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Associations of ambient temperature and relative humidity with hospital admissions in macau, China using time series analysis

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Climate change and extreme weather are increasing global disease burdens, but the association between weather conditions and hospital admissions in Macau remains unclear. This study was performed in the context of Macau, China. It analyzed daily hospital admissions from Macau's hospitals with emergency departments and local meteorological data (2017–2022) using distributed lag nonlinear models with 21-day lag effects. Results revealed that 14.5 °C was associated with the lowest risk of hospital admissions. Colder temperatures exhibited prolonged effects, elevating risks for up to 21 days, while hotter temperatures' impacts were shorter. Compared with mean relative humidity (81%), the risk was lowest when relative humidity was 33% (RR = 0.87, 95% CI: 0.66–1.14), and the risk was highest when relative humidity was 100% (RR = 1.50, 95% CI: 1.15–1.94). The effects of these weather conditions on hospital admissions varied by disease and age, with smaller differences between sexes. The increased hospital admissions in Macau are associated with hotter and colder temperatures, as well as humidity. As climate change intensifies weather extremes, healthcare systems may face escalating demands, necessitating targeted prevention strategies for high-risk groups and optimized resource allocation.

Keywords Temperature, Relative humidity, Precipitation, Hospital admissions, Macau, Time series study

Abbreviations

CI	confidence interval
df	degree of freedom
DLNM	distributed lag nonlinear models
GLM	generalized linear models
ICD-10	International Classification of Diseases, Tenth Revision
Macau SAR	Macau Special Administrative Region
RR	relative risk
SD	standard deviations

The Macau Special Administrative Region (SAR) of China (longitude 113°31'41.4"~113°37'48.5", latitude 22°04'36.0"~22°13'01.3") is situated on the west bank of the Pearl River Estuary. Macau is adjacent to Guangdong Province in the southern region of China, across the sea from Hong Kong. Macau comprises three areas: the Macau Peninsula, Taipa Island, and Coloane, with a total area of approximately 32.9 square kilometers[1]. The terrain of Macau is predominantly flat, although there are a few hills. The highest point is Mount Tasiktang on Coloane Island.

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Over the past 20 years, Macau has undergone substantial changes in weather conditions, including more extreme temperatures, as well as high and low humidity. According to the Macau Meteorological and Geophysical Bureau[2]the average annual temperature has exhibited an upward trend, consistent with the global warming patterns, with an increase of approximately 0.2 °C per decade. Relative humidity displays a more complex pattern, characterized by extremes during seasonal variations. Notably, during the summer months, relative humidity increases compared to the previous decades[3].

These weather changes substantially impact on human health, influencing both increases in mortality and morbidity rates. Between 2000 and 2019, non-optimal ambient temperatures were responsible for over 5 million deaths worldwide[4]. An example of this is that high heat exposure accounts for approximately 1% of overall mortality[5]. Numerous studies have demonstrated nonlinear relationships between extreme temperatures and poorer health outcomes, indicating that both excessively high and low temperatures elevate the risk of disease[4,6,7]. One study[4] demonstrated that both low and high temperatures in Thailand were linked to increased hospital admissions for various diseases, particularly among women, children, and adolescents. Despite these preliminary findings, evidence of the association between temperature and hospital admissions in China remains limited to date.

Relative humidity also plays a crucial role in health outcomes. High humidity levels can hinder the body's ability to cool itself through sweating, thereby increasing the risk of heat-related illnesses. Conversely, low humidity can result in dry skin, respiratory irritation, and increased susceptibility to respiratory infections[8]. Some studies demonstrated that higher relative humidity was associated with fewer hospital admissions, while lower relative humidity correlated with increased hospital admissions[9,10]. Additionally, a study[10] indicated that low humidity often acts synergistically with cold exposure to substantially elevate the risk of cardiovascular disease. It is important to note, however, that the association between relative humidity and health remains largely understudied globally[11].

The World Health Organization (WHO) emphasizes that changes in weather conditions, including temperature and relative humidity, pose a substantial threat to human health by increasing the frequency and intensity of extreme weather events[12]. Recognizing the need for a deeper understanding of this critical issue, our study aimed to investigate the association between various weather conditions and daily hospital admissions in Macau from 2017 to 2022, considering its unique climate and public health challenges.

Materials and methods

Study background

According to the Census and Statistics Department of Macau, the city's resident population in 2022 is estimated to be around 683,000, with a population density of 20,620 inhabitants per square kilometer, making it one of the most densely populated areas globally[1]. Macau has a subtropical monsoon climate influenced by both the ocean and the monsoon, with a dual season dominant. Summer is usually hot and humid, with perceived temperatures often above 40 °C and frequent thunderstorms; winter is mild with little rain, but cold waves can cause temperatures to drop over 10 °C in a day; spring and autumn are shorter in duration[2] .The average annual temperature is approximately 22 °C, and the annual precipitation is around 2,000 mm, resulting in high relative humidity. Tropical cyclones mainly occur from May to November, peaking from July to September, with an average of five events each year[1,2]. Strong typhoons can trigger storm surges, with destructive power increasing as wind speeds rise near the coast[1,2]. The extremely high population density and fragile climate environment increase the likelihood of adverse health outcomes; therefore, timely weather exposure warnings are essential.

Health data

We collected all daily hospital admissions records, regardless of patient age, from computerized case databases at Kiang Wu Hospital and Centro Hospitalar Conde Da São Januário dos Serviços de Saúde in Macau. These two hospitals are the only two in Macau with accident and emergency departments. We extracted the primary reason for admission using International Classification of Diseases, Tenth Revision (ICD-10) codes and categorized these into broad disease types, Neoplasms (C00-D48), Endocrine, nutritional, and metabolic diseases (E00-E89), Diseases of the circulatory system (I00-I99), Diseases of the respiratory system (J00-J99), Diseases of the musculoskeletal system and connective tissue (M00-M99), and Other and unspecified effects of external causes (T66-T78). The health data collected included the primary reason for hospital attendance upon admission, admission date, and the patient's sex and age group (0–20, 21–70, 70 plus). Data were cleaned by removing cases with missing admission dates, sex, and age information (22 cases). This retrospective study used fully de-identified patient data, with all identifiers (e.g., name, date of birth) removed. As this study was intended to benefit the public health of Macau and involved no more than minimal risk to participants, the University of Macau Research Committee (SSHRE24-APP087-FHS; 09/08/2024) waived the requirement for informed consent. This study adhered to the ethical recommendations of the Declaration of Helsinki on the use of data[13]which permits the exemption of informed consent for de-identified retrospective data analyses under strict ethical oversight. We ensured data privacy and confidentiality throughout the study. Weather and air pollution data.

Daily weather and air pollution data were obtained from a database collected during the same period by the Macau Meteorological and Geophysical Bureau and the Macau Environmental Protection Bureau[14]. The data recorded included daily mean temperature, daily mean relative humidity, daily precipitation, daily average particulate matter 10 (PM10) concentration, daily peak 1-hour average nitrogen dioxide (NO_2) concentration, and daily average sulfur dioxide (SO_2) concentration, as measured at the meteorological and air pollutant monitoring stations in Macau. The weather data were taken from an average of 10 weather stations to reflect the average weather conditions for the entire region. Air pollution data were taken from an average of 6 air pollutant monitoring stations to represent the average air pollution situation. Because of the small size of the urban area of Macau and the small difference in measurement results among the stations, we used the average data from all the stations. All data was complete except for August 4, 2017, which had missing PM10 values.

Statistical analyses

Descriptive analyses

We used R version 4.4.1 for data analysis and descriptive statistics, including counts, percentages, means, and standard deviations (SD) for weather conditions, air pollutants, and the number of cause-specific hospital admissions. The R package 'ggplot2' was employed to visualize daily weather and air pollutants data from 2017 to 2022, while the 'mice' package was used to perform multiple imputations for the missing PM10 data.

Estimation of associations between hospital admissions and weather conditions

We conducted a time series analysis to examine the associations between daily temperature, relative humidity, and hospital admissions. Due to the over-discretization of daily hospital admissions, this analysis employed generalized linear models (GLM) based on negative binomial distributions. For the lag effects and nonlinear associations, we employed distributed lag nonlinear models (DLNM) to deal with them. We built two two-dimensional matrices for temperature-lag times and relative humidity-lag times using crossbasis functions from the R package 'dlnm'[15,16].

For exposure-response associations, we used natural cubic splines (three equal internal knots for temperature; three internal knots at the 10th, 75th, and 90th percentiles for relative humidity) to capture nonlinearities and directional changes in weather conditions-hospitalization relationships[17,18]. For lag-response associations, we applied natural cubic splines with intercepts and four equidistant internal knots on a log scale to model a 21-day lag on hospital admissions, allowing for flexibility[19]. We addressed seasonality and long-term trends with a natural cubic spline with six degrees of freedom (df) per year and included categorical variables representing the days of the week and dichotomous variables representing public holidays to address the impact of weekday and holiday patterns on the model, respectively. We also included PM10, NO2, and SO2 as covariates, using natural cubic splines with $3df$ for these variables. When studying the lag effect of temperature on the hospital admissions, we added the spline function with 3 df of relative humidity as a covariate to control the co-occurrence in the model (the model for relative humidity also controls the co-occurrence for temperature). We selected the best-fitting model based on the AIC information criterion, likelihood ratio test, and generalized cross-validation[7,20]. We repeated analyses across subgroups, including disease type, sex, and age groups, to test result robustness.

To investigate the association between hospital admissions and weather conditions (daily mean temperature, relative humidity), we employed a GLM model based on a negative binomial distribution for temperature and relative humidity. For reference level, we designated the temperature corresponding to the lowest risk of hospital admission as the reference point, identifying the minimum risk temperature as 14.5 °C. For relative humidity, we selected the mean value of 81%. Details on the model and sensitivity analysis can be found in full in Supplementary Document 1.

By reporting cumulative effects within lag periods, adjustments for multiple comparisons to a single estimate for each exposure level are made. The contour maps of temperature and relative humidity at each lag time display only the trend to reduce multiplicity effects. Cumulative relative risk ratios quantify the total burden of patients caused by exposure events. To address issues of multiplicity across the exposure-response continuum, simultaneous confidence bands via 1,000 bootstrap resampling were computed[21]. This approach controls the family-wise error rate at $\alpha = 0.05$, ensuring 95% confidence that the entire true association curve lies within the band[16,18]. More details are reported in Supplementary Document 1.

Results

Descriptive analysis

Descriptive statistics of hospital admissions are presented in Table 1. This study included a total of 106,794 admissions from January 1, 2017, to December 31, 2022, of which 18,858 (18%) were due to neoplasms, 29,566 (28%) were related to diseases of the circulatory system, and 48,232 (45%) were attributed to diseases of the respiratory system. Endocrine, nutritional, and metabolic diseases, as well as immune disorders, represented 4% of admissions, and diseases of the musculoskeletal system and connective tissue accounted for 5%. Among the total admissions, 55,542 were male and 51,230 were female, resulting in a male-to-female ratio close to 1.1:1. When stratified by age, 29,091 admissions were for individuals aged 0–20 years, 44,501 for those aged 21–70 years, and 33,197 for individuals aged 70 years or older. Descriptive statistics of daily hospital admissions are presented in Supplementary Document 1.

Descriptive statistics for weather conditions and air pollutants are presented in Table 2. We recorded yearly means of weather conditions in Macau from 2017 to 2022, where the mean temperature was 23.2 °C (SD: 5.1), mean relative humidity was 81% (SD: 11.3), precipitation was 5.4 mm (SD: 17.6), PM10 concentration was 42.6 $\mu g/m^3$ (SD: 22.4), the peak one-hour NO_2 concentration was 50.7 $\mu g/m^3$ (SD: 28.1), and SO_2 concentration of 4.4 $\mu g/m^3$ (SD: 2.4). Descriptive statistics of daily weather conditions and air pollutants are presented in Supplementary Document 1. The time trends of these variables are also illustrated in Supplementary Document 1, which indicates that they exhibit strong temporal trends and seasonality.

Associations between hospital admissions and temperature

Figure 1 presents the cumulative risk-response curves illustrating the association between daily temperature and hospital admissions, along with a contour map across different lag days. A nonlinear association between admissions at both cold and hot temperatures (Fig. 1A). After 21 cumulative days compared to the minimum

Characteristic	Number (Percent)	2017 (Percent)	2018 (Percent)	2019 (Percent)	2020 (Percent)	2021 (Percent)	2022 (Percent)
Total admissions	106,794 (100%)	17,358 (16%)	19,593 (18%)	21,394 (20%)	14,877 (14%)	16,608 (16%)	16,964 (16%)
Sex							
Male	55,542 (52%)	8961 (8%)	10,485 (10%)	11,091 (10%)	7622 (7%)	8555 (8%)	8828 (8%)
Female	51,230 (48%)	8393 (8%)	9107 (9%)	10,302 (10%)	7251 (7%)	8247 (8%)	8130 (8%)
Age							
0–20	29,091 (27%)	4808 (5%)	6618 (6%)	7740 (7%)	2557 (2%)	3680 (3%)	3688 (3%)
21–70	44,501 (42%)	7294 (7%)	7584 (7%)	7787 (7%)	7720 (7%)	7367 (7%)	7246 (7%)
70 plus	33,197 (31%)	5256 (5%)	5391 (5%)	5867 (5%)	5100 (5%)	5559 (5%)	6024 (6%)
Primary diagnosis at admission							
Neoplasms	18,858 (18%)	2698 (3%)	2890 (3%)	2798 (3%)	3452 (3%)	3743 (4%)	3304 (3%)
Endocrine, Nutritional and Metabolic Diseases, and Immunity Disorders	4233 (4%)	699 (1%)	719 (1%)	699 (1%)	656 (1%)	726 (1%)	734 (1%)
Diseases of The Circulatory System	29,566 (28%)	4820 (5%)	4820 (5%)	5007 (5%)	4857 (5%)	5117 (5%)	4941 (5%)
Diseases of The Respiratory System	48,232 (45%)	8224 (8%)	10,153 (10%)	11,893 (11%)	4940 (5%)	5957 (6%)	7065 (7%)
Diseases of the Musculoskeletal System and Connective Tissue	5771 (5%)	900 (1%)	983 (1%)	982 (1%)	962 (1%)	1045 (1%)	899 (1%)

Table 1. Baseline statistical analysis for yearly hospital admissions from 2017 to 2022 in Macau. Notes: The descriptive statistics of yearly hospital admissions from 2017 to 2022 in Macau were reported by number and percent.

Variable	Mean (SD)	2017 (SD)	2018 (SD)	2019 (SD)	2020 (SD)	2021 (SD)	2022 (SD)
Mean temperature (°C)	23.2 (5.1)	23.0 (5.1)	22.9 (5.4)	23.6 (4.6)	23.3 (5.0)	23.5 (5.0)	22.8 (5.6)
Mean relative humidity (%)	81.0 (11.3)	81.0 (11.0)	81.0 (10.8)	82.2 (10.8)	82.2 (10.9)	78.2 (11.8)	81.5 (11.9)
Mean precipitation (mm)	5.4 (17.6)	4.9 (14.7)	4.9 (14.3)	6.2 (15.0)	4.7 (14.7)	6.0 (25.0)	5.6 (19.5)
Mean PM10 (daily µg/m3)	42.6 (22.4)	46.7 (26.6)	45.0 (21.6)	46.6 (23.2)	39.8 (19.9)	41.0 (22.4)	36.6 (18.0)
Mean NO2 (1-hour µg/m3)	50.7 (28.1)	69.7 (21.7)	63.2 (26.0)	61.6 (24.3)	51.2 (22.9)	30.5 (15.2)	27.7 (12.2)
Mean SO2 (daily µg/m3)	4.4 (2.4)	7.1 (2.6)	4.6 (2.3)	1.8 (1.4)	3.3 (1.3)	5.3 (0.9)	4.5 (0.8)

Table 2. Baseline statistical analysis for yearly weather conditions and air pollutants from 2017 to 2022 in Macau. Notes: The descriptive statistics of yearly weather conditions and air pollutants from 2017 to 2022 in Macau from 2017 to 2022 in Macau were reported by mean and standard deviation (SD).

risk temperature, the relative risk (RR) of hospital admission in an extremely cold environment (1% of the temperature distribution: 10.3 °C) increased (RR: 1.21, 95% CI: 1.06–1.37). The RR in an extremely hot environment (99% of the temperature distribution: 30.4 °C) increased (RR: 1.42, 95% CI: 1.17–1.73). Figure 1B illustrates the effect of temperature on the risk of hospital admissions at a single lag time; the duration of the cold weather, temperature below 10 °C, appeared to have a sustained increased association of hospital admissions, with cold always remaining positively associated with higher RR, although a brief decrease in the RR brought about by low temperatures on days 2–3. The duration of the high temperatures on increased hospital admissions, above 20 °C, was shorter compared to cold temperatures, with 5 days of increased risk observed. The highest observed risk occurred in hot weather during the first day of lag, after which the risk of heat and hospital admissions continued to decrease with increasing lag time. Results with statistical significance are presented in Supplementary Document 1.

The association between temperature and hospital admissions demonstrated consistency across various types of diseases (Supplementary Document 1). The three groups (neoplasms, diseases of the circulatory system, and diseases of the respiratory system) exhibited similar cumulative risk-response curves, despite variations

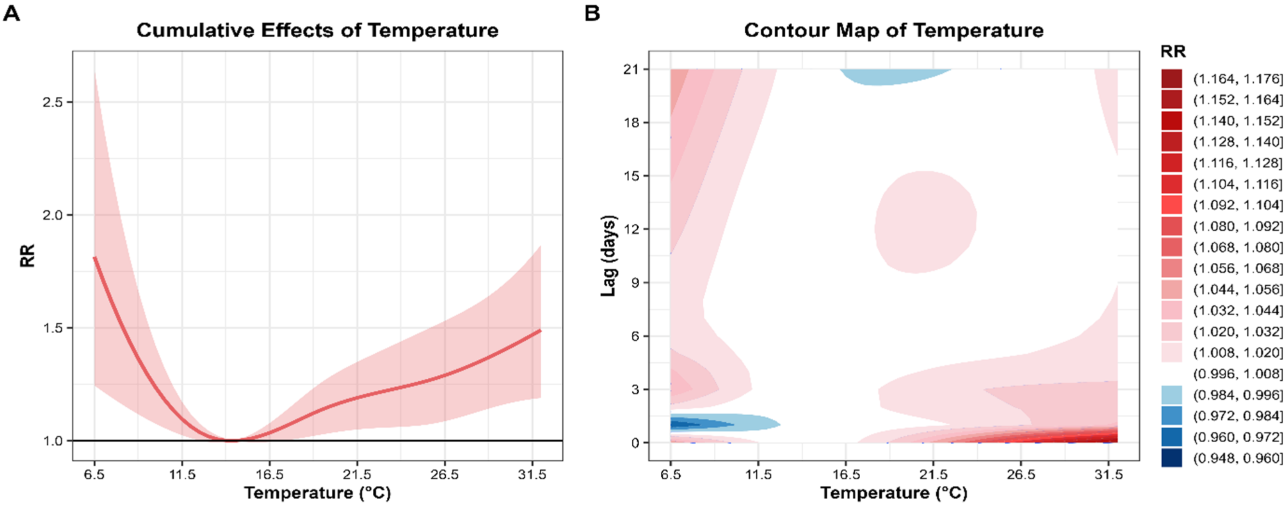

Fig. 1. Cumulative risk-response curves and contour map for temperature *Notes: a). Plot A shows the exposure-response association between temperature and total hospital admissions. The red lines represent the cumulative exposure-response specific relative risks (RR), and the shaded areas represent the 95% confidence intervals. All confidence intervals account for multiplicity via bootstrap-derived simultaneous inference. b). Plot B shows the exposure-lag-response contour map of temperature with specific RRs. In this plot, darker shades of red color represent larger RRs, and darker blue colors represent smaller RRs.*

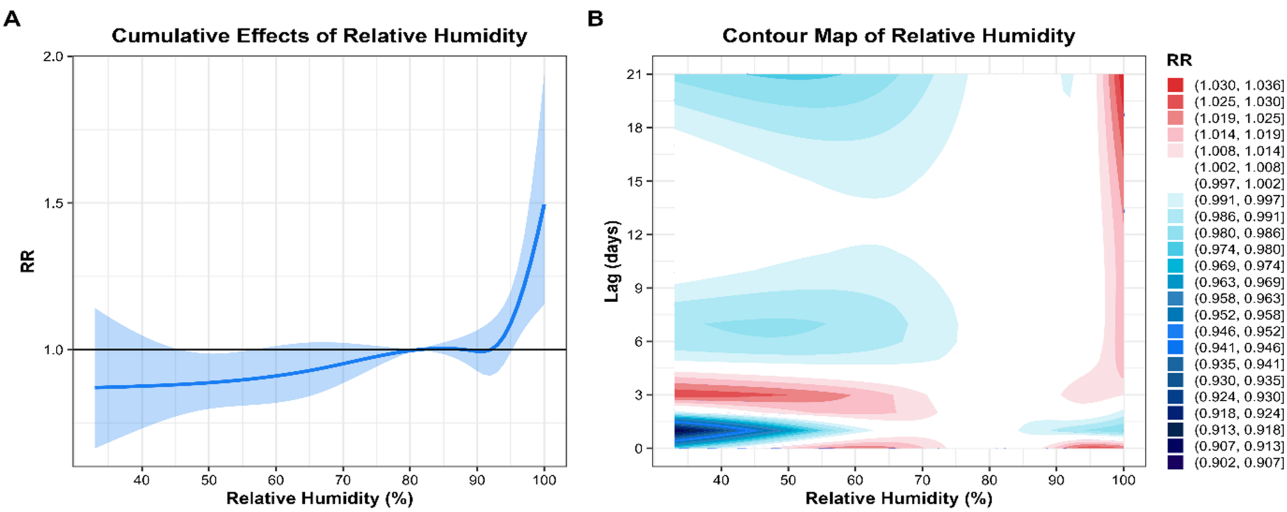

Fig. 2. Cumulative risk-response curves and contour map for relative humidity *Notes: a). Plot A shows the exposure-response association between relative humidity and total hospital admissions. The blue line represents the cumulative exposure-response specific relative risks (RR), and the shaded areas represent the 95% confidence intervals. All confidence intervals account for multiplicity via bootstrap-derived simultaneous inference. b). Plot B shows the exposure-lag-response contour map of relative humidity with specific RRs. In this plot, darker shades of red color represent larger RRs, and darker blue colors represent smaller RRs.*

in minimum risk temperature (26.5 °C, 25.4 °C, and 15.1 °C, respectively). Among the age subgroups, a high degree of concordance was observed in the 0–20 and 21–70 age groups, with a notable exception in the 70-plus age group, where the curve generally tended to decline as temperature increased. In the sex subgroups, the cumulative risk-response curves displayed smaller differences between the sexes.

Associations between hospital admissions and relative humidity

Figure 2 illustrates the association between daily mean relative humidity and hospital admissions, along with a contour map across lag days. A positive association between relative humidity and risk of admissions was observed (Fig. 2A). After a cumulative period of 21 days, the RR tended to increase when the relative humidity exceeded 88% and reached 1.50 (95% CI: 1.15–1.94) at 100%. Conversely, the RR decreased when relative humidity fell below 81%, reaching a minimum RR of 0.87 (95% CI: 0.66–1.14) at 33%. Figure 2B illustrates the impact of relative humidity on the risk of hospital admission at a single lag time. When relative humidity was below 50%, the RR decreased at shorter lag times (days 0–2). In contrast, when relative humidity exceeded 50%, the risk tended to increase during lag days 0–1. Extending the lag time for relative humidity levels between 33% and 70%, the RR increased on days 3–4 of the lag but decreased on days 5–10 and 15–21. When relative humidity surpassed 90%, the RR increased during lag days 0–1 and 4–21 across two time periods, while it decreased on days 2–3. Results with statistical significance are presented in Supplementary Document 1.

The association between relative humidity and hospital admissions exhibited a non-linear curve for neoplasms and diseases of the circulatory system (Supplementary Document 1). The lowest RR was observed at 59% (RR: 0.65, 95% CI: 0.53–0.80) for neoplasms and at 58% (RR: 0.89, 95% CI: 0.75–1.05) for diseases of the circulatory system. When relative humidity exceeded 85%, the RR again displayed a decreasing trend followed by an increasing trend, with turning points at 93% and 91%, respectively. For diseases of the respiratory system, the trend was consistent overall, with an increasing risk as relative humidity rose. In the age subgroups, the risk was consistent with a whole in the 0–20 age group. The increased risk of hospital admission for those aged 21–70 had a non-linear pattern and reached a minimum at 60% (RR: 0.78, 95% CI: 0.67–0.90). The increased risk of hospital admissions for those aged 70-plus had a non-linear pattern, with a minimum RR at 84% (RR: 0.99, 95% CI: 0.97–1.02). In the sex subgroups, the differences in cumulative risk-response curves were smaller and remained in close agreement with the whole, but there was a downward and then upward trend in risk in the female group when below 88%.

Sensitivity analysis

In the sensitivity analyses (Supplementary Document 1), varying the df of the time variables in the model (df = 5, 7, 8), the maximum number of lag days (maximum lag = 19, 20, 22, 23), and the df of the covariates (df = 4, 5) demonstrated that the association between mean daily temperatures, relative humidity and the risk of hospital admissions remained robust. In addition, we included seasonal categorical covariates for further adjustment, and the results showed that the model also remained robust. The detailed results are presented in Supplementary Document 1.

Discussion

To the best of our knowledge, this is the first study conducted in Macau to evaluate the impact of environmental weather conditions on hospital admissions. Our findings indicate that different weather conditions are associated with increased hospital admissions over several days. Cold weather can have a prolonged association with increased hospital admissions, observed up to 21 days. The cumulative risk-response curves for temperature and relative humidity exhibited varying trends across different diseases and age groups. Furthermore, except for temperature, there were fewer differences in the cumulative risk-response curves among different sexes.

Consistent with previous studies, a V-like shaped association between temperature and hospital admissions[4,5,22]where the risk increased both when temperatures fell below and rose above the minimum risk temperature. However, unlike previous findings, the minimum risk temperature in Macau was notably low at 14.5 °C. A study examining all-cause hospital admissions in Hong Kong indicated that the risk was lowest at approximately 27°C[6]. This result is likely due to the differences in the types of diseases in the hospital admissions data of the two studies. The results of disease subgroups showed that the minimum risk temperatures of neoplasm and disease of the circulatory systems were similar to the results of Hong Kong. The lower minimum risk temperature of disease of the respiratory system and its larger proportion (45%) in the sample data contribute to this phenomenon. Other potential reasons include the key differences between Hong Kong and Macau's population demographics, urban design and access to healthcare. Regarding the lag effects of temperature, heat effects (temperatures exceeding 20 °C) may have an immediate impact but tend to last for a shorter duration. In contrast, cold effects (temperatures below 10 °C) may exhibit a more prolonged lag effect, persisting for several weeks. This association was like previous papers[5]which found that the effects of high temperatures on cardiovascular-related hospital admissions were compared to cold weather effects that lasted for up to three weeks shorter in the south-central coast of Vietnam.

This study has indicated that relative humidity was associated with an increased risk of hospital admissions. The cumulative exposure-response curves exhibited a smaller increase when below the mean and a substantial increase when above the mean, consistent with findings from a previous multicenter study[23]. The combination of rainy and highly humid weather may lead to the effect of relative humidity and hospital admissions, as previously suggested[24,25].

In the subgroup analysis, all three disease categories displayed similarly shaped cumulative risk-response curves. For neoplasms, a specific temperature was identified as showing the lowest risk of hospital admissions. Increased admissions due to circulatory system diseases were observed in hotter weather compared to other diseases, aligning with previous studies[4,26]. Conversely, the minimum risk temperature for respiratory system diseases was relatively cooler (15.1 ℃) compared to other disease types, indicating that respiratory system-related admissions are more sensitive to cold weather. This sensitivity may be attributed to colder temperatures causing bronchoconstriction and weakening the respiratory immune response, thereby increasing susceptibility to infections[27,28].

Regarding age subgroups, there was a notable difference between the 70-plus age group and others. Older adults have previously been shown to face a higher risk of earlier mortality with temperature increases in summer[29]. Despite the 0–20 and 21–70 age groups displaying similar cumulative risk-response curves, the risk of hospital admissions among children and adolescents (0–20) was larger during temperature changes. This could be due to underdeveloped core thermoregulatory capacity in children and adolescents[29,30]. No substantial differences were found between the sexes, contrasting with prior studies suggesting males or females were more prone to hospitalization during extreme temperatures[5,23].

For the neoplasms and circulatory system disease groups, the risk of hospital admissions reached its lowest point at 59% humidity. At approximately 60% humidity, the air feels neither too dry nor overly humid, facilitating efficient sweat evaporation[31]which helps in cooling the body and preventing potential heat-related illnesses. Children and adolescents are more sensitive to humidity changes due to their increased outdoor exposure[32,33]. Older individuals, who are often less capable of regulating body temperature, benefit from high humidity, which helps keep the respiratory tract moist and maintains blood volume, thus reducing the risk of dehydration and cardiovascular strain[30]. Consequently, the 70-plus age group experienced the lowest risk at around 80% humidity. Females exhibited a lower risk at higher humidity levels than males, possibly because females tend to have higher skin blood flow, improving the efficiency of heat dissipation and helping maintain a stable core temperature in humid environments[34].

Our study has several strengths. First, the hospital data was extracted from the sole providers of accident and emergency departments in Macau, representing the total number of admissions from those departments for the region. Given the small land area of the Macao region (32.9 km^2), the weather measurement stations and hospitals were near one another, and the daily weather measured would be similar to that experienced around the hospitals. The second strength of our study is that we examined the association between weather conditions and specific diseases in addition to all hospital admissions; this level of detail allows us to observe the association of weather factors on specific sub-populations of individuals with diseases[27,35]. Finally, our investigation also offers insights into the burden of morbidity across different sex and age subgroups, which helps in identifying vulnerable populations at risk from climate-related challenges[22].

Several limitations of this study should be acknowledged. Firstly, the sample size was relatively small compared to similar previous studies, limiting the interpretation of the subgroup analysis. Second, while our models adjusted for humidity when assessing temperature effects (and temperature was adjusted for when assessing humidity), the high complexity of the DLNM model makes complete disentanglement challenging. Therefore, the complex interactive effect of these weather variables is not analyzed. Thirdly, the data were derived from only two hospitals in Macau and given that Macau is close to Zhuhai in Mainland China and Hong Kong, Macau residents may opt to seek medical treatment in these neighboring regions. Fourth, our identification of hospital admissions and disease-specific subgroups relied on diagnoses using ICD-10 codes. Misclassification of coding may have influenced these findings. Fifth, the data extracted from hospitals were daily counts of admissions and not individual-level data, meaning accounting for individual confounding factors was not possible[22]. Daily count data was extracted to compile with data protection, preventing individual patients from being identifiable within this study. Finally, data in this study included time during the COVID-19 pandemic affecting Macau from 2020 to 2022 and may have contributed some bias to our findings[24,36].

This study revealed a unique climate-health pattern in Macau, which requires public health adaptation measures for its specific urban environment. Given the vulnerability of the elderly to low-temperature exposure, the temperature sensitivity of children and adolescents often shows significant lagged effects after exposure to extreme heat. These identified temperature thresholds and lagged patterns must provide a robust forecasting framework[37]. Healthcare systems can use local weather forecasts combined with epidemiological data to anticipate surges in demand for healthcare services, enabling proactive mobilization of resources and capacity planning ahead of predicted extreme temperatures[37]. Besides, this study also promotes integrating emergency data to break the blind spots in extreme weather conditions monitoring and provide a corresponding support for climate health decision-making in Macau[38].

Furthermore, these insights can facilitate targeted public health interventions. Understanding specific weather-disease relationships, especially for diseases such as respiratory illnesses, can help optimize prevention programs. For example, seasonal influenza vaccination campaigns can be strategically timed to maximize population coverage ahead of predicted risk periods, incorporating local climate patterns and short-term weather forecasts[12]. Implementing such adaptive measures—including vaccination programs and dynamic resource allocation based on predicted demand—has demonstrated significant cost-effectiveness in increasing the climate resilience of healthcare systems worldwide[39,40]. In addition, Macau's compact administrative structure enables rapid policy implementation, and our proposed threshold warning can be integrated into the health bureau's real-time monitoring dashboard[39]. More information on precipitation is available in Supplementary Document 2.

Data availability

All data generated or analyzed during this study are included in this published article and its Supplementary Document. We are unable to directly share the original data used in this study as the data custodians, Kiang Wu Hospital and Centro Hospitalar Conde Da São Januário dos Serviços de Saúde have not given permission for data sharing.

Received: 17 April 2025; Accepted: 14 July 2025
Published online: 17 July 2025

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Acknowledgements
The researchers would like to acknowledge the staff at both Macau hospitals for their kind cooperation with data extraction for this study. The researchers acknowledge that the data for this study are derived from Macau SAR hospital patients as part of their care and support.

Author contributions
B.W. and S.S. contributed to the study in the conceptualization of the study, formal analysis, validation (B.W. conducted the formal analysis and S.S. validated the analysis), investigation, methodology and writing - original draft. R.D.S. contributed to the study in conceptualization, funding acquisition, project administration, supervision and writing - review & editing. E.P.L.L. contributed to the study in conceptualization, supervision and writing - review & editing. L.W.I., L.W.K., I.T.C., C.B.H., J.Q.H. and U.H.W. contributed to the study in conceptualization, methodology, data curation and writing - review & editing.

Funding
This research was funded by the internal grant of the Faculty of Health Sciences, University of Macau.

Declarations

Competing interests
The authors declare no competing interests.

Ethics approval and consent to participate
The study was conducted in accordance with the ethical standards of the University of Macau Research Committee. The health data used in this study were extracted from the computerized case databases of Kiang Wu Hospital and Centro Hospitalar Conde Da São Januário dos Serviços de Saúde in Macau. All cases in this study were de-identified at the hospital before researchers were granted access to the data. This study was approved by the University of Macau Research Committee reference number SSHRE24-APP087-FHS and got the support of Centro Hospitalar Conde Da São Januário dos Serviços de Saúde Ethics Committee and Kiang Wu Hospital Continued Medical Education and Research Department.

Additional information
Supplementary Information The online version contains supplementary material available at https://doi.org/10.1038/s41598-025-11913-y.

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