Environmental Science and Pollution Research
https://doi.org/10.1007/s11356-022-21963-8

RESEARCH ARTICLE

Systematic identification of heat events associated with emergency admissions to enhance the heat-health action plan in a subtropical city: a data-driven approach

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Received: 24 January 2022 / Accepted: 7 July 2022

Abstract

According to the United Nations Office for Disaster Risk Reduction (UNDRR), a heat-health action plan should address various impacts of hazards at different levels, including an early warning system to monitor risks and behaviour enhancement to increase disaster preparedness. It is necessary to comply with guidelines regarding heat duration/intensity. In this study, we developed a data-driven approach to rapidly and systematically estimate the impacts of various heat events on emergency admissions among the adult population ($n=7{,}086{,}966$) in Hong Kong in order to enhance the heat-health action plan. Immediate, short-term, and long-term impacts determined by 1-day, 4-day, and 8-day windows were estimated to identify specific heat events suitable for early warnings. In addition, underestimated risk, determined by a continuous increase in heat risk after days without significant emergency admissions, was estimated to evaluate potential maladaptive behaviours among a specific subpopulation. Based on age- and gender-specific analyses, 1D, 1D1N, and 2D2N were observed to have a stronger immediate impact on emergency admissions. 1D1N and 2D2N also showed notable short-term and long-term impacts. Based on heat vulnerability factors (age and gender), 2D2N was a higher-priority extreme heat event for early warning measures than 1D1N. Furthermore, men aged 19 to 64 had the highest underestimated risk. Specifically, they had IRR values of 1.113 [1.087, 1.140], 1.061 [1.035, 1.087], and 1.069 [1.043, 1.095] during lag days 3–5 of 3D2N, respectively, possibly due to a lack of adaptive behaviour. By adopting our approach, the duration of heat events with significant health impacts can be identified in order to further enhance relevant heat stress information. This framework can be applied to other cities with a similar background for rapid assessment.

Keywords Heat wave definitions · Heat duration · Heat-health · Emergency admissions · Asian cities · Subtropical cities

Introduction

Extreme heat can lead to excessive mortality and morbidity in tropical and subtropical cities (Chan et al. 2018; Royé 2017; Tawatsupa et al. 2014), despite the fact that most of the local population is acclimatized to hot and humid summers. Recent studies have observed that the duration and intensity of extreme heat events can modify the health impacts on subtropical populations (Chen et al. 2015; Gao et al. 2015; Yang et al. 2019). For example, a period of consecutive days and nights could induce a higher mortality

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risk in Hong Kong than a single hot day (Wang et al. 2019), and five or more non-consecutive hot days in a week could result in fatal effects on the local population (Ho et al. 2017a, b). Thus, better preparedness for extreme heat events is necessary.

Concept of heat-health action plans

In terms of disaster preparedness for climate mitigation, establishing a heat-health action plan is a common approach to minimize the health risk and socioeconomic losses in a city (Mayrhuber et al. 2018; Kotharkar and Ghosh 2022; Ragettli and Röösli 2019). This includes two dimensions for local citizens at the individual level: (1) developing an early warning system and (2) enhancing disaster preparedness and adaptive behaviours of the local population. Based on the definition given by the United Nations International Strategy for Disaster Reduction (UNDRR), an effective protocol to minimize disaster risks should consist of an integrated system that monitors, forecasts, and predicts a type of hazard (e.g. earthquake, temperature extremes). This can be used for disaster risk assessment and as a communication tool for preparedness activities that can enable both individuals and communities to take immediate action towards reducing future disaster risks. Therefore, the UNDRR has promoted four major elements that should be inclusively considered in order to develop an effective end-to-end, people-centred early warning systems with action plans: (a) disaster risk assessment based on systematic data collection to deliver knowledge of disaster risk; (b) accurate detection, monitoring, analysis, and forecasting of the types of hazards and their possible consequences based on a series of systematic procedures; (c) a top-down approach to disseminate and communicate a series of timely, accurate, and actionable warnings and associated information related to the likelihood of a particular hazard and its impact, based on an official source (e.g. government authority); and (d) disaster risk preparation at all levels in order to respond to warnings from official sources. All of these elements are interrelated and interlocked. Furthermore, there should be coordination among multiple government and non-government entities to optimize the systems and mechanisms for disaster management.

According to this, the best mechanism is to develop an early warning system along with a heat-health action plan that can address the impacts of hazardous events under different scenarios that occur independently, dependently, or continuously, using the best communication through different sectors based on the four elements described above. Such an early warning system and heat-health action plan for extreme heat events should help raise the awareness of the local population in the short term (Hajat et al. 2010). Therefore, a better version of the early warning system and heat-health action plan would be a multilevel system that can enhance the efficiency and consistency of alerts based on possible coordination and capacity in local scenarios, along with a mechanism that can identify, monitor, and update information regarding hazardous events in the future.

Various cities have adopted a conceptual framework for an early warning system as a "heat watch" to identify extreme heat events. Several studies have also noted that the appropriate use of an early warning system can reduce the health risks caused by extreme heat events (Bassil and Cole 2010; Pascal et al. 2006; Ragettli and Röösli 2019; Tan et al. 2004; Toloo et al. 2013). For example, Ebi et al. (2004) found that developing a heat warning system reduced fatalities in Philadelphia, Pennsylvania, USA. However, numerous early warning systems, including in subtropical cities, were developed based on a temperature threshold to identify a "single hot event" (Chau et al. 2009; Lowe et al. 2011). They failed to address the various impacts of multilevel hazards, as indicated in the conceptual framework of the early warning system. Specifically, this simplified application may be insufficient to minimize health risks, because variations in the duration and intensity of hot events may act as effect modifiers (Ho et al. 2017b; Kent et al. 2013; Wang et al. 2019; Xu et al. 2018; Zhang et al. 2012).

In addition, traditional heat-health action plans are intended to enhance disaster preparedness and adaptive behaviours among vulnerable groups, in order to minimize underestimated risks from potential lack of protection. Action plans can also provide relevant information to set up protocols (e.g. disaster-related training courses) to increase disaster awareness of the local population in advance. Specifically, disaster awareness is linked to people's awareness of their vulnerability (Bartlett and Brannelly 2019), as some individuals are not aware that they may be facing a risky scenario, which could result in increased disaster risk when faced with the uncertainty of an extreme heat event. As mentioned above, the end-to-end and people-centred recommendations of the UNDRR should include disaster risk assessment based on systematic data collection in order to deliver appropriate information. This information, along with the use of health data to analyse the relationship between morbidity/mortality and various heat events, is used not only to define a specific threshold for heat warning when using a top-down monitoring system, but also to evaluate specific heat events that may need bottom-up support from stakeholders and the community, as self-management could mitigate disaster risk among local people with maladaptive behaviour.

Multilevel framework of heat-health action plans

With respect to government actions and plans worldwide, one of the most notable examples is the National Heat

Action Plan (NHAP) commonly used in Europe, which categorizes important elements of an effective heat-health watch into four categories in order to help health and social care professionals to develop better disaster management through the hot summer period. For example, the Heat-Health Alert service in the UK (https://www.metoffice.gov.uk/public/weather/heat-health/) includes the following categories: (1) level 1, which is a minimum alert (basic warning) every year in summer declaring a full period with hazardous events associated with extreme heat, in order to increase the disaster preparedness of the local population; (2) level 2, which is an alert based on forecasted reports of temperature extremes higher than a critical threshold in the coming few days; (3) level 3, which is a warning on days when there is already extreme heat, based on monitored temperatures higher than the critical threshold; and (4) level 4, which is an advanced warning when a prolonged heat event leading to severe health impacts occurs. Based on these definitions, most tropical and subtropical cities applied levels 1, 2, and 3 to some degree when developing their local warning systems; however, the critical category associated with the duration and intensity of hot events (level 4) is missing.

Therefore, it would be ideal to have a better understanding of the potential health impacts of heat events based on their duration and intensity by incorporating climate information in order to identify representative those heat events that pose a significant threat to public health. Previous studies also noted the importance of comparing different definitions or metrics of heat waves to better identify representative heat events (Kent et al. 2013; Zhang et al. 2012).

In this study, we developed a two-sided data-driven approach with a cross-sectional ecological analysis to (1) identify the types of prolonged heat events that could continuously affect emergency admissions among the adult population for a certain period, for the purpose of developing an early warning system, and (2) identify the types of heat events that could potentially have underestimated risk due to maladaptive behaviour, for the enhancement of disaster preparedness. The data-driven approach is a mathematical framework for systematically reporting results through data modelling and statistical analyses, in which the framework is more robust and can be directly implemented in other locations (Ho et al. 2017a, b; Krstic et al. 2017). Hong Kong was selected as our study site because it has long been identified as a subtropical city with low but significant health risk from hot days above a temperature threshold (Chan et al. 2012, 2013; Ho and Wong 2019; Yi and Chan 2015). Local studies have indicated adverse effects on human health contributed by spatiotemporal variations of temperature and adaptive behaviours of different populations (Chan et al. 2012; Goggins et al. 2012; Ho and Wong 2019; Ho et al. 2018; Tam et al. 2009; Thach et al. 2015), including a study which pointed out the differences in mortality attributed to various prolonged heat events in Hong Kong (Ho et al. 2017b). More importantly, the local government has already established an early warning system to identify "very hot days" and "hot nights" by applying levels 1, 2, and 3 when developing a heat-health watch; however, level 4 is still missing in the current local system and must be added.

Thus, the objectives of this study were as follows: (1) evaluate the impacts of prolonged heat events on emergency admissions between 0 and 7 days after the event and (2) identify representative heat events with significant health impacts considering both aspects of heat warning development and disaster preparedness, based on the proposed data-driven approach. The use of emergency admission data instead of mortality data for analysis can enhance the development of a heat warning system and heat-health action plan not only by providing information related to extremely disastrous scenarios (mortality effect), but also by considering all populations that could be severely impacted, in order to set up better emergency services and provide better health preparedness. This can help facilitate preparations in the pre-hospital period as well as resource management in emergency services. Therefore, the results can provide a scientific basis for early warning and heat-health information services when handling heat-health risk. Furthermore, the data-driven framework used in this study can be applied to other locations where various types of health records share a similar data structure.

Data and methods

Data collection

A dataset of all-cause emergency admissions from all public hospitals in Hong Kong between 2007 and 2014 was obtained from the Hong Kong Hospital Authority. This dataset included the daily record of emergency admissions among the adult population, classified based on age (19–64, ≥ 65) and gender. Daily maximum and minimum temperatures and humidity records (2007–2014) retrieved from the weather station located at the headquarters of the Hong Kong Observatory were also used. Air quality data from 7 non-roadside monitoring stations operated by the Environmental Protection Department (EPD), covering both urban and rural areas, were also obtained (Central Western, Sham Shui Po, Sha Tin, Tai Po, Tsuen Wan, Kwai Chung, and Tap Mun). This dataset included information of respirable suspended particulates (PM_{10}), nitrogen dioxide (NO_2), ozone (O_3), and sulphur dioxide (SO_2). Note that PM_{10} monitored by EPD includes both fine and coarse particulate matter ($PM_{2.5}$ and $PM_{10\text{-}2.5}$).

Epidemiological design

This study carried out a cross-sectional ecological analysis with a Poisson regression to evaluate the impact of prolonged heat events on emergency admissions. Cross-sectional ecological analysis is an epidemiological design which was used in a previous study for heat-health analysis in Hong Kong (Thach et al. 2015). The daily count of emergency admissions from May 1 to October 30 in 2007 to 2014 was used as the dependent variable of the Poisson regression. Following the conceptual framework of other heatwave and health studies (Khalaj et al. 2010; Kosatsky et al. 2012; Madrigano et al. 2015), the major independent variables of the regression model included classification of the following heat events: (1) a non-consecutive hot day (1D), (2) a consecutive event with a hot night before a hot day (1D1N), (3) a consecutive event with 2 hot days and 1 hot night (2D1N), (4) a consecutive event with 2 hot days and 2 hot nights (2D2N), (5) a consecutive event with 3 hot days and 2 hot nights (3D2N); and (6) a consecutive event with at least 3 hot days and 3 hot nights (3D3N +). As this study is an extension of previous work on the heat-health impacts in Hong Kong (Ho et al. 2017b), a hot day (called a "very hot day" in local terminology) is defined as daily maximum temperature ≥ 33 °C, and a hot night is defined as daily minimum temperature ≥ 28 °C, according to the definitions of the Hong Kong Observatory. Additional independent variables of the regression included daily averages of PM_{10}, NO_2, O_3, and SO_2 from 7 non-roadside monitoring stations as covariates of air quality, the daily average of humidity as a covariate of other meteorological information, a continuous variable of day of the week to control for the weekday/weekend effect, and a continuous variable of month to control for the seasonal effect.

The incidence rate ratio (IRR) was reported as an estimation of independent effects contributed by each heat event. In addition, 95% upper confidence interval (UCI) and 95% lower confidence interval (LCI) were used to test for the statistical significance of each independent effect. Based on the classification of age and gender, cross-sectional ecological analyses were repeated for 4 subgroups of the population: (1) men aged 19–64, (2) women aged 19–64, (3) men aged ≥ 65, and (4) women aged ≥ 65.

Identification of prolonged heat events for the early warning system

Three durations of heat-related impacts were examined in this study: (1) immediate impact, (2) short-term impact, and (3) long-term impact. In this study, we defined a prolonged heat event with immediate impacts as an event with significant influence on emergency admissions within a day, in which IRR, UCI, and LCI values should be higher than 1.00 during the lag 0 day. A prolonged heat event with short-term impact was defined as an event with significant influence on emergency admissions lasting for 4 days, in which IRR, UCI, and LCI values for a continuous 4-day window (lag days 0–3) should be higher than 1.00. A prolonged heat event with long-term impact was defined as an event with significant influence on emergency admissions lasting for 8 days, in which IRR, UCI, and LCI values for a continuous 8-day window (lag days 0–7) should be higher than 1.00. This data-driven approach was adopted to minimize the bias of indirect effects contributed by unknown factors in order to identify representative heat events suitable for consideration in heat-health early warning using evidence-based results.

Theoretically, a heat event that has a significant impact can be identified when it surpasses cross-sectional ecological analysis among all subgroups of the population. If no such event can pass the sensitivity tests for the 4 subpopulations, an additional judgement is applied by counting the number of tests among the subpopulations that can be passed and ranking them based on the vulnerability of each subpopulation. Based on past studies, including local and global studies (Chan et al. 2012; Yang et al. 2019), older adults are commonly more vulnerable to heat, followed by women. Based on the level of vulnerability, results from the analysis among women aged ≥ 65 were weighted as the most vulnerable, followed by men aged ≥ 65 and women aged 19–64. The lowest vulnerability was observed for men aged 19–64.

Identification of prolonged heat events for the enhancement of disaster preparedness

In this study, we assumed the "underestimated risk from maladaptive disaster behaviour" as a (re)occurrence of heat risk after a period without observable heat risk. The hypothesis is that individuals may believe themselves to be well-protected; therefore, they do not expect to face high health risks from heat events. As a result, sudden (and continuous) increased heat risk occurs after a day or several days without heat risk for this type of person.

Based on this hypothesis, two types of heat-related impacts were applied in this study: fairly underestimated risk and extremely underestimated risk. We defined a prolonged heat event with fairly underestimated risk as having a significant influence on emergency admissions for 2 consecutive days (IRR, UCI, and LCI values higher than 1.00), with (at least) a day before those days without a significant influence on emergency admissions. A prolonged heat event with extremely underestimated risk was defined as having a significant influence on emergency admissions for at least 3 consecutive days, with a day before those days without any significant influence.

Based on the subgroup analysis, we could identify the subpopulations that had a lower awareness of vulnerability, which ultimately influenced their adaptive disaster behaviour towards appropriate health and emergency preparation.

Results

Data summary

There were 7,086,966 records of emergency admissions for the adult population (age ≥ 19) between May and October in 2007–2014. An average of 4,814.5 daily admissions were recorded during this period, including an average of 1,556.0 admissions of men aged 19–64, ranging from 1,279 to 1,930 cases with a standard deviation of 110.2 cases per day; 1,720.0 admissions of women aged 19–64, ranging from 1,340 to 2,167 cases with a standard deviation of 139.5 cases; 751.0 admissions of men aged 65 or above, ranging from 488 to 955 cases with a standard deviation of 67.5 cases; and 788.3 admissions of women aged 65 or above, ranging from 521 to 1,005 cases with a standard deviation of 66.3 cases.

There were 56 events of 1D, 35 of 1D1N, 4 of 2D1N, 12 of 2D2N, 4 of 3D2N, and 6 of 3D3N + between May and October in 2007–2014, with an average of 5,913.8, 5,993.4, 5726.5, 5,844.8, 5,798.0, and 6,074.5 emergency admissions, respectively.

Results: perspectives of heat warning systems

Based on the results for men aged 19–64, all events, except 3D2N, were identified as having an immediate impact on emergency admissions (Table 1). However, only 1D1N and 3D3N + met the requirements to be identified as heat events with short-term impact, and only 1D1N could be identified as a prolonged heat event with long-term impact. The variation in long-term impact of 1D1N on emergency admissions among men aged 19–64 ranged from 2.2 to 5.0%.

The heat events with an immediate impact on women aged 19–64 were 1D, 1D1N, and 2D2N (Table 2), with IRR values of 1.021 [1.014, 1.027], 1.031 [1.023, 1.039], and 1.036 [1.021, 1.50], respectively, controlling for seasonality, weekday/weekend effects, and air quality. Based on the stability of IRR values, 1D1N and 2D2N were the prolonged heat events with both short-term and long-term impacts. The variation of long-term impact of 1D1N and 2D2N on emergency admissions among women aged 19–64 ranged from 1.7 to 3.6% and 1.7 to 4.8%, respectively.

The heat events with an immediate impact on men aged 65 or above were 1D, 1D1N, and 2D2N (Table 3), with IRRs of 1.018 [1.008, 1.028], 1.017 [1.004, 1.029], and 1.033 [1.012, 1.056], respectively, controlling for seasonality, weekday/weekend effects, and air quality. However, none of the heat events could meet the requirements for both short-term and long-term impact.

Table 1 Incidence rate ratio (IRR) of heat events for men aged 19–64. Asterisk (*) indicates significant results with IRR, upper confidence interval (UCI), and lower confidence interval (LCI) higher than 1.00. Bold black text indicates heat event with significant immediate impact within 1-day window; bold brown text indicates heat event with significant immediate impact within 4-day window; bold orange text indicates heat event with significant immediate impact within 8-day window. Green and blue highlight indicate heat events with fairly underestimated risk and extremely underestimated risk due to maladaptive behaviour, respectively

Men (Age 19–64)	Long-term Impact							
	Short-term impact							
	Immediate Impact							
Heat Event	Lag 0	Lag 1	Lag 2	Lag 3	Lag 4	Lag 5	Lag 6	Lag 7
1D	**1.027 [1.020, 1.034]***	1.002 [0.995, 1.009]	1.002 [0.995, 1.009]	1.015 [1.008, 1.022]*	1.017 [1.010, 1.024]*	1.024 [1.017, 1.031]*	1.026 [1.019, 1.033]*	1.030 [1.023, 1.037]*
1D1N	**1.050 [1.012, 1.060]***	**1.025 [1.016, 1.034]***	**1.033 [1.024, 1.042]***	**1.023 [1.014, 1.032]***	**1.027 [1.018, 1.036]***	**1.034 [1.025, 1.043]***	**1.022 [1.013, 1.030]***	**1.035 [1.027, 1.044]***
2D1N	**1.032 [1.007, 1.058]***	1.022 [0.997, 1.048]	1.014 [0.989, 1.039]	1.004 [0.979, 1.029]	1.106 [1.080, 1.133]*	1.060 [1.034, 1.086]*	1.070 [1.044, 1.096]*	1.016 [0.991, 1.041]
2D2N	**1.034 [1.020, 1.049]***	1.009 [0.994, 1.023]	0.992 [0.978, 1.006]	1.003 [0.988, 1.017]	1.002 [0.987, 1.016]	1.027 [1.012, 1.042]*	1.028 [1.013, 1.043]*	1.016 [1.002, 1.031]*
3D2N	1.002 [0.978, 1.028]	1.033 [1.008, 1.059]*	1.013 [0.989, 1.039]	1.113 [1.087, 1.140]*	1.061 [1.035, 1.087]*	1.069 [1.043, 1.095]*	1.005 [0.980, 1.030]	0.995 [0.970, 1.020]
3D3N+	**1.027 [1.007, 1.048]***	**1.024 [1.004, 1.045]***	**1.084 [1.064, 1.106]***	**1.025 [1.005, 1.046]***	1.005 [0.985, 1.026]	0.972 [0.952, 0.993]	0.989 [0.989, 1.010]	1.000 [0.980, 1.021]

Table 2 Incidence rate ratio (IRR) of heat events for women aged 19–64. Asterisk (*) indicates significant results with IRR, upper confidence interval (UCI), and lower confidence interval (LCI) higher than 1.00. Bold black text indicates heat event with significant immediate impact within 1-day window; bold brown text indicates heat event with significant immediate impact within 4-day window; bold orange text indicates heat event with significant immediate impact within 8-day window. Green and blue highlight indicate heat events with fairly underestimated risk and extremely underestimated risk due to maladaptive behaviour, respectively

Women (Age 19–64)	Long-term Impact							
	Short-term impact							
	Immediate Impact							
Heat Event	Lag 0	Lag 1	Lag 2	Lag 3	Lag 4	Lag 5	Lag 6	Lag 7
1D	**1.021 [1.014, 1.027]***	0.997 [0.990, 1.003]	1.007 [1.000, 1.013]*	1.015 [1.008, 1.021]*	1.007 [1.000, 1.013]*	1.015 [1.009, 1.022]*	1.029 [1.023, 1.036]*	1.015 [1.008, 1.022]*
1D1N	**1.031 [1.023, 1.039]***	**1.017 [1.009, 1.025]***	**1.028 [1.020, 1.037]***	**1.018 [1.009, 1.026]***	**1.036 [1.028, 1.045]***	**1.026 [1.018, 1.034]***	**1.025 [1.017, 1.033]***	**1.018 [1.010, 1.026]***
2D1N	1.003 [0.979, 1.027]	1.018 [0.994, 1.042]	0.984 [0.961, 1.008]	0.966 [0.943, 0.989]	1.057 [1.033, 1.081]*	1.043 [1.019, 1.067]*	0.991 [0.968, 1.015]	1.011 [0.987, 1.035]
2D2N	**1.036 [1.021, 1.050]***	**1.024 [1.010, 1.038]***	**1.017 [1.003, 1.031]***	**1.025 [1.011, 1.039]***	**1.023 [1.009, 1.037]***	**1.048 [1.034, 1.062]***	**1.042 [1.028, 1.056]***	**1.022 [1.008, 1.036]***
3D2N	1.013 [0.989, 1.037]	1.015 [0.992, 1.040]	0.988 [0.964, 1.011]	1.075 [1.051, 1.100]*	1.058 [1.034, 1.083]*	1.004 [0.981, 1.028]	1.009 [0.986, 1.034]	1.002 [0.978, 1.026]
3D3N+	0.992 [0.972, 1.011]	1.006 [0.987, 1.026]	1.043 [1.024, 1.064]*	0.996 [0.976, 1.015]	0.970 [0.951, 0.990]	0.956 [0.937, 0.975]	0.969 [0.950, 0.989]	0.982 [0.963, 1.001]

Table 3 Incidence rate ratio (IRR) of heat events for men aged 65 or above. Asterisk (*) indicates significant results with IRR, upper confidence interval (UCI), and lower confidence interval (LCI) higher than 1.00. Bold black text indicates heat event with significant immediate impact within 1-day window; bold brown text indicates heat event with significant immediate impact within 4-day window; bold orange text indicates heat event with significant immediate impact within 8-day window. Green and blue highlight indicate heat events with fairly underestimated risk and extremely underestimated risk due to maladaptive behaviour, respectively

Men (Age ≥65)	Long-term Impact							
	Short-term impact							
	Immediate Impact							
Heat Event	Lag 0	Lag 1	Lag 2	Lag 3	Lag 4	Lag 5	Lag 6	Lag 7
1D	**1.018 [1.008, 1.028]***	0.987 [0.977, 0.997]	0.994 [0.984, 1.004]	1.012 [1.002, 1.022]*	1.003 [0.993, 1.013]	0.988 [0.978, 0.998]	1.015 [1.005, 1.025]*	1.019 [1.009, 1.029]
1D1N	**1.017 [1.004, 1.029]***	1.000 [0.988, 1.013]	1.021 [1.008, 1.034]*	1.010 [0.997, 1.023]	1.013 [1.001, 1.026]*	1.031 [1.018, 1.044]*	1.023 [1.010, 1.036]*	1.017 [1.004, 1.030]*
2D1N	0.975 [0.940, 1.011]	0.998 [0.962, 1.034]	1.006 [0.971, 1.043]	0.968 [0.934, 1.004]	1.026 [0.991, 1.063]	1.036 [1.000, 1.073]*	0.972 [0.938, 1.008]	1.004 [0.969, 1.040]
2D2N	**1.033 [1.012, 1.056]***	1.030 [1.009, 1.051]*	0.999 [0.978, 1.020]	1.031 [1.010, 1.052]*	1.014 [0.993, 1.035]	1.079 [1.057, 1.101]*	1.032 [1.011, 1.054]*	1.040 [1.019, 1.062]*
3D2N	0.977 [0.942, 1.013]	1.034 [0.998, 1.071]	0.989 [0.954, 1.025]	1.042 [1.006, 1.079]*	1.051 [1.015, 1.089]*	0.992 [0.957, 1.028]	1.014 [0.978, 1.051]	1.005 [0.969, 1.042]
3D3N+	0.974 [0.945, 1.003]	0.960 [0.932, 0.990]	1.021 [0.992, 1.051]	0.982 [0.953, 1.011]	0.980 [0.951, 1.010]	0.949 [0.921, 0.979]	0.942 [0.914, 0.972]	0.942 [0.914, 0.971]

The heat events with an immediate impact on women aged 65 or above were 1D, 1D1N, and 2D2N (Table 4), with IRRs of 1.015 [1.005, 1.025], 1.014 [1.002, 1.026], and 1.065 [1.044, 1.086], respectively. However, only 2D2N could meet the requirement for both short-term and long-term impact. The variation of long-term impact of 2D2N on emergency admissions among women aged 65 or above ranged from 3.3 to 6.8%.

Results: perspectives of disaster preparedness and adaptive behaviours

Based on the results, men may underestimate their personal risk from the heat effect, especially those aged 19–64.

In general, men aged 19–64 (Table 1) extremely underestimated the risk from 1D during lag days 3–7, with

Table 4 Incidence rate ratio (IRR) of heat events for women aged 65 or above. Asterisk (*) indicates significant results with IRR, upper confidence interval (UCI) and lower confidence interval (LCI) higher than 1.00. Bold black text indicates heat event with significant immediate impact within 1-day window; bold brown text indicates heat event with significant immediate impact within 4-day window; bold orange text indicates heat event with significant immediate impact within 8-day window. Green and blue highlight indicate heat events with fairly underestimated risk and extremely underestimated risk due to maladaptive behaviour, respectively

Women (Age ≥ 65)	Long-term Impact							
	Short-term impact							
	Immediate Impact							
Heat Event	Lag 0	Lag 1	Lag 2	Lag 3	Lag 4	Lag 5	Lag 6	Lag 7
1D	**1.015 [1.005, 1.025]***	0.990 [0.980, 1.000]	0.992 [0.983, 1.002]	1.013 [1.003, 1.023]*	1.013 [1.003, 1.023]*	0.998 [0.988, 1.007]	1.010 [1.001, 1.020]*	1.016 [1.006, 1.026]*
1D1N	**1.014 [1.002, 1.026]***	0.996 [0.984, 1.009]	1.007 [0.995, 1.019]	1.015 [1.003, 1.027]*	1.020 [1.008, 1.032]*	1.022 [1.009, 1.034]*	1.018 [1.006, 1.031]*	1.016 [1.004, 1.029]*
2D1N	1.003 [0.968, 1.038]	1.026 [0.991, 1.063]	1.026 [0.991, 1.062]	0.997 [0.963, 1.033]	1.047 [1.012, 1.084]*	1.018 [0.983, 1.053]	0.983 [0.949, 1.018]	1.008 [0.973, 1.044]
2D2N	**1.065 [1.044, 1.086]***	**1.037 [1.016, 1.058]***	**1.043 [1.022, 1.064]***	**1.038 [1.017, 1.059]***	**1.033 [1.012, 1.054]***	**1.068 [1.047, 1.089]***	**1.044 [1.023, 1.065]***	**1.061 [1.040, 1.082]***
3D2N	1.011 [0.976, 1.046]	1.052 [1.016, 1.089]*	1.017 [0.982, 1.053]	1.066 [1.030, 1.102]*	1.034 [0.999, 1.070]	1.001 [0.966, 1.037]	1.017 [0.982, 1.053]	1.004 [0.970, 1.040]
3D3N+	0.988 [0.960, 1.017]	0.985 [0.957, 1.014]	1.020 [0.991, 1.050]	0.997 [0.969, 1.026]	1.005 [0.977, 1.034]	0.981 [0.952, 1.010]	0.979 [0.951, 1.008]	0.954 [0.927, 0.983]

IRRs of 1.015 [1.008, 1.022], 1.017 [1.010, 1.024], 1.024 [1.017, 1.031], 1.026 [1.019, 1.033], and 1.030 [1.023, 1.037], respectively. Men aged 19–64 may also have extremely underestimated the risk from 2D1N during lag days 4–6, 2D2N during lag days 5–7, and 3D2N during lag days 3–5. Specifically, 2D1N and 3D2N had a high impact on emergency admissions. During lag days 3—5 of 3D2N, IRR values were 1.113 [1.087, 1.140], 1.061 [1.035, 1.087], 1.069 [1.043, 1.095], respectively, and for lag day 4 of 2D1N, IRR values were 1.106 [1.080, 1.133], 1.060 [1.034, 1.086], and 1.070 [1.044, 1.096], respectively.

We also found extremely underestimated risk from 1D1N and 2D2N among men aged 65 or above, as well as a fairly underestimated risk of 3D2N. Specifically, 2D2N and 3D2N had a high impact; for lag days 5–7 of 2DN2, IRR values were 1.079 [1.057, 1.101], 1.032 [1.011, 1.054], and 1.040 [1.019, 1.062], respectively, and for lag days 3–4 of 3D2N, IRRs were 1.042 [1.006, 1.079] and 1.051 [1.015, 1.089], respectively.

Compared to men, only 1D contributed to extremely underestimated risk among women aged 19–64 and fairly underestimated risk among women aged 65 or above, 3D2N contributed to fairly underestimated risk among women aged 19–64, and 1D1N contributed to extremely underestimated risk among women aged 65 or above. Except the high impact of 3D2N on women aged 19–64 during lag days 3–4, with IRRs of 1.075 [1.051, 1.100] and 1.058 [1.034, 1.083], respectively, the impact from other events caused by underestimation of risk were fairly low for women.

Discussion

Implications for heat risk actions and city planning

In this study, we applied a systematic approach to quantify the relationship between temperature and emergency admissions during the summer. Our results show generally higher IRRs for 2D + events than 1D related events. These results are consistent with previous studies, which demonstrated that prolonged heat events contributed more to health risks than a single hot day in Hong Kong (Ho et al. 2017b; Wang et al. 2019). The results are also comparable with findings from nearby cities/regions, such as Guangzhou (Zeng et al. 2014). This indicates the need for heat-health action plans related to local warning systems and adaptive behaviour for disaster preparation in this subtropical city. In addition, one characteristic of our data-driven approach is the stratification of subpopulation data for modelling, which can be used to separately identify vulnerable populations during different types of heat events. Furthermore, the supplementary guidelines on heat awareness along with weather alerts can be changed and updated based on the characteristics of the heat events. Thus, identifying heat events with three levels of impact (immediate, short-term, long-term) can help further enhance heat-related information or early warning services by tailoring different advisories/messages regarding heat awareness for particular vulnerable population groups during events with different impacts.

Therefore, in terms of city-wide planning and heat-health actions, our study can be implemented for two strategic purposes, a heat warning system and enhancement of adaptive behaviours. For a heat warning system, as 1D, 1D1N, and 2D2N heat events show a consistent immediate impact on health risk associated with emergency admissions in Hong Kong, these events should be included as part of the new definitions for local warnings in the future. Considering the existing definitions of heat vulnerability and relatively stable results of cross-sectional ecological analyses, 2D2N would best represent heat events in terms of both short-term and long-term impacts, followed by 1D1N. This priority of heat events can also be reflected by the magnitude of health risk characterized by both short-term and long-term impacts, with generally higher IRRs for 2D2N than 1D1N. Similar results were also found in the comparison of three events regarding immediate impact, in which the cross-sectional ecological analysis generally showed higher IRRs for 2D2N than 1D and 1D1N. With an identifiable impact on emergency admissions, 2D2N is a representative heat event that requires early alerts/advisories and relevant mitigation measures to alleviate the health risks up to the following eight days due to the hazardous exposure of extreme heat.

According to the perspective of adaptive behaviours, we found that men aged 18–64 significantly underestimated their health risks during a time of prolonged heat risk. This is consistent with previous studies demonstrating that young and working adults (Glazer 2005; Kilbourne 1992; Kovats and Hajat 2008; Lefevre et al. 2015) could have severe heat-related illnesses due to prolonged heat and engage in inappropriate physical activity (e.g. vigorous outdoor activity). Therefore, to protect this subpopulation from maladaptive behaviour, stakeholders should provide workshops through community centres to minimize these individuals' over-confidence in "being safe" in hot weather, which could result in a lack of adaptation for heat protection (Lefevre et al. 2015). In addition, multiple channels should be used to deliver messages regarding appropriate adaptive behaviours, especially through the Internet and online messenger services. Previous studies found that young adults are more willing to continue engaging in protective behaviours when they are successfully educated (Lefevre et al. 2015). Furthermore, "channel complementarity theory" suggests that a complementary information-seeking environment that is modernized and has multiple channels can encourage users to obtain health-related information in order to improve their adaptive behaviours (Rains and Ruppel 2016). Based on this, local government agencies (e.g. Hong Kong Observatory, Hospital Authority, Department of Health) should add new channels, such as mobile apps and social media platforms, to deliver information on disaster risk reduction during prolonged heat events to younger men in Hong Kong.

Limitations and future directions

Infants and adolescents were excluded in this study as their emergency admissions were mostly related to infectious diseases, such as hand, foot, and mouth disease (Chan et al. 2000; Hii et al. 2011; Onozuka and Hashizume 2011), which are highly controlled by the community setting (e.g. school). In addition, the bodies of infants and adolescents are in developmental stages, such that their levels of resilience and adaptation to extreme heat are significantly different from those of adults. In order to mitigate the health risk due to extreme hot weather among infants and adolescents, it is necessary to design a specific heat-health warning system for these population groups, using health datasets that include more details (e.g. age subgroups, school settings, time spent in school per day, ICD codes, location of residence) for a comprehensive assessment. Based on the current data obtained from the Hospital Authority of Hong Kong, the level of detail of the dataset is not sufficient to conduct such analyses. Therefore, further studies should be conducted for these two population groups, if more detailed data are available from the Hospital Authority. However, it is also important to mention that disaster preparedness targeted at infants and adolescents should be based on health education, especially to improve knowledge, attitudes, and practices among children, parents, teachers, and caregivers. This is because younger populations, especially infants, have relatively low or minimal ability to obtain proper information from health surveillance systems. Therefore, information disseminated through the heat-health warning system may not be applicable to these younger populations. Based on this assumption, developing a heat-health warning system particularly for adults in Hong Kong is more appropriate.

In addition, one of the aims of our study was to develop a protocol to enhance the heat warning system and heat action plans in Hong Kong. Therefore, we used the definitions of "very hot days" and "hot nights" from the current heat warning plans instead of the definitions commonly used in the other studies, such as 90th or 95th percentile of temperature, for statistical analyses (Kent et al. 2013). Therefore, while our data-driven analysis can be used as a test case for a conceptual framework that may be applicable to other cities, heat wave definitions should be adjusted to the local setting before developing a specific model.

Finally, we conducted an ecological cross-sectional analysis restricted only in the summer using a Poisson regression, instead of using time-series analysis with a distributed lag nonlinear model (DLNM) to estimate the temperature effect on emergency admissions. This is because in our epidemiological design the interference of the cold effect from modelling can be left out, while DLNM must include both hot and cold effects to find the minimum temperature associated with elevated mortality for further analysis. Since the influence of cold weather on emergency admissions and other health outcomes across Hong Kong is quite different from the heat effect (Chan et al. 2013; Thach et al. 2015), especially sudden cold waves that caused severe disease outbreaks in the past (Ho et al. 2020; Qiu et al. 2016), our study, which restricts the model design to only summer, may be more appropriate. For future studies in other cities/countries, a sensitivity analysis to compare the results from ecological cross-sectional and time-series studies may be needed.

Conclusions

In this study, we developed a data-driven approach to systematically identify representative heat events that have a significant public health impact. Based on the scenario of Hong Kong, we identified that 1D, 1D1N, and 2D2N heat events make a notable contribution to the immediate impact on emergency admissions, while 1D1N and 2D2N contribute to both short-term and long-term impacts in continuous 4-day and 8-day windows. In terms of heat vulnerability, 2D2N as a heat event has the greatest impact. This was confirmed by the magnitude of health risk estimated based on IRR. Therefore, we conclude that 2D2N should be the heat event of particular concern when exploring further enhancement of heat-health related information services and mitigation measures in Hong Kong, given the highest priority indicated by the results. In addition, men aged 19 to 64 had the highest underestimated risk, especially during lag days 3–5 of 3D2N, possibly due to maladaptive behaviour. Therefore, stakeholders should provide workshops through community centres and multiple channels (e.g. social media) to minimize their overconfidence in "being safe" in hot weather, which could result in a lack of adaptation for heat protection. Finally, following a data-driven approach to estimate the health impacts from various extreme heat events, this framework not only is applicable to Hong Kong to enhance relevant heat-health related information and early warning services, but could also be applied to other cities where health data with a similar structure are available for systematic identification.

Acknowledgements We acknowledge the partial support from Research Impact Fund 2018−19, Hong Kong Research Grants Council (Ref No: R4046-18, Title: Increasing the Resilience to the Health Impacts of Extreme Weather on Older People under Future Climate Change) and Guangdong Natural Science Fund (Project code: 2021A1515012571).

Author contribution HCH developed the contextual design, conducted the data analysis, and wrote the draft of manuscript. KL provided insights on urban climate. DW provided insights on public health. CR provided financial support. All authors approved the final version of the manuscript.

Funding The study was partially supported by the Vice-Chancellor's Discretionary Fund of the Chinese University of Hong Kong. It was also partially supported by General Research Fund Project Grant 2017/18 (Project No. RGC-GRF 14611517, "Climatic-responsive planning and action for mitigating heat-related health risk at community level in high density cities– A Case of Hong Kong"), Research Impact Fund 2018/19 (Project No. R4046-18, "Increasing the resilience to the health impacts of extreme weather on elderly people under future climate change") of the Hong Kong Research Grants Council, and Guangdong Natural Science Fund (Project code: 2021A1515012571).

Data availability Data and materials are available upon request.

Declarations

Ethics approval Not applicable.

Consent to participate Not applicable.

Consent for publication Not applicable.

Competing interests The authors declare no competing interests.

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