyclone to justify the longest period that the tropical cyclone effects might persist; controlling the seasonality and long-term trends using a different df (2, 3, 4, or 5) for calendar year and month; and not adjusting temperature or controlling the temperature with a different df (3, 5, or 6).

Furthermore, to explore the potential effect modifiers on tropical cyclone–infectious disease association, we further conducted subgroups analysis by age (≤19, 20–59, and ≥60 years), sex (female *vs* male), region (tropical and subtropical *vs* extratropical) and tertiles of location-level GDP per capita and RDI. The significance of the effect modification across subgroups was evaluated using a Wald-type test.[38]

Additionally, for each month in each location, we calculated the overall, age-specific, sex-specific, and cause-specific number of hospitalisations for infectious diseases attributable to tropical cyclone exposure using the pooled cumulative RR corresponding to each month's tropical cyclone days.[39] The detailed methodology of the calculation of attributable fraction is presented in the appendix (pp 2–3). Briefly, the total attributable number caused by tropical cyclone exposure was given by the sum of the contributions from all the months of the series, and its ratio with the total number of hospitalisations for infectious diseases provided the attributable fraction. To evaluate the temporal trends of the attributable burden in different countries or territories, we also estimated the fraction of hospitalisations for infectious diseases attributable to tropical cyclone exposure based on the corresponding yearly cumulative RR and tropical cyclone exposure in each country and territory.[40] Thailand was not

included in the temporal analysis due to the relatively short study period (2015–19).

All data organisation and analyses were conducted in R software, version 4.1.3. The first-stage and second-stage analyses were conducted using the R packages of dlnm and mixmeta.

Role of the funding source

The funders had no role in study design, data collection, data analyses, data interpretation, or writing of the manuscript.

Results

The tropical cyclone frequency for each location in Canada, South Korea, New Zealand, Viet Nam, Thailand, and Taiwan is shown (figure 1). Locations in Taiwan, the southern part of South Korea, and the east coast of Viet Nam experienced the highest frequency of tropical cyclones (≥10 tropical cyclone days per decade), with less frequent exposures in Canada and New Zealand (<5 per decade). A total of 179 locations from the six countries and territories that experienced at least one tropical cyclone during the study period, with a total of 124 tropical cyclones and approximately 2·2 million hospitalisations for infectious diseases, were included in the analysis (appendix p 4). Each location contributed an average of 14·2 years (SD 4·2) of data. Participants who were hospitalised for infectious diseases were more likely to be female (*vs* male) and older (aged ≥20 years *vs* ≤19 years) in Canada and South Korea, and to be male (*vs* female) and younger (≤19 years *vs* ≥20 years) in Taiwan. The five studied causes (intestinal infectious diseases, malaria, sepsis, dengue, and tuberculosis) accounted for 66·4% of total infectious disease hospitalisations in the tropical cyclone-exposed locations in Canada, 73·8% in South Korea, 57·8% in New Zealand, 77·8% in Thailand, and 25·0% in Taiwan. Intestinal infectious diseases and sepsis were the leading causes across these countries and territories, whereas tuberculosis, malaria, and dengue accounted for notably fewer cases.

The elevated hospitalisation risks for all-cause and cause-specific infectious diseases peaked within the first 2 months after a tropical cyclone (ie, lag 0–1 months) and tended to be minimal after that, with a relatively longer persistence for sepsis (figure 2). The observed lag patterns were robust to various numbers of knots for the lag effects (appendix p 8). Lags of up to 2 months were sufficient to capture the lag effects of tropical cyclone exposure, as no significant risks were generally observed beyond this time (figure 2), including when the maximum lag was extended to 18 months (appendix p 9). We thus focused on the risks of infectious diseases over the first 2 months after tropical cyclone exposure.

We observed an approximately linear and non-threshold exposure–response relationship of infectious disease hospitalisation risks with cyclone intensity

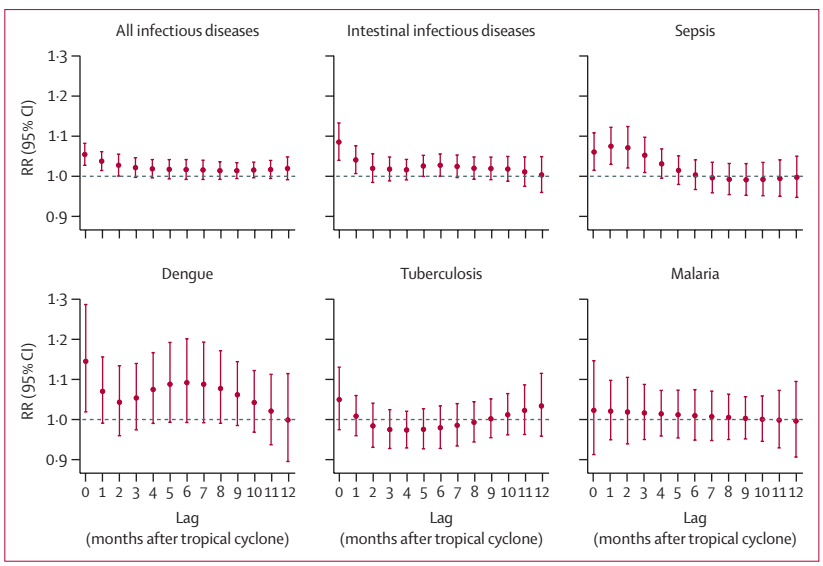

Figure 2: **Overall lag effects of tropical cyclones on hospitalisations for all-cause and cause-specific infectious diseases along lag 0–12 months**
RR=relative risk.

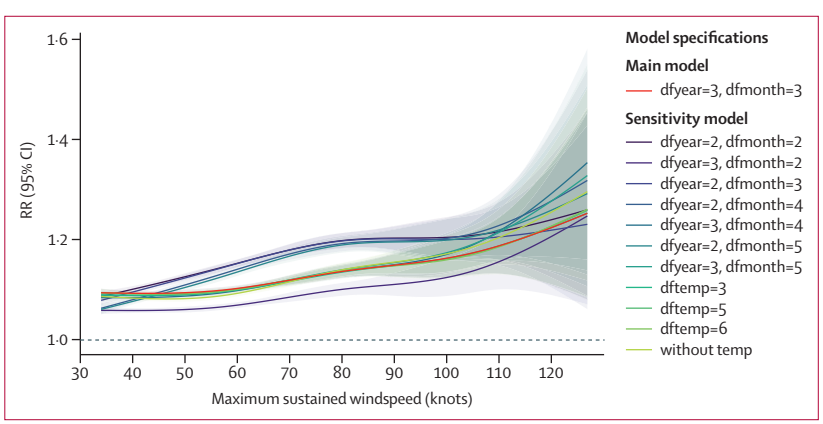

Figure 3: **Overall risk of infectious disease hospitalisations for each additional cyclone day**
Overall risk of hospitalisations defined with different thresholds of maximum sustained windspeed (knots), using models with various degrees of freedom for year (dfyear), month (dfmonth), and temperature (dftemp), or models without temperature adjustment (without temp). RR=relative risk.

(figure 3). The cumulative RR for infectious diseases hospitalisations risks for each additional cyclone day over the first 2 months after tropical cyclone exposure shows a linear and increasing trend as the maximum sustained windspeed of the cyclone days increased. This trend did not change substantially with different model specifications (figure 3). Overall, each additional tropical cyclone day was associated with increased hospitalisation risks over the first 2 months following a cyclone for all infectious diseases (cumulative RR 1·09 [95% CI 1·05–1·14]), intestinal infectious diseases (1·13 [1·05–1·21]), sepsis (1·14 [1·05–1·23]), and dengue (1·22 [1·03–1·46]; table). Associations with tuberculosis and malaria were in the same directions as intestinal infectious diseases, sepsis, and dengue but were not significant. The effect estimates were not statistically

	All infectious diseases	Intestinal infectious diseases	Sepsis	Dengue	Tuberculosis	Malaria
Overall	1·09 (1·05–1·14)	1·13 (1·05–1·21)	1·14 (1·05–1·23)	1·22 (1·03–1·46)	1·06 (0·95–1·18)	1·04 (0·89–1·23)
Age, years						
≤19	1·20 (1·11–1·31)	1·20 (1·06–1·34)	2·59 (1·81–3·72)	1·54 (0·77–3·07)	1·02 (0·89–1·17)	1·03 (0·89–1·19)
20–59	1·15 (1·07–1·23)	1·19 (1·08–1·31)	1·38 (1·16–1·64)	1·16 (0·98–1·37)	0·99 (0·87–1·12)	1·04 (0·88–1·21)
≥60	1·10 (1·05–1·16)	1·19 (1·08–1·32)	1·20 (1·10–1·30)	1·46 (0·71–2·98)	1·10 (0·97–1·25)	0·96 (0·84–1·10)
Sex						
Female	1·12 (1·06–1·18)	1·16 (1·07–1·26)	1·22 (1·12–1·32)	1·12 (0·95–1·33)	1·01 (0·88–1·16)	1·01 (0·87–1·18)
Male	1·15 (1·08–1·22)	1·19 (1·09–1·30)	1·20 (1·08–1·32)	1·18 (0·99–1·40)	1·07 (0·95–1·20)	1·03 (0·88–1·20)
Region*						
Tropical or subtropical	1·09 (1·00–1·19)	0·98 (0·89–1·08)	1·25 (1·03–1·51)	1·35 (0·60–3·06)	1·00 (0·87–1·15)	0·64 (0·24–1·70)
Extratropical	1·11 (1·05–1·17)	1·19 (1·09–1·29)	1·12 (1·02–1·23)	1·09 (0·89–1·33)	1·10 (0·93–1·32)	1·06 (0·90–1·26)
Country or territory						
Canada	1·15 (1·07–1·24)	1·27 (1·14–1·41)	1·21 (1·09–1·36)	1·06 (0·87–1·30)	1·12 (0·80–1·58)	1·15 (0·87–1·51)
New Zealand	1·14 (1·05–1·25)	1·21 (1·06–1·38)	1·01 (0·82–1·24)	7·07 (1·03–48·42)	11·66 (3·61–37·64)	..
Taiwan	1·07 (0·97–1·18)	0·93 (0·74–1·18)	1·13 (1·03–1·24)	..	0·84 (0·26–2·68)	..
Thailand	1·17 (0·97–1·41)	1·00 (0·88–1·13)	1·53 (1·01–2·30)	1·35 (0·60–3·06)	0·97 (0·84–1·13)	0·64 (0·24–1·70)
Viet Nam	0·98 (0·78–1·23)	..	..	..	..	..
South Korea	0·87 (0·76–1·00)	0·83 (0·68–1·02)	0·81 (0·64–1·02)	..	1·00 (0·81–1·23)	1·00 (0·81–1·24)

Table shows cumulative relative risks over the first 2 months following the tropical cyclone exposure. *Tropical or subtropical region includes Taiwan, Viet Nam, and Thailand and extratropical region includes Canada, New Zealand, and South Korea.

Table: **Relative risks with 95% CI of hospitalisations for overall and cause-specific infectious diseases per 1-day increase in monthly tropical cyclone exposure by sex–age–region and country or territory**

different across age, sex, and region groups for all-cause infectious diseases (p>0·05), with consistently elevated tropical cyclone-associated hospitalisation risks in different age and sex groups. In comparison, higher risks of sepsis in the younger population (aged ≤19 years) and intestinal infectious diseases in the extratropical region were observed. The results were generally insensitive to models with varying degrees of freedom for controlling temporal trends and temperature, and models with or without the temperature adjustment (appendix p 10).

At the country level, tropical cyclone exposure was associated with increased hospitalisation risks for all-cause infectious diseases in Canada (cumulative RR 1·15 [95% CI 1·07–1·24]) and New Zealand (1·14 [1·05–1·25]; table). For the risks of cause-specific infectious diseases, statistically significant and particularly high tropical cyclone-associated hospitalisation risks were observed for intestinal infectious diseases in Canada and New Zealand, for sepsis in Canada and Thailand, and for dengue and tuberculosis in New Zealand among all studied causes of infectious diseases and countries and territories (table). No significant elevated risks were consistently observed for South Korea (table). Higher tropical cyclone-associated hospitalisation risks for infectious diseases were observed among the locations with higher levels of RDI (figure 4). In contrast, non-significant effect modifications of age, sex, and GDP per capita were consistently observed at the country or territory level.

In total, 15 667 (95% CI 8658–22 134) infectious disease hospitalisations were attributable to tropical cyclone exposures over the 2-month post-cyclone period in the six studied countries and territories, accounting for 0·72% (0·40–1·01) of the total number of infectious disease hospitalisations (appendix pp 5–6). The greatest attributable fractions were observed among males and the younger population (aged ≤19 years), compared with their counterparts, especially for intestinal infectious diseases (appendix p 6). For different causes, the percentage of hospitalisations attributable to tropical cyclones for sepsis was the highest among all studied causes of infectious diseases, particularly among the population aged ≥60 years. At the country level, particularly high tropical cyclone-attributable fraction of sepsis hospitalisations was found in Taiwan. Nearly 2·30% (0·65–3·66) of the sepsis hospitalisation cases were attributable to tropical cyclones in Taiwan. When viewed on a temporal scale, an overall decreasing trend in tropical cyclone-attributable fraction of infectious disease hospitalisations was observed for South Korea during the study period (figure 5). However, the attributable fractions appear to be increasing in Viet Nam, Taiwan, and New Zealand.

Discussion

Our large-scale population-based study found that tropical cyclone exposure was associated with persisting elevated hospitalisation risk of infectious diseases, especially for intestinal infectious diseases and sepsis.

The risks peaked within the first 2 months and tended to dissipate beyond this period. Younger populations (aged ≤19 years) and males appeared to have higher tropical cyclone-attributable hospitalisation burden for infectious diseases than their counterparts, particularly for intestinal infectious diseases. The heterogeneous spatiotemporal pattern was further revealed at the country level—eg, the particularly high tropical cyclone-attributable hospitalisation burden of sepsis in Taiwan. Furthermore, the proportion of infectious disease hospitalisations that were attributable to tropical cyclone exposures appears to have decreased in South Korea and increased in Viet Nam, Taiwan, and New Zealand during the study period.

To our knowledge, this is the first multi-country study investigating tropical cyclone–infectious disease associations. Based on a systematic review,[9] we found that previous studies involving a quantitative risk assessment of infectious diseases morbidity or mortality were scarce. There were also major differences in modelling strategies (eg, exposure assessment, exposure window ascertainment, and statistical model), study period, and setting across previous studies. Additionally, studies on tropical cyclone epidemiology largely focused on a single tropical cyclone event (eg, Hurricane Katrina or Hurricane Sandy) or were restricted to a single year or area. Tropical cyclone hazards vary substantially in terms of frequency, intensity, population background, and infrastructure development. Thus, the results of single-tropical cyclone studies might not be comparable or generalisable. To compensate for this limitation, several recent studies have included multiple tropical cyclones spanning more than a decade and provided high-quality evidence on tropical cyclone epidemiology.[7,28,29,41,42] However, only two studies reported tropical cyclone-associated risks of infectious diseases in the USA alone.[7,28] For example, one time-series study included all mortality and tropical cyclone events in the USA between 1988 and 2018 and reported an elevated death risk of all-cause infectious diseases associated with tropical cyclones, persisting up to 2 months after the cyclone.[28] This finding is generally consistent with our own on cause-specific infectious disease hospitalisations on a multi-country scale, which showed prolonged elevated hospitalisation risks in the first 2 months after the tropical cyclone exposure, especially for sepsis.

Tropical cyclones could potentially lead to a persistent elevated risk of infectious diseases through various interconnected pathways. The heavy rainfall, strong winds, and large storm surges that usually accompany tropical cyclones can facilitate a favourable environment for disease transmission (eg, by contaminating freshwater sources with sewage containing bacterial and parasitic pathogens) and lead to the disruption of infrastructure and health-care services, furthering the risk of exacerbation for the emerging infectious diseases cases.[9] Notably, the interruption of medical support would lead to fewer visits and admissions shortly after the tropical cyclone event (eg, during the first hours and days).[29,43] Therefore, a relatively long hypothetical exposure window for the tropical cyclone is needed to fully capture the health risks and burden when assessing their impacts (at least a 2-month post-tropical cyclone period, as suggested by our results). Additionally, some population groups might be more vulnerable to the adverse health effects of tropical cyclones. Vulnerability could also vary across countries and causes of infectious diseases. We observed higher tropical cyclone-attributable hospitalisation burden for infectious diseases among the younger population (aged ≤19 years) and males compared with their counterparts, especially for intestinal infectious

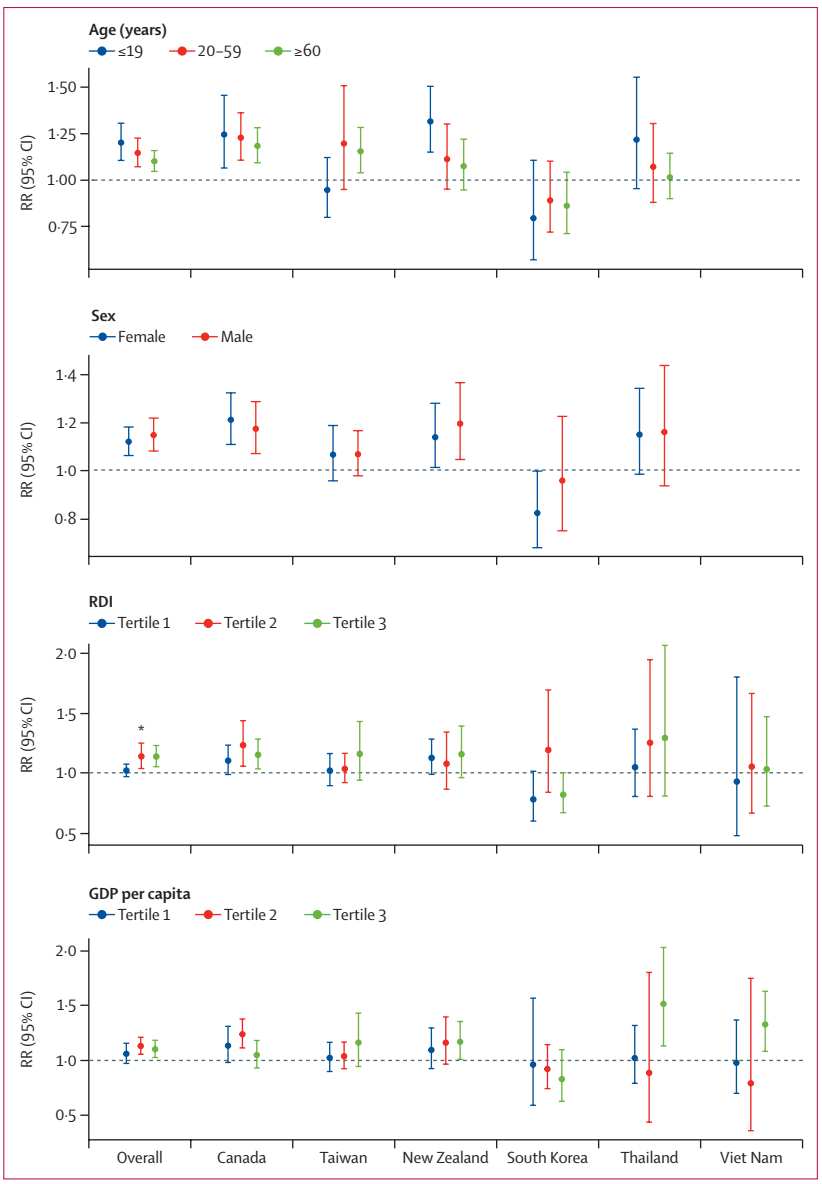

Figure 4: **Overall risk of infectious diseases hospitalisations with 95% CIs for each additional tropical cyclone day, stratified by sex, age, RDI, and GDP per capita**

Age-specific and sex-specific data were not available from Viet Nam. GDP=gross domestic product. RDI=relative deprivation index. RR=relative risk. *p<0·05.

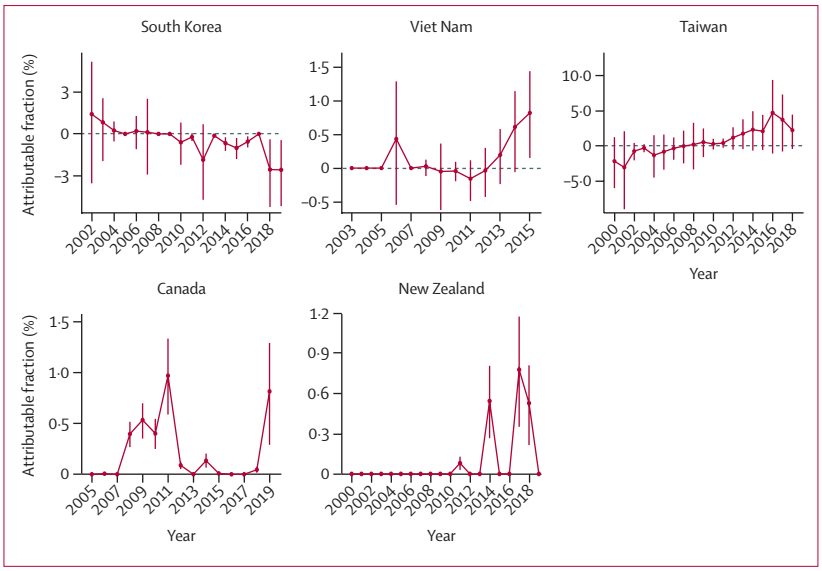

Figure 5: **Overall and country-specific or territory-specific temporal evolution of the proportion (%) with 95% CIs of infectious diseases hospitalisations attributable to tropical cyclone exposures**

diseases. However, the specific reasons for the disproportionate risks and burden across population groups such as sex and age remain unclear, especially for different subtypes of infectious diseases. Differences in physiology, activity pattern (eg, mobility level),[43] awareness (eg, disaster preparedness),[44] and social support[45] could potentially be contributing factors. For example, compared with adults, younger populations generally tend to have less mature immune systems, higher likelihood of engaging in behaviours that facilitate transmission (eg, close contact in school environments), and potentially less stringent adherence to hygiene practices. These factors could collectively elevate their risk of infections, including intestinal infections. To date, minimal evidence is available on the potential effect modifiers on the tropical cyclone–infectious diseases associations.[9] To enhance our understanding of the tropical cyclone health effects, more studies on tropical cyclone epidemiology with a long-term follow-up for multiple cyclones and thorough subgroup analysis across countries are needed. Public and personal services and assistance might need to be extended beyond the immediate aftermath of the cyclone, particularly to these identified disadvantaged populations in the susceptible countries and territories.

We further evaluated the tropical cyclone-attributable risk and burden of infectious disease hospitalisations on a multi-country and a temporal scale, which has rarely been investigated in previous studies. Relatively high tropical cyclone-attributable hospitalisation risk was observed for sepsis in Taiwan. Many interconnected factors, such as tropical cyclone characteristics, topography, socioeconomic status and living conditions, health-care infrastructure availability, and disaster preparedness and management practices could contribute to the observed differences across countries. For example, the relatively stronger tropical cyclones with heavier rainfalls and subsequent flooding, coupled with a relatively high population density in Taiwan, could increase the risk of infections and sepsis.[46] We also investigated the potential association of tropical cyclone with malaria in Canada and New Zealand. Although malaria has traditionally been considered an imported communicable disease unrelated to the climate in Canada,[47,48] more recent evidence challenges this assumption of negligible malaria risk in Canada with climate change.[49] Notably, competent malaria vectors currently exist in southern Canada, including several major urban centres, and historical conditions have supported endemic malaria transmission in these regions.[49] The occurrence of climate extremes, such as cyclones, is likely to exacerbate the malaria transmission risk by fostering environmental conditions conducive to increased risks of disease transmission (eg, via increased disease vectors, disrupted sanitation and hygiene, and overcrowded and displaced populations). Similarly, the passage of a cyclone will also probably affect the transmission pattern and risks of malaria, especially in malaria-endemic regions. Factors such as international travel, immigration, and drug resistance could further amplify this issue in Canada.[49] However, we did not find sufficient evidence to support a positive tropical cyclone-malaria association in these two countries due to the very small number of cases.

It is also noteworthy that the proportion of infectious disease hospitalisations attributable to tropical cyclone appeared to be decreasing in South Korea but increasing in Viet Nam, Taiwan, and New Zealand. This finding highlights the effectiveness and progress of the disaster management measures and devoted prevention efforts in South Korea. However, the poleward migration of tropical cyclones due to climate change, as well as the population ageing, could contribute to an increasing trend in tropical cyclone-related disease risk, particularly for countries and territories without sufficient experience in dealing with tropical cyclones due to relatively limited historical tropical cyclone exposure (eg, New Zealand). Although the physical characteristics of tropical cyclones (eg, frequency, intensity, and duration) have been well characterised[26,50] and there is a consensus on the generally increasing number of intense tropical cyclones, no studies have yet estimated the change of the infectious diseases burden accounting for the changing population vulnerability. To our knowledge, only one study examined the temporal change in the risk of homelessness, casualties, and property losses induced by tropical cyclones in South Korea. This study found a decreasing trend in these risks over 1979–2010, which is generally consistent with our findings for South Korea, despite the different study periods.[51] Further studies are needed to elucidate the underlying causes for the spatiotemporal risk differences across countries and formulate targeted approaches to mitigate the burden and reverse the increasing trends.

Strengths of this study include the incorporation of numerous tropical cyclones (ie, 124 tropical cyclones) and infectious diseases hospitalisations over two decades across six countries and territories, as well as a comprehensive analysis (eg, lag effect pattern, spatiotemporal risk and burden estimation, and cause-specific analysis) based on a well established and advanced modelling strategy. Nevertheless, some limitations should also be acknowledged. As an observational study, inherent limitations such as the possibility of residual confounding cannot be avoided. Furthermore, the tropical cyclone exposure was not assessed at the individual level, which could introduce exposure misclassification bias. However, this bias tends to make the exposures non-differential and thus bias the effect estimates towards the null, which indicates our results are more likely to be conservative, especially for the study locations with larger area sizes (eg, locations in Viet Nam and Thailand).[52,53]

Additionally, population displacement and the integrity of hospitalisations and other vital infrastructures during tropical cyclones could be important influential factors in the health impacts of tropical cyclones, but were not accounted for in this study due to a lack of data.[54] However, the effects of this limitation on our results might be modest. First, because short-term population displacement would not substantially affect the moderate-term and long-term effects of a tropical cyclone, as most displaced individuals would return to the location of residence post-tropical cyclone (eg, to rebuild the houses), keeping the total population relatively stable in the moderate and long term (and infectious disease transmissions could occur after their return). Second, because individuals who migrated for treatment to other locations during and after the tropical cyclone due to the compromised integrity of vital infrastructures would still be assigned to the location of residence affected by the tropical cyclone. Nevertheless, these factors are crucial for assessing resilience and the pathways through which climate-related and weather-related disasters affect infectious diseases. To improve the health impact assessment and minimise their health threats, it is necessary to systematically collect, compile, and incorporate richer data on these factors on a multi-tropical cyclone scale in future studies.

Moreover, the cumulative precipitation associated with tropical cyclones was an important contributor to infectious disease dynamics and we did not account for it in this study. Instead, we modelled tropical cyclone exposure days defined with windspeed threshold, as there is currently no standard definition for tropical cyclone exposure based on the associated rainfall amounts. However, the maximum sustained windspeed associated with the tropical cyclone is the most well established and accurate indicator for defining tropical cyclone exposures and classifying different cyclone types, both in previous research[6,28,55] and official organisations. Studies across different regions have also established a strong correlation between higher tropical cyclone wind speeds and greater cumulative rainfall over land areas affected by the tropical cyclones.[56–58]

Furthermore, due to the small number of tropical cyclone exposure days and hospitalisations for cause-specific infectious diseases, along with constraints in data availability on specific ages and pathogens, the data were aggregated and analysed within relatively broad categorisation of age (≤19 years, 20–59 years, and ≥60 years) and intestinal infectious diseases, to improve the model fit and ensure data integrity. Although the effect estimates reflect the overall impact of tropical cyclones on these age groups and gastrointestinal health, this broad categorisation might lead to an underestimation of the effect estimates due to the differing sensitivities of age and pathogen types (eg, bacterial, parasitic, and viral pathogens) to tropical cyclones. To gain deeper insights into age-specific and pathogen-specific risks and provide a more comprehensive understanding of the nuanced factors influencing vulnerabilities, particularly among the younger population highlighted in our study, further investigations using more detailed individual data are warranted.

Finally, although this is the first multi-country study on tropical cyclone-related infectious disease risks, we only had data from six countries and territories. In addition, cause-specific infectious disease data were not consistently available from each study country and territory due to data restrictions (eg, Viet Nam data were only available for all-cause infectious diseases). These restrictions hindered us from conducting a more thorough and informative analysis, especially for low-income and tropical cyclone-prone countries and regions (eg, Bangladesh, Myanmar, and sub-Saharan Africa), where the health systems are weaker and the threats from tropical cyclones could be a major public health concern.[1] The considerable diversity in the tropical cyclone climatology and resilience of health systems across regions increases the uncertainty of generalising our results to other countries.[59] This limitation should be lessened in future research by extension of the dataset. Results of future studies from other countries or territories could also complement the evidence provided in this study.

There was an elevated risk for infectious disease hospitalisations that persisted months after a cyclone, especially for sepsis and intestinal infectious diseases. The tropical cyclone-attributable risks and burdens of cause-specific infectious disease hospitalisations varied across different population subgroups and countries. Given the anticipated intensification of tropical cyclones in a warming climate, it is imperative to integrate climate change mitigation efforts with evidence-based tropical cyclone preparedness and intervention strategies targeted for different populations, regions, and causes to mitigate the substantial risks and burden.

Contributors

YG and SL set up the collaborative network and conceptualised the study. WH, TV, and EAR designed the methodology. WH took the lead in manuscript drafting and results interpreting. All authors contributed to the data collection and the critical revision of the manuscript. YG, SL, and WH accessed and verified the data. All authors were responsible for the decision to submit the manuscript.

Declaration of interests

We declare no competing interests.

Data sharing

All hospitalisation data used in our study were obtained from the local official authorities of each study country or territory under a data sharing agreement and we are not permitted to directly share the third-party raw data used in the analyses. Researchers can refer to collaborative participants, who are listed in the author list part of our study, for information on accessing the data for each country or territory. Historical information on the temporal dynamics of cyclone events was collected from the IBTrACS data (https://www.ncei.noaa.gov/products/international-best-track-archive).

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