Urban Climate 59 (2025) 102240

Contents lists available at ScienceDirect

Urban Climate

journal homepage: www.elsevier.com/locate/uclim

Ambient temperature-related attributable risk for emergency asthma hospitalizations and length of stay in Hong Kong

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ARTICLE INFO

Keywords:
Ambient temperature
Attributable risk
Emergency asthma hospitalizations
Length of hospital stay
Disease burden
Hospital utilization

ABSTRACT

We aimed to examine the association of ambient temperature with asthma exacerbations and assess the temperature-attributable disease burden changes. Daily count of asthma emergency hospitalizations and corresponding length of hospital stay, daily mean temperature, relative humidity, and air pollution concentrations from 2004 to 2019 in Hong Kong were collected. Time-series quasi-Poisson model integrated with the distributed-lag-nonlinear model was used to examine the relationships of temperature with asthma hospitalizations and length of stay. Measures of the risk attributable to nonoptimal temperature were calculated to summarize the disease burden and hospital utilization for periods of 2004–2011 and 2012–2019, respectively, and compared the temporal changes. Significantly higher risks at cold/cool temperatures for both admission counts and bed-days were found. Around 19.7 % (95 % CI: 14.1–24.3 %) of hospitalization counts and 22.6 % (95 % CI: 15.5–28.4 %) of bed-days were attributed to ambient temperature, which mainly occurred on cold and cool days. Compared with the early period of 2004–2011, the cold temperature-related attributable fraction in 2012–2019 decreased from 11.0 % to 8.9 % ($p = 0.005$) for admission counts but increased from 10.8 % to 12.6 % ($p = 0.003$) for bed-days. Hospital utilization and expenditure due to the longer hospital stays during cold days would play an adverse role in the healthcare system.

1. Introduction

Asthma is one of the most common chronic non-communicable diseases worldwide, characterized by airway inflammation and airflow obstruction. The prevalence of asthma varies widely across countries, with higher prevalence rates in developed countries and

Abbreviations: AIC, Akaike information criterion; AF, attributable fraction; AN, attributable number; AR, attributable risk; CI, confidence interval; DLNM, distributed lag nonlinear model; DOW, day of the week; GAM, generalized additive model; HA, hospital authority; ICD-9, ninth revision of the International Classification of Diseases; NO2, nitrogen dioxide; MMT, minimum morbidity-related temperature; O3, ozone; PM2.5, particulate matter with an aerodynamic diameter less than or equal to 2.5 μm; RH, relative humidity; RR, relative risk.

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https://doi.org/10.1016/j.uclim.2024.102240
Received 20 June 2024; Received in revised form 4 December 2024; Accepted 7 December 2024
Available online 18 December 2024

lower rates in developing countries, ranging from 0.2 % in China to 21 % in Australia (Papi et al., 2018). While in Hong Kong, according to the health status report of a territory-wide household survey in 2014, about 68,000 persons (or 1.0 % of the total population) had asthma attacks (HKCSD, 2015). The determinates associated with asthma prevalence may include heredity, viral infections, obesity, genetic predisposition, gender (before puberty), exposure to allergens, tobacco smoke and air pollution, socioeconomic status, and occupational exposures (in adults), etc. (Porsbjerg et al., 2023). Severe asthma exacerbations, inadequate response to outpatient treatment, and asthma cases with severe complications should be admitted to hospitalizations. The length of hospital stay may vary from case to case and be determined by the healthcare team based on the individual patient's needs and response to treatment. Asthma-related expenditure has continued to increase, the majority of which come from emergency care and severe complications or comorbidities (Porsbjerg et al., 2023).

There is plenty of evidence in the literature on the associations of environmental and meteorological factors with asthma exacerbations, including pollen (De Roos et al., 2020; Lappe et al., 2023; Smith et al., 2022), air pollution (Leung et al., 2021; Sharma et al., 2023; Zhang et al., 2016), temperature variation within one day or between neighboring days (Kim et al., 2014; Lee et al., 2019; Qiu et al., 2015; Wu et al., 2021), extreme cold and hot temperatures (Chen et al., 2022; Fitzgerald et al., 2014; Han et al., 2023; O'Lenick et al., 2017), humidity, wind speed, and barometric pressure (Lam et al., 2016; Zhang et al., 2020). The outcomes in these studies mainly focused on asthma morbidity such as hospital admissions and emergency department visits, only one study looked at the length of hospital stay which is a better indicator to denote hospital utilization and expenditure (Wu et al., 2021). Furthermore, few studies assessed the attributable risk and its potential temporal variation of environmental exposures to respiratory diseases (Lu et al., 2020; Sun et al., 2019), especially focused on asthma exacerbations (Wu et al., 2021).

Hong Kong, located on the southeastern coast of China, has a subtropical climate with hot and humid summer and mild cold winter, bringing apparent seasonal variations in ambient temperature. Hong Kong is one of the most densely populated regions in the world, with over 7.5 million residents in a 1104-square-kilometre territory. Hong Kong has a well-developed healthcare system that provides accessible and high-quality medical services to its residents and is known for its efficiency, advanced medical technology, and high standards of care (Jasser, 2023). The government continually invests in healthcare infrastructure and strives to ensure that its residents have access to quality healthcare services (HKGOV, 2014).

In the current study, we took advantage of daily routinely collected data on environmental exposures from the fixed monitoring stations and hospital admission records abstracted from the Hospital Authority (HA) Corporate Data Warehouse to examine the associations of ambient cold and hot temperatures with asthma hospitalizations and length of hospital stays using a 16 years' time-series approach. We further assessed the risk of asthma exacerbation attributed to ambient temperature and its potential temporal changes. We hypothesized a significant association of cold temperature with asthma hospitalizations and bed-days, and the temperature-related attributable risk may vary over early and late periods. Findings from the current study may provide information for the government to understand the asthma disease burden special from the ambient cold temperature and design strategies to improve healthcare utilization.

2. Materials and methods

2.1. Data collection

2.1.1. Hospital admission data

We obtained the daily number of hospital admissions through Accident & Emergency Services and the corresponding length of hospital stay from January 1, 2004, to December 31, 2019. We focused on the principal diagnosis of asthma using the Ninth Revision of the International Classification of Diseases code 493 (ICD-9: 493), which was abstracted from the Hospital Authority (HA) Corporate Data Warehouse. The length of hospital stay was calculated from the date of admission to the date of discharge or death for each inpatient. The daily bed-days represented the aggregated number of stays by all cases admitted on the same day, while the latter was defined as the daily admission counts. The admission records were sourced from publicly funded hospitals, which provide 24-h accident and emergency services. The public hospitals under the HA manage approximately 80 % of all hospital admissions, and their contribution to the total number of bed-days approaches 90 % (HKGOV, 2016). Daily numbers of admissions for influenza (ICD-9: 487) were also abstracted and used to identify influenza epidemics which were treated as a potential confounding factor in the subsequent data analysis (Qiu et al., 2016; Xiong et al., 2023). Considering the potential influence of the population change during the study period, we also obtained the mid-year population size from the Census and Statistics Department of Hong Kong. Given that our study solely utilized aggregated data and did not involve individualized information, ethical approval and consent from individual subjects were waived.

2.1.2. Meteorological and environmental data

We collected data on the daily mean temperature and relative humidity (RH) between January 1, 2004, and December 31, 2019, sourced from the Hong Kong Observatory. Extreme cold or hot weather was defined as a daily mean temperature falling below the 1st percentile or exceeding the 99th percentile of the temperature distribution during the study period (Chen et al., 2013). Cold or hot days were defined as daily mean temperatures lower than the 25th percentile or higher than the 75th percentile. Meanwhile, we obtained the air pollution concentrations during the same period from the Hong Kong Environmental Protection Department. We calculated the daily 24-h mean concentrations of particulate matter with an aerodynamic diameter less than or equal to 2.5 μm ($PM_{2.5}$) and nitrogen dioxide (NO_2), as well as ozone (O_3) from each pollutant monitoring station and then averaged them across the 10 general monitoring stations (Qiu et al., 2016). Air pollutants were considered potential confounding factors in the subsequent data analysis as previous studies have demonstrated their associations with emergency asthma hospitalizations in Hong Kong (Ko et al., 2007; Lee et al., 2006) and in other regions (Zhang et al., 2016).

2.2. Statistical methods

2.2.1. Statistical model

This is a time-series analysis of the population level. The generalized additive quasi-Poisson model (GAM) integrated with the distributed lag nonlinear model (DLNM) was used to examine the association of ambient temperature with emergency asthma hospitalizations after adjusting the time-varying confounders (Gasparrini, 2011, 2014). The potentially lagged and nonlinear association between temperature and asthma hospitalization was explored by including a *crossbasis* function for temperature in the model and the cumulative temperature exposure over multiple days was assessed.

Specifically, in the DLNM part, we constructed a *crossbasis* function for temperature exposure using a natural cubic spline with 4 internal knots placed at equal spaces in the temperature range, and a natural cubic spline with 3 internal knots placed at equally spaced values in the log scale of the lags (Guo et al., 2011). The number of knots for both exposure and lag was selected by the lowest Akaike information criterion (AIC). We extended the lag period to 21 days to capture the long delay in the effects of cold and adequately assess the hot effects after excluding emergency hospitalizations advanced only by a harvesting effect (Qiu et al., 2016).

In the GAM part, we included a natural cubic spline of time with 8 degrees of freedom (df) per year to control for long-term trends and seasonality, a natural cubic spline of RH with 3 dfs, and dummy variables for day of the week (DOW), public holidays, influenza epidemics, and an offset term of the logarithm of mid-year population size to control for these time-varying confounders (Peng et al., 2006). Air pollutants ($PM_{2.5}$, NO_2, and O_3) were controlled by including third-degree constrained polynomial distributed lags with a maximum lag of 3 days (Qiu et al., 2016). The autocorrelation of the residuals of the model was checked by the residual plot and partial autocorrelation function (Costa et al., 2017).

2.2.2. Minimum morbidity-related temperature and temperature-related relative risk

We defined the minimum morbidity-related temperature (MMT) as the temperature corresponding to a minimum risk of asthma hospitalization. The MMT was determined based on the threshold model and the exposure-response curves. We employed a threshold model with the threshold ranging from 22 and 30 °C at intervals of 0.1 °C, and selected the model with the lowest residual deviance (Guo et al., 2011). Subsequently, the identified MMT was used as the reference point to re-center the natural cubic spline which captured the non-linear effects of temperature. We estimated the cold and hot temperature-related asthma risk by computing the relative risks (RRs) with comparison to the MMT. Specifically, we computed the RR of asthma hospitalization on extremely cold (1st percentile of the temperature distribution), cold (10th percentile), cool (25th percentile), and extremely hot (99th percentile) days compared with the MMT. Besides the cumulative RRs over 0–21 lag days, we also estimated temperature effects during the lag periods of 0–6, and 7–21 to represent the short-term and delayed effects, respectively.

2.2.3. Temperature-related attributable risk

Temperature-related attributable risks for asthma hospitalization were computed from the overall cumulative RR corresponding to each day's temperature, using the approach previously described by Gasparrini and Leone (Gasparrini and Leone, 2014) and commonly used in the scientific community (Gasparrini et al., 2015b; Qiu et al., 2016; Tian et al., 2016; Yang et al., 2015) that summarized the disease burden due to the temperature exposures. The total attributable number (AN) of hospitalizations due to non-MMT was given by the sum of the contributions from all of the days in the series, and its ratio with the total number of hospitalizations provided the total temperature-related attributable fraction (AF). We also computed the components attributable to cold and hot weather by summing the corresponding days with temperatures lower than the 25th percentile or higher than the 75th percentile, respectively. The empirical confidence intervals (CIs) for AF and AN were estimated through Monte Carlo simulations by simulating 5000 samples from a multivariate normal distribution of the coefficients (Gasparrini and Leone, 2014).

2.2.4. Two periods comparison

We divided the entire time series into two equal-length periods, 2004–2011 as the early period and 2012–2019 as the late period, and applied the same analytic models for each period, respectively. We compared the temperature-related RR and AF in two periods using a significance test (Zeka et al., 2006) and explored the potential changes.

2.2.5. Sensitivity analysis

We applied the time-varying DLNM (Gasparrini et al., 2015a) as a sensitivity analysis to estimate the yearly-specific temperature-related AF to explore the potential temporal fluctuations during the study period. Time-varying DLNM was applied by adding an interaction term between time (centered on 1st July, the middle day of each corresponding year) and the created *crossbasis* term of temperature to estimate the yearly-specific association of temperature with asthma hospitalizations or bed-days (Gasparrini et al., 2015a) (Lu et al., 2020). Then the yearly-specific temperature-related AF based on this time-varying DLNM can be estimated. A detailed description and application of this approach has been published elsewhere (Gasparrini et al., 2015a, 2016; Sun et al., 2019). The temporal trend of the yearly-specific AF was examined through the Mann-Kendall Trend Test (Wang et al., 2021).

All analyses were conducted in R, version 4.3.0 (R Development Core Team, Vienna, Austria, 2023). We used the "*dlnm*" package (Gasparrini, 2011) to fit the distributed-lag-nonlinear model and the updated version of "*attrdl*" function created by Gasparrini (Gasparrini, 2017) to calculate the attributable risk measures of AF and AN.

3. Results

In this 16-year time-series analysis, we included a total of 245,333 emergency hospital admissions for asthma and the corresponding length of stay of 367,070 bed-days, resulting in an average of 1.5 bed-days for each asthma inpatient. Table 1 shows the daily number of emergency asthma hospitalization counts, length of hospital stays, weather conditions, and air pollution concentrations in the two periods of 2004–2011 and 2012–2019, respectively. As there were some extremely large values in the length of hospital stay due to several chronic refractory patients, the top 1 % values in bed-days were excluded from the analyses. The daily admission counts increased from 40.5 to 43.5 while the length of hospital stay increased from 59.3 to 62.9 bed-days. The daily mean temperature increased a bit from 23.4 to 23.8 °C. Due to the clean air action, the daily mean concentrations of $PM_{2.5}$ and NO_2 had a distinct reduction of 13.7 and 8.0 μg/m^3, respectively, however, the O_3 concentration had a notable increase of 10.2 μg/m^3 (Table 1). The time-series plot shows the temporal variation of the asthma hospitalization counts and bed-days (Fig. 1). The distribution of the ambient temperature exposure for the two periods is shown in Fig. 2.

The MMT was identified as 28.6 °C for both admissions counts and bed-days, corresponding to the 82nd percentile in the temperature during 2004–2011 and the 77th percentile for 2012–2019. The cumulative temperature exposure-response curves showed non-linear relationships and significantly higher RRs on cold and cool days (Fig. 3). The temperature-related RR of asthma emergency hospitalization at the 1st, 10th, 25th, and 99th percentiles (comparing to the MMT of 28.6 °C) over the 0–21 lag days revealed that the risk associated with significant cold appeared at the first week and lasted for 2–3 weeks, whereas the risk associated with hot weather was not apparent and approached null. The overall cumulative relative risks of cold temperature distributed over the 0–21 lag days (P_{10} vs. MMT) was reduced from 1.55 (95 % CI: 1.23–1.95) in 2004–2011 to 1.42 (95 % CI: 1.12–1.79) in 2012–2019 for admission counts. The corresponding RRs for bed-days had a bit increase from 1.50 (95 % CI: 1.11–2.04) to 1.69 (95 % CI: 1.25–2.28), though these RR differences between the two periods were statistically non-significant (Table 2).

Table 3 shows the estimations for total temperature-related AF and AN for asthma emergency hospitalizations and length of stay, which mainly occurred on cold days rather than hot days. The cold days with temperatures in the lower quartile accounted for around half of the total temperature-related AF and AN, while we did not observe the statistically significant attributable risk from the hot days with temperatures in the upper quartile. During the entire period, 19.7 % (95 % CI: 14.1–24.3 %) of hospitalization counts and 22.6 % (95 % CI: 15.5–28.4 %) of bed-days were attributed to ambient temperature. Meanwhile, a daily average number of 8.3 (95 %CI: 5.9–10.2) admission counts and 13.7 (95 % CI: 9.4–17.2) bed-days were attributed to temperature. Compared with the earlier period of 2004–2011, the total temperature-related AF in 2012–2019 decreased from 22.3 % (95 % CI: 14.1–28.9 %) to 17.7 % (95 % CI: 9.4–24.5) for emergency hospitalization counts but increased from 21.9 % (95 %CI: 10.4–30.8) to 24.5 % (95 %CI: 15.4–31.9 %) for bed-days. Among them, the cold temperature-related AF decrease for admission count (from 11.0 % to 8.9 %, $p = 0.005$) and increase for bed-days (from 10.8 % to 12.6 %, $p = 0.003$) were statistically significant (Table 3). The daily average temperature-related AN decreased from 9.0 (95 %CI: 5.7–11.7) in 2004–2011 to 7.7 (95 %CI: 4.1–10.7) in 2012–2019 for admission counts but increased from 12.9 (95 %CI: 6.1–18.1) in 2004–2011 to 15.2 (95 %CI: 9.5–19.8) in 2012–2019 for bed-days (Table 3).

Sensitivity analysis using the time-varying DLNM estimated the yearly-specific temperature-related AF along the entire period from 2004 to 2019, showing a consistently decreasing temporal trend of cold temperature-related AF for emergency asthma hospitalization

Table 1
Daily Numbers of Emergency Hospital Admissions for Asthma, Weather Conditions, and Air Pollution Concentrations in Hong Kong, in Two Periods of 2004–2011 and 2012–2019, respectively.

	Mean (SD)	P_1	P_{25}	P_{50}	P_{75}	P_{99}
Period of 2004–2011						
Asthma emergency hospitalizations (per day)						
Admission counts	40.5 (12.3)	15	33	39	48	72
Bed-days	59.3 (21.4)	20	44	58	72	117
Weather conditions						
Mean temperature (°C)	23.4 (5.2)	11.0	19.3	24.6	27.8	30.6
Relative humidity (%)	77.9 (10.5)	45	73	79	85	96
Pollution concentration (μg/m^3)						
$PM_{2.5}$	38.0 (22.5)	9.0	19.5	33.8	50.7	105.2
NO_2	56.7 (20.0)	24.2	41.8	54.0	68.2	113.7
O_3	55.7 (30.2)	12.2	29.3	52.3	75.0	140.5
Period of 2012–2019						
Asthma emergency hospitalizations (per day)						
Admission counts	43.5 (12.2)	18	36	42	51	72
Bed-days	62.9 (21.4)	23.8	47	61	76	121
Weather conditions						
Mean temperature (°C)	23.8 (5.2)	11.8	19.5	25.0	28.3	30.8
Relative humidity (%)	78.8 (10.2)	46	74	79	86	96
Pollution concentration (μg/m^3)						
$PM_{2.5}$	24.3 (14.9)	5.9	13.1	21.0	31.0	74.8
NO_2	48.7 (17.1)	20.6	36.5	46.1	57.4	103.4
O_3	65.9 (36.3)	14.6	35.6	60.0	87.7	174.4

Abbreviations: $PM_{2.5}$, particulate matter with an aerodynamic diameter less than or equal to 2.5 μm; NO_2, nitrogen dioxide; O_3, ozone; SD, standard deviation; Px, the xth percentile.

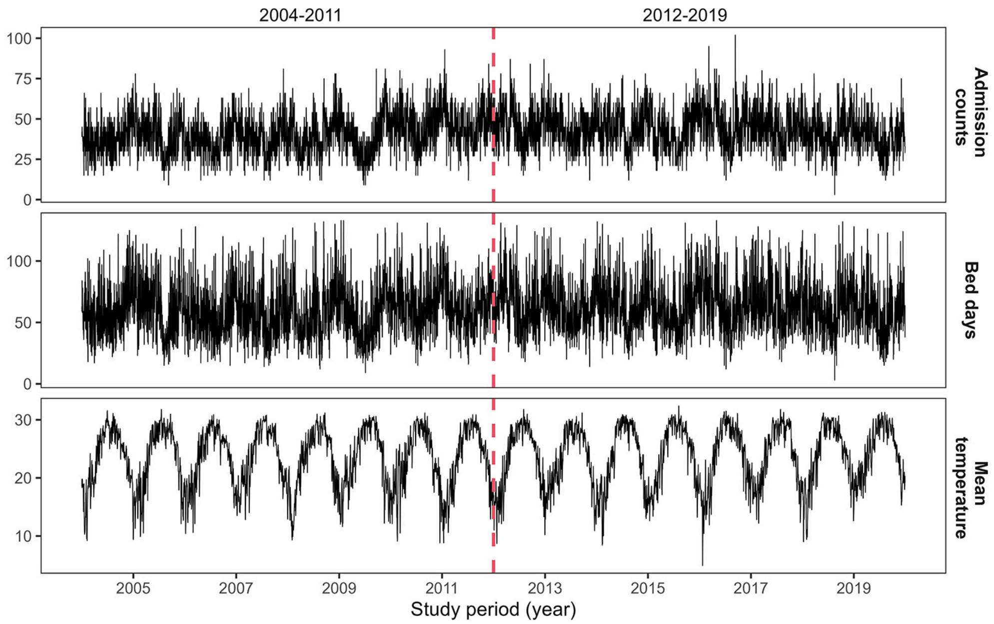

Fig. 1. Time-series plot of the daily asthma emergency hospital admission counts, bed-days, and daily mean temperature (°C) in Hong Kong, 2004–2019.

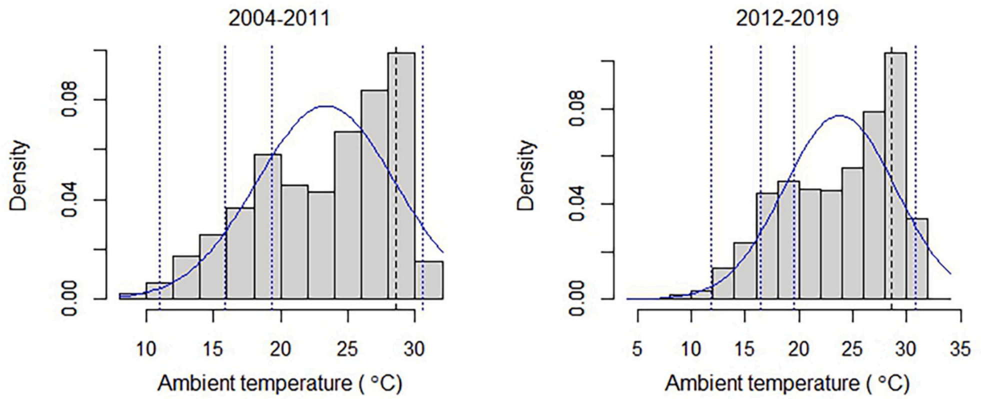

Fig. 2. Distribution of ambient temperature in the period of 2004–2011 and 2012–2019, respectively.
Notes: The 4 vertical dashed lines from left to right represent the 1st, 10th, 25th, and 99th percentile of ambient temperature, and the bold vertical dashed line represents the minimum morbidity-related temperature (MMT) at 28.6 °C which corresponds to a minimum number of emergency hospitalizations for asthma.

counts (p = 0.003), and an increasing temporal trend of total and cold temperature-related AF for length of stay over time ($p < 0.001$ and $p = 0.008$ respectively) (Fig. 4).

4. Discussion

In the current study, we demonstrated significant associations of ambient extreme cold, cold, and cool but not hot temperatures with both emergency asthma hospitalization count and length of hospital stay. Around 19.7 % of hospitalization counts and 22.6 % of bed-days were attributed to ambient temperature. A bit decreased trend of cold temperature-related AF for hospitalization counts was observed, as well as a significantly increased trend of total and cold temperature-related AF for length of hospital stay over the study period from 2004 to 2019.

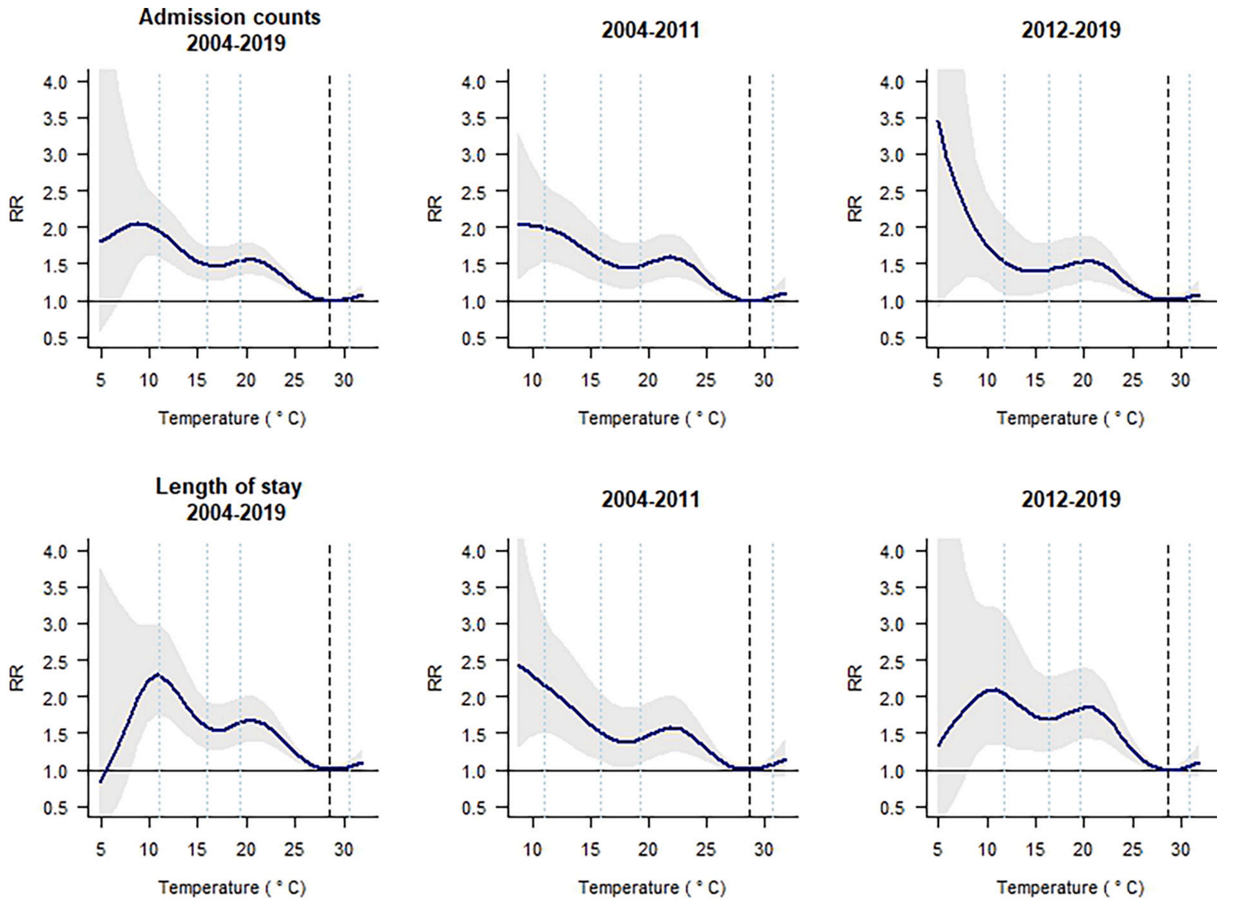

Fig. 3. Association between cumulative temperature exposures over 0–21 lag days and emergency hospitalizations for asthma in different periods in Hong Kong, centering at 28.6 °C (dashed line in black).
Notes: The 4 vertical dashed lines in light blue from left to right represent the 1st, 10th, 25th, and 99th percentile of ambient temperature. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.1. Association of ambient temperature with asthma exacerbation

There is plenty of evidence in the literature demonstrating the significant association of asthma exacerbations with short-term temperature changes (Kim et al., 2014; Lee et al., 2019; Qiu et al., 2015), or extreme cold and hot temperatures (Chen et al., 2022; Fitzgerald et al., 2014; Han et al., 2023; O'Lenick et al., 2017). Consistent with the effect estimates for the extreme cold temperature reported in the previous studies, we also observed the adverse associations of milder cold and cool weather with asthma hospitalizations in the current study, expanding our understanding of cold weather in the etiology of asthma. The underlying biological mechanisms behind the association between cold exposure and asthma exacerbations should include inflammatory mechanisms, in which the regulatory role of immunological pathways and transient receptor potential ion channels in asthma triggered by extreme temperatures has been highlighted (Han et al., 2023). However, we could not find a significant effect estimate for the extremely hot temperature which may probably be due to the extensive use of air conditioning in such hot and humid summers in Hong Kong. Air conditioning has been proven as a modifiable factor, and people may adapt to extreme heat through increased use of air conditioning (Huang et al., 2011).

4.2. Temperature-related attributable risk for asthma hospitalizations

The MMT corresponding to the minimal asthma hospitalizations identified in Hong Kong is 28.6 °C, which is a bit higher than that observed in other places, for instance, 22 °C in Beijing, China (Chen et al., 2022), and similar to 27.4–30.5 °C for minimum cause-specific cardiovascular hospitalizations in Japan (Pan et al., 2023). A higher prevalence of air conditioners used in Hong Kong than in mainland China may make the people living in Hong Kong better adapted to hot weather conditions (Dewolf, 2021; Pan et al., 2023). We observed 19.7 % of asthma hospitalizations that can be attributed to non-optimal temperature, among which 10.4 % was attributed to cold temperatures lower than the 25th percentile. These fractions were a bit lower than the results from the only one similar study conducted in Beijing, China, which used data collected from 2012 to 2015 and demonstrated that 29.1 % of adult asthma

Table 2
Relative Risk (RR with 95 % CI) of Emergency Hospitalization for Asthma Associated with Cold and Hot Ambient Temperatures in Hong Kong, in Two Periods of 2004–2011 and 2012–2019, respectively. [a]

Temperature-related relative risk	Extreme Cold [b]	Cold [c]	Cool [d]	Extreme Hot [e]
Period of 2004–2011				
Admission counts				
Lags 0–6	1.58 (1.39, 1.81)	1.35 (1.21, 1.52)	1.33 (1.19, 1.47)	1.03 (0.98, 1.10)
Lags 7–21	1.26 (1.03, 1.54)	1.14 (0.97, 1.35)	1.11 (0.95, 1.29)	1.01 (0.94, 1.09)
Lags 0–21	1.99 (1.51, 2.62)	1.55 (1.23, 1.95)	1.47 (1.20, 1.81)	1.05 (0.94, 1.16)
Bed-days				
Lags 0–6	1.68 (1.41, 2.00)	1.38 (1.19, 1.61)	1.33 (1.16, 1.52)	1.03 (0.95, 1.11)
Lags 7–21	1.29 (0.99, 1.68)	1.09 (0.87, 1.36)	1.07 (0.88, 1.31)	1.03 (0.93, 1.15)
Lags 0–21	2.17 (1.51, 3.11)	1.50 (1.11, 2.04)	1.43 (1.09, 1.87)	1.06 (0.93, 1.21)
Period of 2012–2019				
Admission counts				
Lags 0–6	1.15 (0.99, 1.34)	1.19 (1.07, 1.33)	1.20 (1.09, 1.33)	1.07 (1.01, 1.13)
Lags 7–21	1.32 (1.03, 1.68)	1.18 (1.00, 1.41)	1.27 (1.09, 1.48)	0.98 (0.90, 1.05)
Lags 0–21	1.52 (1.09, 2.12)	1.42 (1.12, 1.79)	1.53 (1.24, 1.89)	1.04 (0.94, 1.16)
Bed-days				
Lags 0–6	1.26 (1.04, 1.53)	1.25 (1.09, 1.44)	1.29 (1.14, 1.47)	1.05 (0.98, 1.12)
Lags 7–21	1.61 (1.17, 2.20)	1.35 (1.08, 1.69)	1.42 (1.17, 1.73)	1.00 (0.91, 1.11)
Lags 0–21	2.03 (1.32, 3.12)	1.69 (1.25, 2.28)	1.83 (1.40, 2.40)	1.05 (0.92, 1.20)

Abbreviations: CI, confidence interval; RR, relative risk.
[a] All RRs were estimated from the distributed-lag nonlinear model integrated with quasi-Poisson regression, comparing with the minimum morbidity-related temperature (MMT) of 28.6 °C.
[b] The 1st percentile of temperature (11.0 °C in 2004–2011 and 11.8 °C in 2012–2019).
[c] The 10th percentile of temperature (15.9 °C in 2004–2011 and 16.4 °C in 2012–2019).
[d] The 25th percentile of temperature (19.3 °C in 2004–2011 and 19.5 °C in 2012–2019).
[e] The 99th percentile of temperature (30.6 °C in 2004–2011 and 30.8 °C in 2012–2019).

Table 3
Attributable Risk of Emergency Hospitalization for Asthma Associated with Cold and Hot Ambient Temperatures in Hong Kong, in Two Periods of 2004–2011 and 2012–2019, respectively. [a]

Temperature-related attributable risk	Admission counts			Bed-days		
	Entire period 2004–2019	2004–2011	2012–2019	Entire period 2004–2019	2004–2011	2012–2019
AF						
Total [b]	19.72 (14.12, 24.28)	22.25 (14.06, 28.89)	17.73 (9.37, 24.52)	22.61 (15.49, 28.43)	21.89 (10.38, 30.82)	24.53 (14.38, 31.85)
Cold [c]	10.41 (7.21, 13.28)	10.95 (6.07, 14.77)	8.86 (3.91, 12.80) [e]	11.98 (7.84, 15.52)	10.76 (4.10, 15.84)	12.59 (6.69, 16.93) [e]
Hot [d]	0.19 (−0.31, 0.69)	0.21 (−0.41, 0.81)	0.30 (−0.58, 1.24)	0.26 (−0.42, 0.89)	0.31 (−0.56, 1.07)	0.33 (−0.85, 1.34)
AN (daily average)						
Total [b]	8.28 (5.93, 10.19)	9.00 (5.69, 11.69)	7.71 (4.08, 10.67)	13.67 (9.37, 17.19)	12.88 (6.11, 18.14)	15.22 (9.54, 19.76)
Cold [c]	4.37 (3.02, 5.58)	4.43 (2.45, 5.97)	3.86 (1.70, 5.57)	7.24 (4.74, 9.38)	6.33 (2.41, 9.32)	7.81 (4.15, 10.51)
Hot [d]	0.08 (−0.13, 0.29)	0.09 (−0.17, 0.33)	0.13 (−0.25, 0.54)	0.16 (−0.26, 0.54)	0.18 (−0.33, 0.63)	0.20 (−0.63, 0.83)

[a] The cumulative relative risks over the range of 0–21 lag days (comparing the minimum morbidity-related temperature of 28.6 °C) were used to compute the attributable fraction (AF) and attributable number (AN).
[b] Total AF or AN attributable to ambient temperatures.
[c] Cold was defined as the ambient temperature lower than the 25th percentile.
[d] Hot was defined as the ambient temperature higher than the 75th percentile.
[e] Comparison between two periods, $p < 0.01$.

hospitalizations were attributable to non-optimum temperatures and moderately cold temperatures yielded most (20.3 %) of the burdens (Chen et al., 2022). Such geographical heterogeneity may probably be due to the differences in climate, study period, age and sex structures of the population, healthcare system, people's acclimatization, etc. Although not comparable, another nationwide study conducted in Brazil observed a fraction of asthma hospitalizations attributable to short-term temperature variability increased from 5.3 % in 2000 to 5.9 % in 2015 (Wu et al., 2021), showing that in addition to cold temperature, temperature fluctuation also plays an important role in the asthma exacerbations.

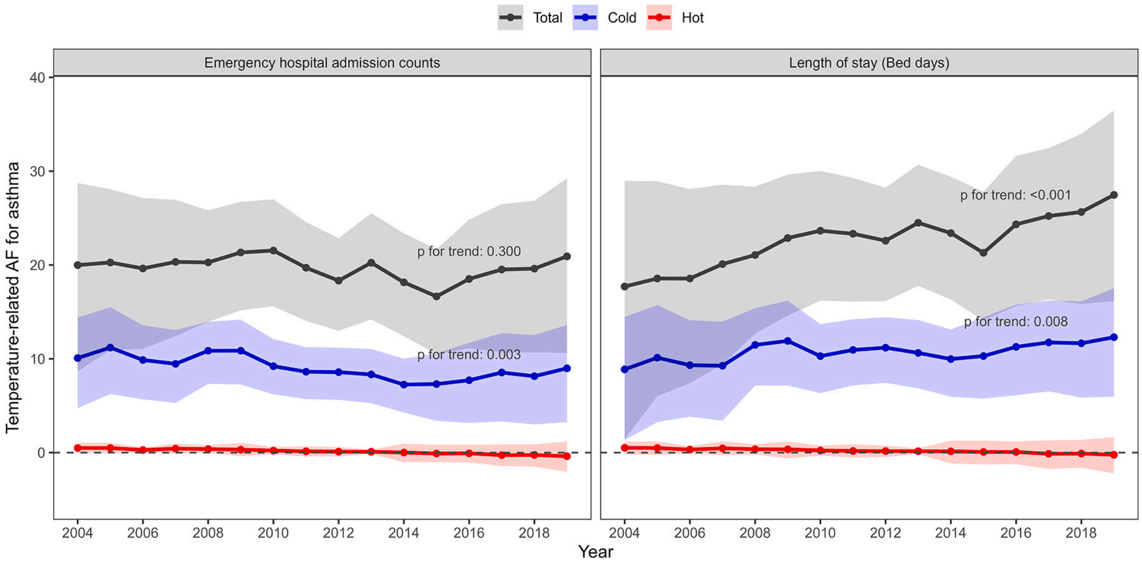

Fig. 4. Yearly-specific attributable fraction of total, cold, and hot ambient temperatures for asthma emergency hospitalizations and length of stay in Hong Kong, 2004–2019.

4.3. Temperature-related attributable risk for bed-days and its temporal changes

The yearly-specific temperature-related AF along the entire period from 2004 to 2019 estimated from the time-varying DLNM showed consistent temporal trends with the two-period comparison. The daily number of bed-days taking both hospital admission count and individual length of hospital stay into account is a better indicator of the severity of disease, hospital utilization, and expenditure. Although we observed a bit of temporal decrease in cold-attributed hospitalization count for asthma, the total and cold temperature-attributed bed-days increased over 2004–2019, indicating longer stays in the hospitals and growing demand and utilization of hospital services within the healthcare system. This can strain the resources, including hospital beds, staff, and other facilities, potentially leading to increased waiting times, overcrowding, and challenges in providing timely and efficient care. Since the longer bed-days may be due to more severe medical conditions, the increasing cold-related bed-days indicated that severe asthma patients were more sensitive to cold temperature exposure. On the other hand, longer hospital stays mean more expenditure and disease burden, showing that ambient temperature-related asthma expenditure and burden may have increased over the past years. Such economic burden is potentially preventable or modifiable through interventions targeting temperature-related factors which may inform public health strategies and interventions aimed at mitigating the adverse health effects of ambient temperature. In Hong Kong with extensive use of air conditioning in summer but not any heating in winter, paying heed to cold weather warnings and central heating during cold days may help protect severe asthma patients from exacerbation.

4.4. Strengths and limitations

To the best of our knowledge, this is one of the few studies to examine the association between ambient temperature and length of hospital stays and assess the temperature-related attributable risk for asthma exacerbations up to date. We used 16 years' daily time-series data to examine the temporal changes and compared the potential difference between early and late periods. We added to the literature about the temperature-related attributable risk for both asthma hospitalization counts and length of hospital stay and their temporal changes.

Meanwhile, some limitations should be noted. First, we identified the asthma cases based on the discharge code of 493 (ICD-9) as the principal diagnosis. The asthma cases that require hospital admission typically involve severe or acute exacerbations of the condition, and they always have complications or comorbidities, such as respiratory infections, pneumonia, or other respiratory conditions. In this case, asthma may not always be the principal diagnosis and not be counted in the current analysis. Moreover, milder asthma cases may receive treatments in specialist clinics. Therefore, the daily hospitalization counts and bed-days for asthma collected for the current analysis may most probably be underestimated, which may dilute the true temperature-related attributable risk for asthma. The unavailability of the daily data aggregated by age group and gender prevented us from exploring the potential age and gender difference in the asthma exacerbation attributed to cold temperature. Second, environmental exposures monitored from the fixed site station were denoted as the population exposure and the time-series design as an ecological study may prohibit detangling the causal association. Future studies with cohort study design and more accurate personal exposure assessment may help to overcome these limitations. Third, detailed information on pollen exposure and viral strains' detection for all influenza-like illnesses were not available for the current analysis although they have been demonstrated as risk factors for asthma exacerbation in previous studies (Lappe et al., 2023; Xiong et al., 2023). We adjusted the influenza epidemics in the regression model as we previously did (Qiu et al., 2016), and we acknowledged that some residual confounding bias may not be excluded thoroughly in our results. Finally, it is important to note that the relationship between temperature-related disease burden and hospital utilization can be modified by other factors, such as population susceptibility, geographical location, and climate variability. The impact of temperature on asthma's disease burden and hospital utilization may vary across different populations and regions with different climates and healthcare systems. The generalizability of the findings in Hong Kong should be interpreted cautiously.

5. Conclusions

In conclusion, we found significant associations of ambient cold temperatures with asthma exacerbations, with 19.7 % of hospital admissions and 22.6 % of the length of hospital stays attributed to ambient temperature. Contrary to a bit decreasing fraction of cold temperature-related hospital admissions, we observed a significantly increasing fraction of cold temperature-related length of hospital stay from 2004 to 2019. The findings from this study may offer valuable insights to the government regarding the specific asthma disease burden associated with ambient cold temperatures under the global climate change scenario, and subsequently, aid in formulating effective strategies to optimize healthcare utilization and improve overall asthma management.

Funding

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

CRediT authorship contribution statement

Hong Qiu: Methodology, Investigation, Formal analysis, Writing – original draft. **Shengzhi Sun:** Visualization, Software, Methodology. **Tze-Wai Wong:** Resources, Data curation. **Xing Qiu:** Validation, Conceptualization. **Kin-Fai Ho:** Validation, Conceptualization, Writing – review & editing. **Eliza Lai-Yi Wong:** Supervision, Conceptualization. **Eliza Lai-yi Wong:** Writing – review & editing.

Declaration of competing interest

The authors declare no conflict of interest.

Data availability

Data will be made available on request.

Acknowledgments

The financial support of the Centre for Health Systems and Policy Research is from The Tung's Foundation.

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