The effects of extreme heat events on all-cause mortality: A case study in Ahmedabad city of India, 2002-2018

Ayushi Sharma[1], Priya Dutta[2], Priyanka Shah[2], Veena Iyer[2], Hao He[3], Amir Sapkota[4], Chuansi Gao[5], Yu-Chun Wang*[1,6]

[1] Department of Environmental Engineering, College of Engineering, Chung Yuan Christian University, 200 Chung-Pei Road, Zhongli 320, Taiwan

[2]Indian Institute of Public Health Gandhinagar (IIPHG), Public Health Foundation of India (PHFI), Near Lekwada Bus Stop, Gandhinagar, 382042, Gujarat

[3]Dept. of Atmospheric and Oceanic Science, University of Maryland, College Park, MD, United States

[4]Departement of Epidemiology and Biostatistics, University of Maryland, School of Public Health, College Park, MD 20742

[5]Thermal Environment Laboratory, Ergonomics and Aerosol Technology, Department of Design Sciences, Faculty of Engineering (LTH), Lund University, Sweden

[6]Research Center for Environmental Changes, Academia Sinica, 128 Academia Road, Section 2, Nankang, Taipei 11529, Taiwan

Address correspondence:

*Yu-Chun Wang, Professor

Department of Environmental Engineering, College of Engineering, Chung Yuan Christian University, 200 Chung-Pei Road, Zhongli 320, Taiwan

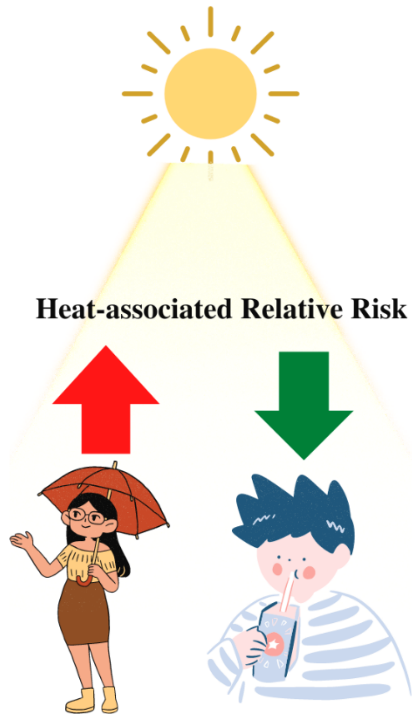
Email: ycwang@cycu.edu.tw; swingapple2@gmail.com

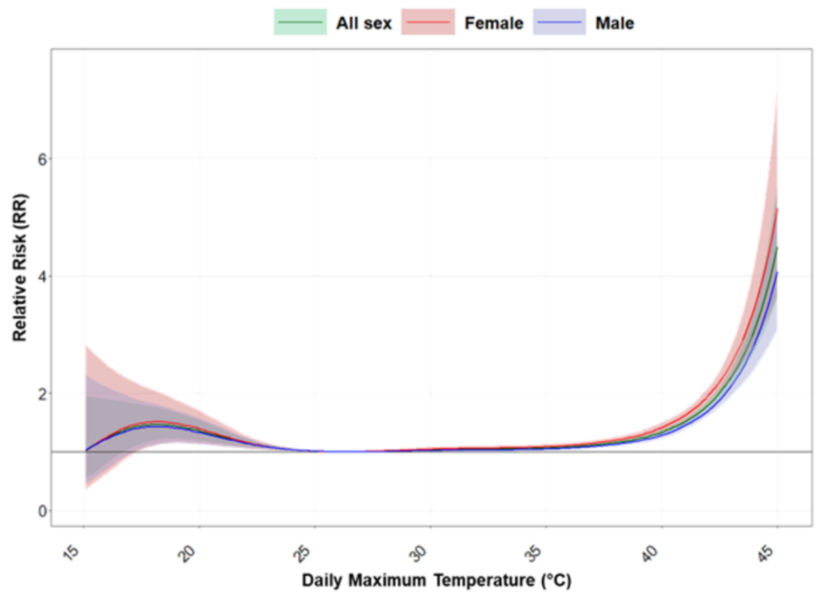
Highlights

- The exposure-response curve revealed a typical *'J'* shaped, with a minimum mortality temperature (MMT) of 26°C.
- A single-day absolute T_{max} above 40°C as the cutoff threshold resulted in a 34% increase in mortality risk (RR:1.34; 95% CI: 1.29-1.39).
- Females are more vulnerable to extreme temperatures than males.
- Lag-specific effect identified mortality risk is highest during the day of exposure (lag 0), it tends to persist for longer for more intense extreme heat events (EHEs).

Graphical Abstract

Is extreme heat an indiscriminate killer?





Abstract

Background: Extreme heat event (EHE) related mortalities have been on rise in India in recent years, yet there is a paucity of data regarding how specific thresholds impact the health risk.

Methods: We used Distributed Lag Non-Linear Model to investigate the association between extreme heat events, calculated using different thresholds, and mortality risk in Ahmedabad city of India, during 2002-2018.

Results: We observed a typical *'J'* shape exposure-response curve, with a minimum mortality temperature (MMT) of 26°C for Ahmedabad. The temperature-mortality relationship showed a higher risk of all-cause mortality for T_{max}>35°C and T_{max}<25°C. EHE determined using a cut-off threshold of $T_{max} \geq$ 40°C leads to 34% increase in all-cause mortality (Relative Risk (RR):1.34, 95% Confidence Interval (95% CI): 1.29-1.39), while considerably higher mortality risk for $T_{max} \geq$ 45°C (RR: 4.50, 95% CI: 3.63-5.58). Gender-stratified analysis showed that females are at higher risk of EHE-related deaths, irrespective of the intensity and highest mortality risk was identified during same day of exposure which tends to persist for longer for more intense EHE.

Conclusion: The activation of heat action plans for Ahmedabad needs to account for the significantly higher risk of mortality below the current threshold (~40°C) and the sustained risk for high-intensity EHE.

Keywords: Extreme heat events (EHEs); Mortality; Exposure-Response; Minimum Mortality Temperature (MMT); DLNM; Ahmedabad

1. Introduction

The most recent Intergovernmental Panel on Climate Change (IPCC) report concluded that extreme heat events (EHEs) have become more frequent, intense, and long-lasting across the globe [1]. Many studies worldwide have evaluated the temperature-mortality association and identified a higher mortality risk associated with extreme temperatures [2–7]. Others have reported excess heat-associated mortality during the heatwave period [8–10]. For instance, the 2003 heat waves in France resulted in 15,000 excess mortality [11]. Similarly, the 2006 heatwaves in California caused around 16,166 excess emergency department visits and 1,182 excess hospitalizations across the state [10]. However, limited evidence on temperature-associated health risks is available from low-and-middle-income countries (LMICs).

Cities and urban areas in LMICs are more vulnerable to EHEs due to Urban Heat Island (UHI) effects [12]. In LMICs, rapid urbanization development has converted the open areas into concrete and heat-trapping roofs resulting in higher UHI effects [13]. Historical evidence suggests that the population's vulnerability to EHE is considerably higher in urban areas [14]. For instance, recent studies from India show that heat wave events increased all-cause mortality by up to 17% in the City of Hyderabad during 2006-2015 [15] and up to 40% in Nagpur during the 2010-2014 period [7], while evidence from rural areas are rarely reported. Likewise, Ahmedabad city of India where South Asia's first heat action plan (HAP) was implemented also experienced heat-associated excess mortalities [13,16,17].

However, how the impact of EHE differs across geographic regions rely on several factors, like access to air conditioning, demographic compositions [14], and thermal acclimatization of the local population, which can be delineated via minimum mortality temperature (MMT) [18]. However, the majority of studies from the region have reported excess heat-associated mortalities [6,13,19], and there is a paucity of data regarding how changes in specific thresholds used to define EHE impact the observed association between heat waves and mortality in India. The lack of such location-specific data has resulted in Indian Meteorological Department (IMD) establishing two absolute thresholds to define heat waves for the entire nation (single-day maximum temperature above 40°C for plains and 30°C for hilly regions) [20], which may not accurately capture the underlying population risk. Prior studies have suggested that definitions of heatwaves may have implications for human health impacts and, thus, must be explored locally [21].

Therefore, in this study, we have focussed on quantifying the risk of mortality with varying temperature thresholds to quantify the impact of EHE on mortality in India. We have also assessed the temperature exposure-response curve for Ahmedabad (reflecting MMT) along with threshold-specific mortality risk. The region-specific exposure-response curve help to understand human heat exchange ability, thermoregulation limits and adaptation to heat of the population at a local level [22]. Additionally, since various factors influence population response to heat, potential effects of gender and time-varying (lagged) exposures were also evaluated.

2. Methodology

2.1 Study area

Ahmedabad city of India, is located on the bank of the seasonal river Sabarmati in the western state of Gujarat. The city's weather is hot and dry, with T_{max} reaching above 45°C in the summers. In recent years, the city has experienced rapid expansion and development in urban boundaries, thereby making the environment conducive to UHI effects. In retrospect, the city of Ahmedabad is facing frequent heat-associated deaths; a major heatwave event in May 2010 resulted in 1,344 additional deaths [13]. The absolute T_{max} cutoffs are used to classify the heatwave events in Ahmedabad, where IMD weather stations' single-day $T_{max} \geq 40$°C for plains and ≥ 30°C for hilly regions are characterized as heatwaves [23].

In response, the city's government developed a Heat Action Plan (HAP) in 2013 [24,25] to facilitate heatwave awareness and adaptation strategies among the population. HAP of Ahmedabad city has aided in avoiding an estimated 1,190 (95%CI 162–2,218) average annualized deaths [16]. Therefore, Ahmedabad is an ideal location to outline the effects of EHEs on all-cause mortality to support existing HAP in the city.

2.2 Data sources

We obtained daily all-cause mortality data (including accidental deaths) from the Ahmedabad Municipal Corporation (AMC) office of the Registrar of Births and Deaths from 2002 to 2018. The census population for the respective period was obtained from the Office of the Registrar General Census, Indian Census Bureau [26]. The daily temperature records for the same period, including maximum temperature (T_{max}), minimum temperature (T_{min}), and average temperature (T_{avg}), were retrieved from ERA5 reanalysis (ECMWF Reanalysis 5th Generation) products. ERA5 provides hourly estimates of climate variables, and the data cover the earth on a 30km grid and resolve the atmosphere using 137 levels from the surface up to a height of 80km. Detailed information on the ERA5 reanalysis product is available at https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era5. In addition, monthly weather station data of Ahmedabad city was also obtained from the Indian Institute of Tropical Meteorology (IITM), Pune, to cross-check the accuracy of the ERA5 reanalysis product. Due to the limited data availability of daily Ahmedabad meteorological records, we used the ERA5 reanalysis product as a substitute for the weather station.

We identified that monthly T_{max} in the ERA5 dataset is comparable to weather station observations, and gridded spatial continuity of ERA5 can have advantages over in-situ measurements for regional modeling applications [27]. The study identified that ERA5 reanalysis product data could adequately report daily weather recordings for Ahmedabad city; a strong R^2 coefficient (0.85) along with a low RMSE (5.44) was identified between the two datasets ***(Supplementary fig.1)***.

2.3 Statistical analysis

Mann Kendall test (at a 95% confidence interval) was used to understand the data trend over time, and the significance of the trend was estimated using the *Kendal* package in *R* software (version 3.4.0). We used Distributed Lag Non-Linear Model (DLNM) to assess the temperature-associated mortality risk available through the *DLNM* package of R software [28]. A maximum lag of 21 days was applied to the daily data matrix to identify T_{max}'s non-linear and delayed effects on mortality. The lag days on the daily data matrix were selected based on the literature [29–31]. The model equation is described below:

$$Log[Y] \sim cb(T, lag) + ns(date, 7\ per\ year) + DOW + Holiday + \log(Population)$$

Here, Y is the daily all-cause mortality or deaths; T is the exposure variable of T_{max} and $T_{min,}$ and *lag* is the lag days. In cross-basis (cb) matrix, basic spline (*bs*) function with seven degrees of freedom (*df*) was used for daily T_{max}, with the three internal knots placed at equal intervals on the log scale. A natural cubic spline (*ns*) with seven *df* was used to control the seasonal effects. The dummy variables of days of the week (*DOW*) and holidays were also included in the model. Additionally, the population log was used as an offset variable to control population effects over mortalities. Cumulative temperature-mortality associations were then identified for lags of up to 21 days. The sensitivity analysis was conducted to confirm the robustness of the model, and the lag range of up to 21 days was examined. Four to seven *df* values were tested for temperature's long-term effects. The lowest Akaike Information Criterion (AIC) values of models were used as the selection criteria.

2.4 Classification of Extreme Heat Events

We investigated how different thresholds of EHEs impact the observed relationship between T_{max} and mortality in Ahmedabad city from 2002 to 2018. We included the IMD definition of single-day absolute temperature above 40°C as a comparison since it is currently used to activate Ahmedabad city's heat action plan. Based on the existing literature, relative temperature cut-offs of 85^{th} to 99.5^{th} percentiles were utilized as relative thresholds. The study considered the EHEs classification based on low (i.e., 85^{th} to 95^{th} percentiles) and high intensities (i.e., 97^{th} to 99.5^{th} percentiles) of T_{max} [32,33]. While for absolute temperature thresholds, cut-offs of 40°C, 41°C, and 45°C were considered. The number of EHEs observed during 2002-2018 based on respective absolute and relative thresholds are shown in ***Table 1***.

3. Results

In total, 684,142 deaths were registered from 2002 to 2018 associated with all-cause mortality in Ahmedabad city of India. Overall, 60% of total deaths were reported among males ***(Table 2)***, with an overall increasing mortality trend among both gender during the study period (***Fig.1)***. The results of the Mann-Kendall test confirmed a significant positive mortality trend (k-tau= 0.59, p-value <0.001) in the city over the years.

During the study period, the daily T_{max} in Ahmedabad city ranged from 15°C to 45°C ***(Table 2)***. The trend of monthly T_{max}, T_{min} and T_{avg} from 2002-2018 is depicted in ***Fig.2***. A steep rise in the slope of T_{min} was identified compared to T_{max} and T_{avg}, which may be a result of severe UHI in the city. The exposure-response curve of the all-age and all-sex population obtained using the DLNM model revealed a typical *'J'* shape with elevated mortality risk on both sides of the temperature distribution, compared to the MMT of 26°C ***(Fig.3)***. MMT represents the temperature at which mortality reaches its minimum value. Thus, mortality attributable to heat is represented on the right side of MMT (red-colored), while cold-attributable mortality is represented to the left (blue-colored).

We further investigated lag and gender-specific temperature-mortality association, and a *minimum mortality risk* temperature of 26°C was set as the centering value for exposure-response curves ***(Fig.4)***. The temperature mortality relationship showed a higher relative risk of all-cause mortality with T_{max}>35°C, and a less pronounced effect for T_{max}<25°C. The all-sex mortality risk varied drastically between the lower temperature range of 17°C (RR: 1.40; 95% CI: 1.06-1.83) and the higher temperature range of 45°C (RR:4.50; 95% CI: 3.63-5.58). ***Table 3*** presents gender-stratified mortality risks for relative and absolute T_{max} thresholds to provide comparative evidence. The findings suggested that mortality risk for all-age-sex-specific populations increased by 16% when using the 85th percentile temperature threshold (RR:1.16; 95% CI: 1.13-1.19). Further, the mortality risk increased to RR:1.22 (95% CI: 1.18-1.26) and RR:1.92 (95% CI: 1.83-2.01) when using the extreme temperature threshold of 90th and 99.5th percentile, respectively. Likewise, using a single-day absolute T_{max} above 40°C as the cut-off threshold resulted in a 34% increase in mortality risk (RR:1.34; 95% CI: 1.29-1.39). As expected, the highest risk was observed when we used 45°C as the threshold (RR:4.50; 95% CI: 3.63-5.58).

Analysis stratified by gender showed higher EHE-related mortality risk among females than males ***(Table 3)***. For example, when T_{max} exceeded 40°C, mortality risk among males increased by 29% (RR:1.29; 95% CI: 1.33-1.35), compared to a 44% increase in risk among females (RR:1.41; 95% CI: 1.33-1.50). Additionally, the mortality risk during severe heatwave events (T_{max} ≥ 45°C) was considerably higher among females (RR: 5.15; 95% CI: 3.68-7.21) compared to males (RR:4.08; 95% CI: 3.09-5.39). Lag-specific analysis ***(Fig.5)*** showed the mortality risk to be highest during the day of exposure (lag 0), with the risk decreasing with increasing lag time. Significant increases in mortality risks were identified up to a lag of two days at lower percentiles of T_{max}. However, higher thresholds (relative and absolute) resulted in a more sustained lag effect. For example, 40°C as a cut-off threshold resulted in increased mortality risk at lag0 and lag1, while using 45°C as a threshold resulted in increased mortality risk from lag 0 through lag 7 days. A significantly increased mortality risk was also identified after a lag of 16 days with 45°C as a threshold, which may be an effect of long-term and continuous exposure to extreme heat days.

3 Discussion

Previous studies have extensively documented the impact of extreme heat exposure on mortality and morbidity. However, several important factors are less understood, such as how the local population adapts to these extreme heat exposure, how different thresholds used to define these extreme events impact observed association, and whether or not the timing of exposure has an implication on observed health burden. Using long historical records (2002-2018) of daily mortality data (684k deaths) recorded in Ahmedabad city, we showed that higher thresholds correspond to a stronger association between EHEs and mortality. More interestingly, we observed that higher thresholds resulted in more sustained risk, lasting up to seven days after the exposure compared to the day observed for lower thresholds. Irrespective of the thresholds used, females appeared to be at higher risk of death from exposure to EHE.

Even though a greater risk was identified to higher intensities of EHEs, low intensities also considerably increased the mortality risk among our study population. Several regional studies have established a higher mortality risk during heatwave periods [6,13]. However, such studies have not quantified the effect of different intensities of EHEs. Moreover, our study identified that a lower temperature range (i.e., T_{max}<17°C) also significantly increases all-cause mortality, which can have significant implications during wintertime.

We also observed higher EHE-related mortality risk among women compared to men. This finding is consistent with other studies of heatwave-related deaths that have reported higher risk among females than males [34–37]. Similarly, a previous study focusing on Ahmedabad's May 2010 Heatwave noted higher female death rates [13]. Previous studies have hypothesized that females' sweat glands are activated at higher temperatures than males causing less heat exchange between the body and environment, which may put women at a higher risk of heat-related mortality [38–40]. Besides, social and cultural norms, including the higher burden of household activities and culturally influenced dressing practices resulting in a higher exposure propensity among women, may explain some of the higher risks [41].

While one might think heat is an indiscriminate killer, however our study confirms women are at higher risk of heat-associated deaths. These findings demand attention particularly for women in developing nations where poverty, social and cultural norms and gender inequity is deeply rooted. The socio-cultural practice, as in many developing countries expect women to stay indoors for household chores which may increase their exposure to indoor heating. To a considerable extent, cooking areas in many Indian households are poorly ventilated [42] and women spend much of their time indoors in cooking areas which exposes them to higher heat effects. Thus, these findings strongly suggest policymakers in developing countries must consider gender-specific heatwave prevention plans. Moreover, low cost household cooling strategies can be lifesaving [43].

From the lag exposure standpoint, the highest risk in Ahmedabad City was observed on the day of exposure, consistent with what has been reported for Varanasi, India [34]. The lag-specific analysis suggests that the impact of more intense heat exposure in Ahmedabad persists for up to seven days after exposure. Public health preparedness and response activities need to account for these subtleties.

Even though this study addressed crucial information about temperature-associated mortality risk, several shortcomings are noted. For instance, the study did not consider individual temperature exposure for evaluation. Likewise, we did not estimate age-specific effects due to data limitations. The mortality rates calculated in the study assumed that population growth remained stagnant for 10 years and utilized census-based population data, updated once per decade, as the denominator. All-cause mortality data that we used in this study (including accidental deaths) for heat-health analysis are generally reliable. We did not use cause-specific mortality data because this information was not available and for India per se, there are several potential issues with cause-specific mortality data; firstly, reporting conventions are not uniform across the country making comparisons between different cities difficult, and secondly, in some regions, the causes of death are not accurately reported if it is case sensitive. In addition, some of the deaths may go unreported, resulting in an underestimation. Moreover, underlying comorbidities could not be accounted for, as such information was unavailable. Likewise, we did not account for other environmental exposures, including air pollution. Finally, while the agreement between ERA5 data and weather stations were very good, the ERA5 data teneded to underestimate the maximum temperature slightly. However this did not differ between heat wave vs non heat wave period, so the potential exposure misclassification is non-differential.

Despite these potential concerns, applying these results is crucial to fill the knowledge gap in heat alert systems and policymaking. Identifying local MMT or an optimum temperature threshold can intensify heatwave prevention measures. With the increasing frequency, duration and intensity of extreme weather events, future heat action plans and management guidelines require consideration of EHEs to minimize the societal and life losses associated with temperature rise. The findings of this study can benefit local government, the health sector, and urban planners to develop effective area-specific integrated risk management measures for reducing heat-associated fatalities. Moreover, the health risk of various temperature intensities or EHEs can facilitate a cost-effective heatwave early warning system.

Conclusion

There is an urgent need to develop local-level heat action plans and early warning systems to enhance community resilience to the threats of climate change-driven extreme heat events. An in-depth understanding of location-specific minimum mortality temperature and the implication of using different thresholds on actual disease burden will help inform appropriate heat action plans and early warning systems. Our data show that magnitude of the risk is related to the scientific threshold used to identify extreme heat events. Likewise, higher threshold results in more sustained risk that exceeds the day of exposure. Additional studies are needed to understand cause-specific death associated with high vs. low-intensity extreme heat events and sustained elevated risk.

Conflict of interest

The authors declare no conflicts of interest.

Acknowledgments

We are highly grateful to the Ahmedabad Municipal Corporation (AMC) office of the Registrar of Births and Deaths for sharing the all-cause mortality data of the city. We would also like to thank the study funders, including the Ministry of Science and Technology (MOST) of Taiwan, National Science Foundation, Swedish Research Council for Health, Working Life and Welfare and Academia Sinica. The work would not have been possible without their financial support.

Fundings

This study is funded by the Taiwan Ministry of Science and Technology (MOST 108-2625-M-033-002, MOST 109-2621-M-033-001-MY3, MOST 109-2625-M-033-002, and MOST 110-2625-M-033-002). Grants from the National Science Foundation and Swedish Research Council for Health, Working Life and Welfare (Forte) (project 2019-01552) provided further support through Belmont Forum (Award Number (FAIN): 2025470). In addition, we are also thankful to Academia Sinica (AS-SS-111-03) for their extended financial support.

4 References

1. Sixth Assessment Report of Intergovernmental Panel on Climate Change (IPCC)*Climate Change 2021, The Physical Science Basis*; 2021; Vol. IPCC AR6 W;

2. Dimitrova, A.; Ingole, V.; Basagaña, X.; Ranzani, O.; Milà, C.; Ballester, J.; Tonne, C.Association between ambient temperature and heat waves with mortality in South Asia: Systematic review and meta-analysis. *Environment International* **2021**, *146*, 106170, doi:https://doi.org/10.1016/j.envint.2020.106170.

3. Hashizume, M.; Wagatsuma, Y.; Hayashi, T.; Saha, S.K.; Streatfield, K.; Yunus, M.The effect of temperature on mortality in rural Bangladesh—a population-based time-series study. *International Journal of Epidemiology* **2009**, *38*, 1689–1697, doi:10.1093/ije/dyn376.

4. Parks, R.M.; Bennett, J.E.; Tamura-Wicks, H.; Kontis, V.; Toumi, R.; Danaei, G.; Ezzati, M.Anomalously warm temperatures are associated with increased injury deaths. *Nature Medicine* **2020**, *26*, 65–70, doi:10.1038/s41591-019-0721-y.

5. Gasparrini, A.; Guo, Y.; Hashizume, M.; Lavigne, E.; Zanobetti, A.; Schwartz, J.; Tobias, A.; Tong, S.; Rocklöv, J.; Forsberg, B.; et al.Mortality risk attributable to high and low ambient temperature: a multicountry observational study. *The Lancet* **2015**, *386*, 369–375, doi:https://doi.org/10.1016/S0140-6736(14)62114-0.

6. Azhar, G.Indian Summer: Three Essays on Heatwave Vulnerability, Estimation and Adaptation. *Indian Summer: Three Essays on Heatwave Vulnerability, Estimation and*

Adaptation **2019**, doi:10.7249/rgsd431.

7. Dutta, P.; Sathish, L.; Mavankar, D.; Ganguly, P.S.; Saunik, S.Extreme Heat Kills Even in Very Hot Cities: Evidence from Nagpur, India. *The international journal of occupational and environmental medicine* **2020**, *11*, 188.

8. Guo, Y.; Gasparrini, A.; Li, S.; Sera, F.; Vicedo-Cabrera, A.M.; deSousa Zanotti Stagliorio Coelho, M.; Saldiva, P.H.N.; Lavigne, E.; Tawatsupa, B.; Punnasiri, K.Quantifying excess deaths related to heatwaves under climate change scenarios: A multicountry time series modelling study. *PLoS medicine* **2018**, *15*, e1002629.

9. Fouillet, A.; Rey, G.; Laurent, F.; Pavillon, G.; Bellec, S.; Guihenneuc-Jouyaux, C.; Clavel, J.; Jougla, E.; Hémon, D.Excess mortality related to the August 2003 heat wave in France. *International archives of occupational and environmental health* **2006**, *80*, 16–24, doi:10.1007/s00420-006-0089-4.

10. Knowlton, K.; Rotkin-Ellman, M.; King, G.; Margolis, H.G.; Smith, D.; Solomon, G.; Trent, R.; English, P.The 2006 California heat wave: impacts on hospitalizations and emergency department visits. *Environmental health perspectives* **2009**, *117*, 61–67.

11. Fouillet, A.; Rey, G.; Laurent, F.; Pavillon, G.; Bellec, S.; Guihenneuc-Jouyaux, C.; Clavel, J.; Jougla, E.; Hémon, D.Excess mortality related to the August 2003 heat wave in France. *International archives of occupational and environmental health* **2006**, *80*, 16–24, doi:10.1007/s00420-006-0089-4.

12. Heaviside, C.; Macintyre, H.; Vardoulakis, S.The urban heat island: implications for health in a changing environment. *Current environmental health reports* **2017**, *4*, 296–305.

13. Azhar, G.S.; Mavalankar, D.; Nori-Sarma, A.; Rajiva, A.; Dutta, P.; Jaiswal, A.; Sheffield, P.; Knowlton, K.; Hess, J.J.Heat-Related Mortality in India: Excess All-Cause Mortality Associated with the 2010 Ahmedabad Heat Wave. *PLOS ONE* **2014**, *9*, e91831.

14. Wang, D.; Lau, K.K.-L.; Ren, C.; Goggins, W.B.I.I.I.; Shi, Y.; Ho, H.C.; Lee, T.-C.; Lee, L.-S.; Woo, J.; Ng, E.The impact of extremely hot weather events on all-cause mortality in a highly urbanized and densely populated subtropical city: A 10-year time-series study (2006–2015). *Science of The Total Environment* **2019**, *690*, 923–931, doi:https://doi.org/10.1016/j.scitotenv.2019.07.039.

15. Rathi, S.K.; Sodani, P.R.Summer temperature and all-cause mortality from 2006 to 2015 for Hyderabad, India. *African Health Sciences* **2021**, *21*, 1474–1481.

16. Hess, J.J.; Lm, S.; Knowlton, K.; Saha, S.; Dutta, P.; Ganguly, P.; Tiwari, A.; Jaiswal, A.; Sheffield, P.; Sarkar, J.Building resilience to climate change: pilot evaluation of the impact of India's first heat action plan on all-cause mortality. *Journal of environmental and public health* **2018**, *2018*.

17. Wei, Y.; Tiwari, A.S.; Li, L.; Solanki, B.; Sarkar, J.; Mavalankar, D.; Schwartz, J.Assessing mortality risk attributable to high ambient temperatures in Ahmedabad, 1987 to 2017. *Environmental research* **2021**, *198*, 111232.

18. López-Bueno, J.A.; Díaz, J.; Follos, F.; Vellón, J.M.; Navas, M.A.; Culqui, D.; Luna, M.Y.; Sánchez-Martínez, G.; Linares, C.Evolution of the threshold temperature definition of a heat wave vs. evolution of the minimum mortality temperature: a case study in Spain during the 1983–2018 period. *Environmental Sciences Europe* **2021**, *33*, 101, doi:10.1186/s12302-021-00542-7.

19. Nori-Sarma, A.; Anderson, G.B.; Rajiva, A.; ShahAzhar, G.; Gupta, P.; Pednekar, M.S.; Son, J.-Y.; Peng, R.D.; Bell, M.L.The impact of heat waves on mortality in Northwest India. *Environmental research* **2019**, *176*, 108546.

20. India Metrological DepartmentIndian Metrological Department (IMD) 2018, *3*, 1–119.

21. Robinson, P.J.On the definition of a heat wave. *Journal of Applied Meteorology and Climatology* **2001**, *40*, 762–775.

22. Follos, F.; Linares, C.; López-Bueno, J.A.; Navas, M.A.; Culqui, D.; Vellón, J.M.; Luna, M.Y.; Sánchez-Martínez, G.; Díaz, J.Evolution of the minimum mortality temperature (1983–2018): Is Spain adapting to heat? *Science of The Total Environment* **2021**, *784*, 147233, doi:https://doi.org/10.1016/j.scitotenv.2021.147233.

23. National Disaster Management Authority (NDMA)Heat Wave Available online: https://www.ndma.gov.in/Natural-Hazards/Heat-Wave (accessed on Oct 17, 2022).

24. Dutta, P.; Golechha, M.; Mavalankar, D.Prioritising climate change and health: The current status of heat-health in India. *Climate Change and the Health Sector* **2021**, 106–115.

25. Knowlton, K.; Kulkarni, S.P.; Azhar, G.S.; Mavalankar, D.; Jaiswal, A.; Connolly, M.; Nori-Sarma, A.; Rajiva, A.; Dutta, P.; Deol, B.; et al.Development and Implementation of South Asia's First Heat-Health Action Plan in Ahmedabad (Gujarat, India). *International Journal of Environmental Research and Public Health* 2014, *11*.

26. Ahmedabad City Census 2011 data Available online: https://www.census2011.co.in/census/city/314-ahmedabad.html (accessed on Oct 25, 2019).

27. Crossett, C.C.; Betts, A.K.; Dupigny-Giroux, L.-A.L.; Bomblies, A.Evaluation of Daily Precipitation from the ERA5 Global Reanalysis against GHCN Observations in the Northeastern United States. *Climate* 2020, *8*.

28. Gasparrinia, A.; Armstrong, B.; Kenward, M.G.Distributed lag non-linear models. *Statistics in Medicine* **2010**, *29*, 2224–2234, doi:10.1002/sim.3940.

29. Fu, S.H.; Gasparrini, A.; Rodriguez, P.S.; Jha, P.Mortality attributable to hot and cold ambient temperatures in India: a nationally representative case-crossover study. *PLoS medicine* **2018**, *15*, e1002619.

30. Guo, Y.; Punnasiri, K.; Tong, S.Effects of temperature on mortality in Chiang Mai city, Thailand: a time series study. *Environmental Health* **2012**, *11*, 36, doi:10.1186/1476-069X-11-36.

31. Guo, Y.; Gasparrini, A.; Armstrong, B.; Li, S.; Tawatsupa, B.; Tobias, A.; Lavigne, E.; Coelho, M. de S.Z.S.; Leone, M.; Pan, X.Global variation in the effects of ambient temperature on mortality: a systematic evaluation. *Epidemiology (Cambridge, Mass.)* **2014**, *25*, 781.

32. Huang, C.; Cheng, J.; Phung, D.; Tawatsupa, B.; Hu, W.; Xu, Z.Mortality burden attributable to heatwaves in Thailand: A systematic assessment incorporating evidence-based lag structure. *Environment International* **2018**, *121*, 41–50, doi:https://doi.org/10.1016/j.envint.2018.08.058.

33. Xu, Z.; FitzGerald, G.; Guo, Y.; Jalaludin, B.; Tong, S.Impact of heatwave on mortality under different heatwave definitions: A systematic review and meta-analysis. *Environment International* **2016**, *89–90*, 193–203, doi:https://doi.org/10.1016/j.envint.2016.02.007.

34. Singh, N.; Mhawish, A.; Ghosh, S.; Banerjee, T.; Mall, R.K.Attributing mortality from temperature extremes: A time series analysis in Varanasi, India. *Science of the Total Environment* **2019**, *665*, 453–464.

35. Lung, S.-C.C.; Yeh, J.-C.J.; Hwang, J.-S.Selecting Thresholds of Heat-Warning Systems with Substantial Enhancement of Essential Population Health Outcomes for Facilitating Implementation. *International journal of environmental research and public health* **2021**, *18*, 9506.

36. Faye, M.; Dème, A.; Diongue, A.K.; Diouf, I.Impact of different heat wave definitions on daily mortality in Bandafassi, Senegal. *PloS one* **2021**, *16*, e0249199.

37. Tong, S.; FitzGerald, G.; Wang, X.-Y.; Aitken, P.; Tippett, V.; Chen, D.; Wang, X.; Guo, Y.Exploration of the health risk-based definition for heatwave: A multi-city study. *Environmental research* **2015**, *142*, 696–702.

38. Kuchcik, M.Mortality and thermal environment (UTCI) in Poland-long-term, multi-city study. *International journal of biometeorology* **2021**, *65*, 1529–1541, doi:10.1007/s00484-020-01995-w.

39. Hajat, S.; Kovats, R.S.; Lachowycz, K.Heat-related and cold-related deaths in England and Wales: who is at risk? *Occupational and environmental medicine* **2007**, *64*, 93–100.

40. Rey, G.; Fouillet, A.; Bessemoulin, P.; Frayssinet, P.; Dufour, A.; Jougla, E.; Hémon, D.Heat exposure and socio-economic vulnerability as synergistic factors in heat-wave-related mortality. *European journal of epidemiology* **2009**, *24*, 495–502.

41. McGregor, G.R.; Bessmoulin, P.; Ebi, K.; Menne, B.*Heatwaves and health: guidance on warning-system development.*; WMOP, 2015; ISBN 9263111421.

42. Padhi, B.K.; Padhy, P.K.Domestic fuels, indoor air pollution, and children's health: the case of rural India. *Annals of the New York Academy of Sciences* **2008**, *1140*, 209–217.

43. Sharma, A.; Andhikaputra, G.; Wang, Y.-C.Heatwaves in South Asia: Characterization, Consequences on Human Health, and Adaptation Strategies. *Atmosphere* 2022, *13*.

List of Figures

The effects of extreme heat events on all-cause mortality: A case study in Ahmedabad city of India, 2002-2018

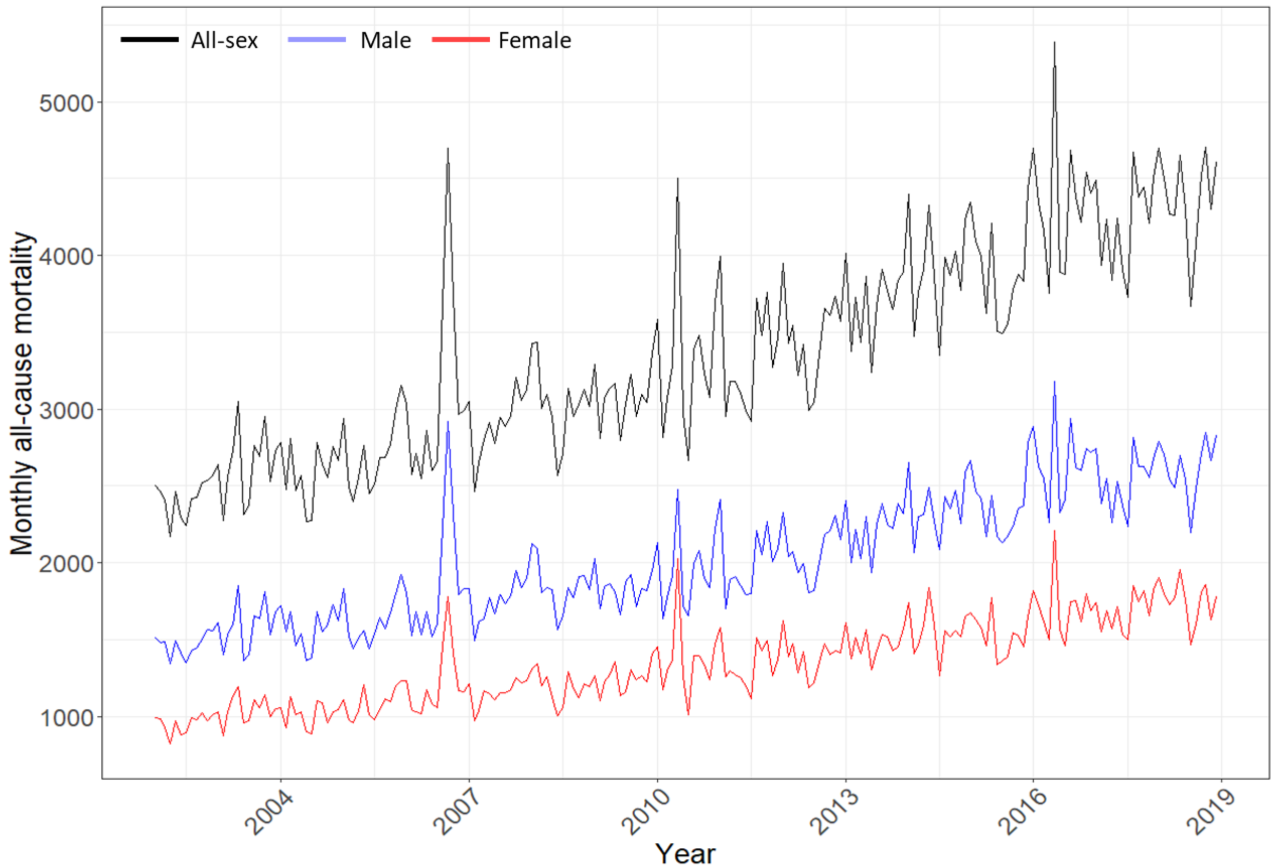


Fig.1 Trend of monthly gender-stratified all-cause mortality from 2002-2018 in Ahmedabad, India

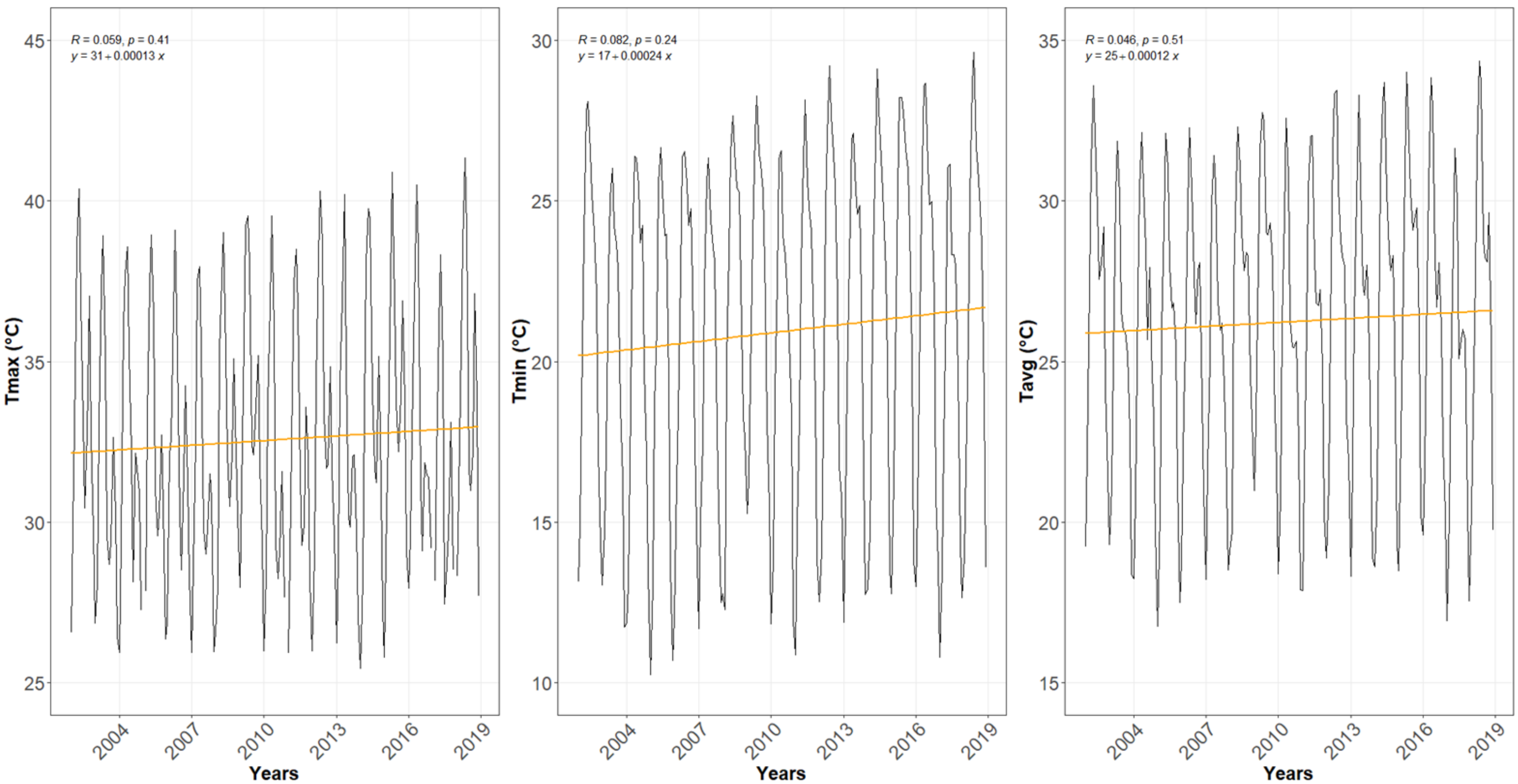


Fig.2 Trends of average monthly (a) Maximum Temperature (T_{max}) (b) Minimum Temperature (T_{min}) (c) Average Temperature (T_{avg}) in Ahmedabad, India, from 2002-2018

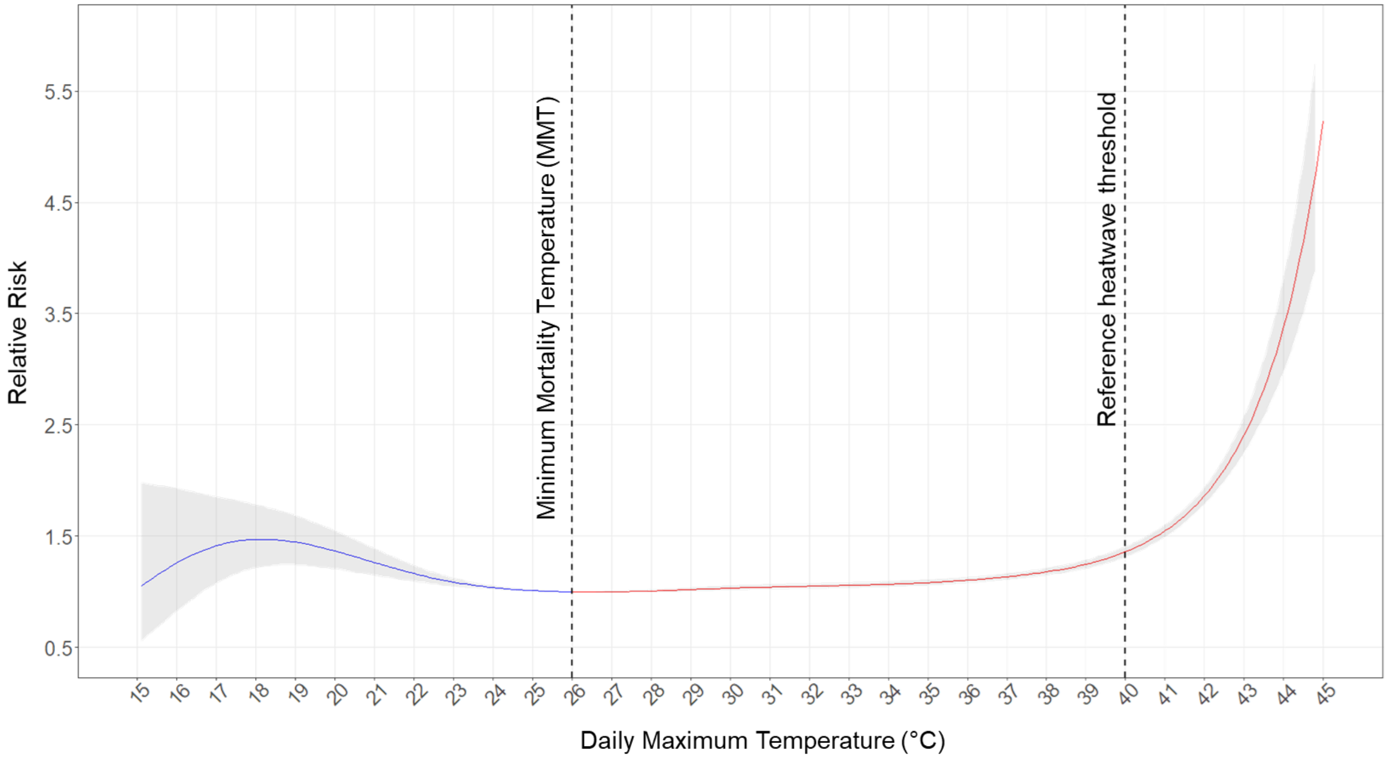


Fig.3 Temperature–mortality relationship for lag 0–21 days from 2002-2018. Dotted vertical line shows the minimum mortality temperature (MMT) and reference heatwave threshold for Ahmedabad.

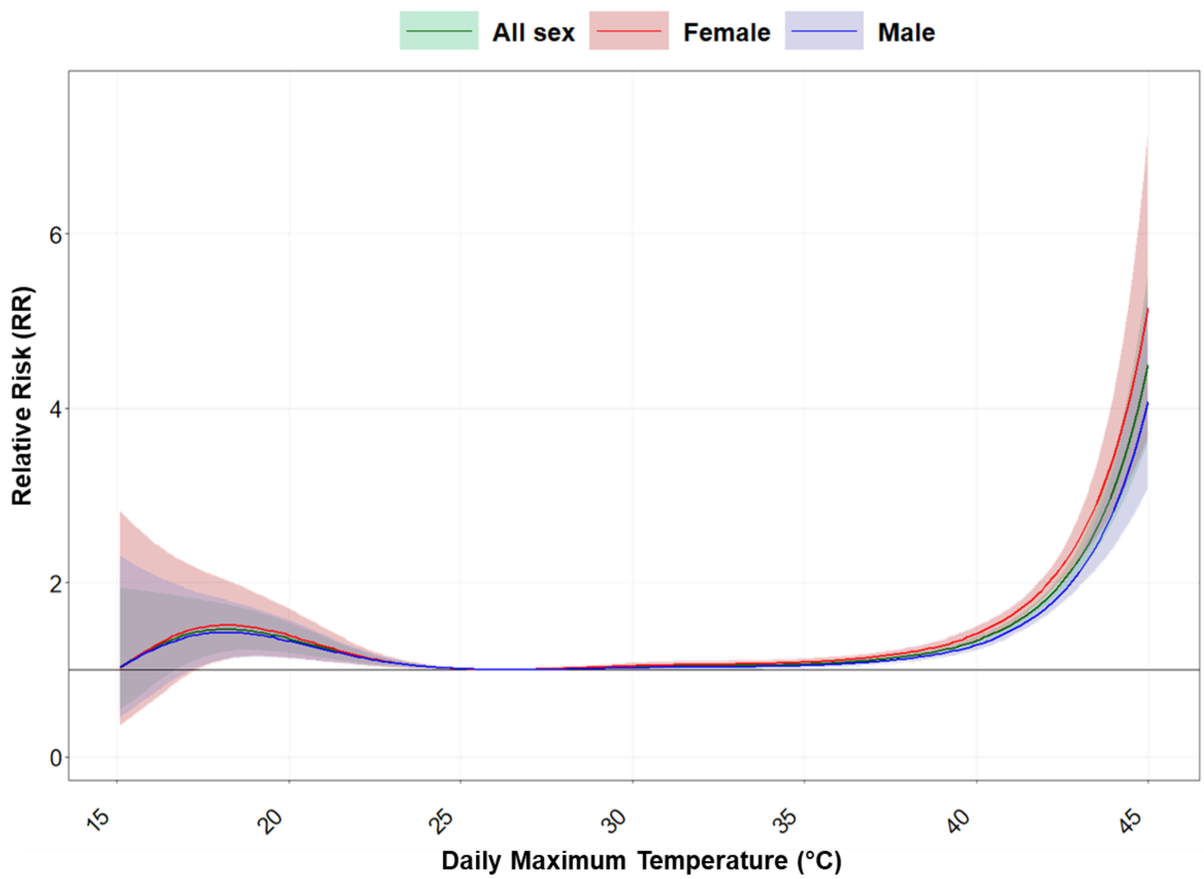


Fig. 4 Exposure-response relationship between T_{max} and all-cause mortality by gender (with 95% empirical confidence interval, shaded) over a lag of 21 days in Ahmedabad from 2002-2018.

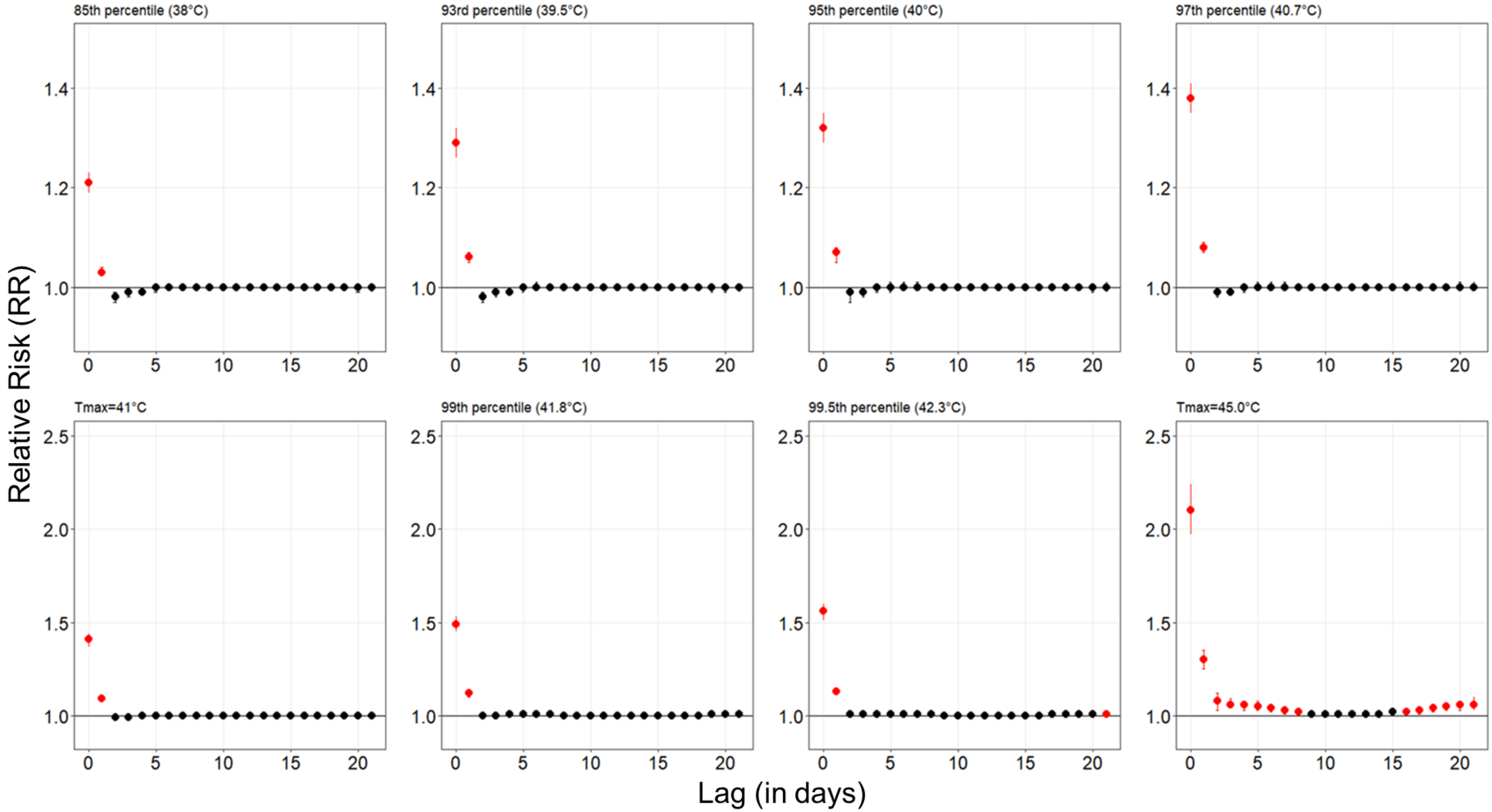


Fig. 5 Lag-specific effect on the relative risk (RR) (at 95% CI) of all-cause mortality at different temperature thresholds in Ahmedabad from 2002-2018 [Red colored error bars represent significant positive RR, while the black represents non-significant RR]

List of Tables

The effects of extreme heat events on all-cause mortality: A case study in Ahmedabad city of India, 2002-2018

Table 1- Threshold based classification of different extreme heat events in Ahmedabad city of, India, from 2002 to 2018

EHEs threshold	**EHEs intensity**	**EHEs definition**	**No. of days**
Absolute		$T_{max} \geq 40°C$	322
		$T_{max} \geq 41°C$	164
		$T_{max} \geq 45°C$	2
Relative	Low	$T_{max} \geq P85$	952
		$T_{max} \geq P90$	652
		$T_{max} \geq P93$	449
	High	$T_{max} \geq P95$	322
		$T_{max} \geq P97$	198
		$T_{max} \geq P99$	77
		$T_{max} \geq P99.5$	33

Note: P85 to P99.5 represent the 85^{th} to 99.5^{th} percentile values

Table 2- Daily number of all-cause mortality and weather variables from 2002-2018 in Ahmedabad, India

	Total Deaths (%)	**Average daily deaths/100,000**	**Mean**	**Min**	**P50**	**P95**	**Max**
Total deaths	684,142 (100)	2.19	111	49	107	156	315
Male deaths	411,749 (60)	1.32	67	25	64	96	176
Female deaths	272,349 (40)	0.87	44	13	43	64	141
Weather Variables							
T_{max} (°C)	-	-	32	15	32	40	45
T_{min} (°C)	-	-	21	6	23	28	32
T_{avg} (°C)	-	-	26	13	27	33	37

Note: P50 and P95 represent the 50^{th} and 95^{th} percentile values

Table 3- Relative risk (at 95% CI) of all-cause mortality at different temperature thresholds in Ahmedabad, India, from 2002-2018

Temperature thresholds	**All-sex RR (95% CI)**	**Male RR (95% CI)**	**Female RR (95% CI)**
T_{max}=40°C	1.34 (1.29, 1.39)	1.29 (1.33, 1.35)	1.41 (1.33, 1.50)
T_{max}=41°C	1.51 (1.46, 1.57)	1.45 (1.38, 1.52)	1.62 (1.53, 1.72)
T_{max}=45°C	4.50 (3.63, 5.58)	4.08 (3.09, 5.39)	5.15 (3.68, 7.21)
P85 (38.0°C)	1.16 (1.13, 1.19)	1.13 (1.09, 1.17)	1.20 (1.15, 1.26)
P90 (38.9°C)	1.22 (1.18, 1.26)	1.18 (1.14, 1.23)	1.27 (1.21, 1.34)
P93 (39.5°C)	1.28 (1.23, 1.32)	1.23 (1.18, 1.29)	1.34 (1.27, 1.42)
P95 (40.0°C)	1.34 (1.29, 1.39)	1.29 (1.33, 1.35)	1.41 (1.33, 1.50)
P97 (40.7°C)	1.45 (1.40, 1.51)	1.39 (1.33, 1.46)	1.55 (1.46, 1.64)
P99 (41.8°C)	1.73 (1.67, 1.80)	1.64 (1.56, 1.73)	1.88 (1.76, 2.00)
P99.5 (42.3°C)	1.92 (1.83, 2.01)	1.81 (1.70, 1.92)	2.09 (1.95, 2.25)

Declaration of interests

☒ The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

☐The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

CRediT author statement

Ayushi Sharma and Yu-Chun Wang: Conceptualization; Priya Dutta, Priyanka Shah, Hao He and Veena Iyer: Data curation; Yu-Chun Wang, Amir Sapkota, and Chuansi Gao: Funding acquisition; Ayushi Sharma: Formal analysis; Ayushi Sharma and Yu-Chun Wang: Writing - Original Draft; Ayushi Sharma, Priya Dutta, Priyanka Shah, Veena Iyer, Hao He, Amir Sapkota, Chuansi Gao, Yu-Chun Wang: Writing – Review & Editing

All authors read and approved the final version of the manuscript.