

# BMJ Open Warmer summer nocturnal surface air temperatures and cardiovascular disease death risk: a population-based study

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## ABSTRACT

**Background** In recent summers, some populous mid-latitude to high-latitude regions have experienced greater heat intensity, more at night than by day. Such warming has been associated with increased cause-specific adult mortality. Sex-specific and age-specific associations between summer nocturnal surface air temperatures (SAT) and cardiovascular disease (CVD) deaths have yet to be established.

**Methods** A monthly time series analysis (June–July, 2001–2015) was performed on sex-specific CVD deaths in England and Wales of adults aged 60–64 and 65–69 years. Using negative binomial regression with autocorrelative residuals, associations between summer (June–July) nocturnal SAT anomalies (primary exposure) and CVD death rates (outcome) were computed, controlling for key covariates. To explore external validity, similar associations with respect to CVD death in King County, Washington, USA, also were calculated, but only for men aged 60–64 and 65–69 years. Results are reported as incidence rate ratios.

**Results** From 2001 to 2015, within these specific cohorts, 39 912 CVD deaths (68.9% men) were recorded in England and Wales and 488 deaths in King County. In England and Wales, after controlling for covariates, a 1°C rise in anomalous summer nocturnal SAT associated significantly with a 3.1% (95% CI 0.3% to 5.9%) increased risk of CVD mortality among men aged 60–64, but not older men or either women age groups. In King County, after controlling for covariates, a 1°C rise associated significantly with a 4.8% (95% CI 1.7% to 8.1%) increased risk of CVD mortality among those <65 years but not older men.

**Conclusion** In two mid-latitude regions, warmer summer nights are accompanied by an increased risk of death from CVD among men aged 60–64 years.

## BACKGROUND

Cardiovascular disease (CVD) is a principal cause of death among adult men and women habiting high-income nations.<sup>1</sup> With warm spells of extreme or sustained elevation in average summer surface air temperatures (SAT) occasioning surges in deaths and hospitalisations,<sup>2–5</sup> their potential contribution to cardiovascular events has been a focus of vigorous recent research.<sup>6</sup> Findings thus far, with respect to age and sex, have

## Strengths and limitations of this study

- Previous population-based studies have shown that summer night-time ambient temperatures are associated with increased risk for either all-cause, heat-related or cardiovascular mortality.
- Sex-specific and age-specific associations between variations in summer night-time air temperatures and cardiovascular disease mortality have not been reported.
- From 2001 to 2015, warmer summer nocturnal (but not diurnal) surface air temperatures (SAT) were associated with significantly increased risk of cardiovascular mortality among men aged 60–64 in both England and Wales and King County, Washington, USA.
- The principal strength of this ecological study accrues from the large population sampled and its linkage with rigorous national mortality and meteorological data.
- The principal limitations are unavailability of 15-year sex- and age-specific weekly outcome and exposure data and the inability to infer causality from these models.

been inconsistent.<sup>6</sup> Some European studies, focusing principally on daytime recordings, report that extreme summer average and/or diurnal SAT increase the risks of all-cause, heat-related and CVD mortality to a greater extent in older (≥65 years) women than men.<sup>5 7–9</sup> Other European studies report the opposite, with men more at risk of an acute CVD event during periods of extreme summer SAT.<sup>10 11</sup> Some have also identified a significant effect of summer average/diurnal SAT on CVD mortality among men aged <65 years.<sup>11–13</sup> Social determinants, including the low prevalence of residential air-conditioning in Europe, may contribute to such variance.<sup>9 14</sup>

In recent summers, some populous mid-latitude to high-latitude regions have experienced greater intensification of nocturnal than daytime heat,<sup>15</sup> with consequent adverse effects on human health.<sup>4 15–17</sup> Anomalously high death rates in the elderly coincident with

the 2003 French heatwave were attributed specifically to elevated nocturnal SAT,<sup>18</sup> and more recently, the magnitude and duration of nocturnal thermal excess was linked to several southern European cities' CVD and respiratory mortality rates.<sup>17</sup> Middle-aged to older-aged populations are generally more vulnerable to intravascular volume depletion when exposed to heat,<sup>19</sup> with consequent hypotension, thrombocytosis and hyperlipidaemia.<sup>3 19</sup> Such maladaptation, often exacerbated by more sedentary behaviour<sup>20</sup> and by disrupted or insufficient sleep,<sup>21</sup> may render men more vulnerable than women to CVD events when exposed to anomalously high average summer SAT.<sup>3 5 19</sup>

There are few present age-specific or sex-specific data concerning associations between summer nocturnal SAT and CVD mortality. We posited that summer nocturnal SAT anomalies (defined as deviations from 30-year [1981–2010] baseline averages<sup>22</sup>) associate with increased CVD mortality among men and women between the ages of 60 and 69 years. To test this hypothesis, we acquired English and Welsh population-based data encompassing the years 2001–2015. Because heatwaves in the UK are most frequent and intense during June and July,<sup>23</sup> we acquired exposure data specific to these 2 months. To assess external validity, we secured corresponding information for King County, Washington, USA, a likewise sea-facing region, at parallel latitude to England and Wales, with comparable land-ocean atmospheric properties and similarly low prevalence of residential air conditioning.<sup>24</sup> These two jurisdictions also were selected because of their large populaces, of whom the majority (~90%) resides in urban or semiurban 'heat-islands', readily accessible statistics, and data affirming that over this time-span both regions witnessed greater increases in night-time than daytime SAT.<sup>15</sup>

## METHODS

### Climatological exposure data

Mid-latitude to high-latitude regions, such as England and Wales and the State of Washington experience similar seasonal cycles, in which diurnal and nocturnal SAT are much higher in summer than winter.<sup>25</sup> Guided by previous observations of positive associations between summer nocturnal SAT and mortality,<sup>5 16</sup> we ascertained, for June and July, minimum SAT for England and Wales (collectively) and King County, Washington, USA from the Meteorology (Met) Office UK: <https://www.metoffice.gov.uk/research/climate/maps-and-data/uk-and-regional-series> and the National Oceanic and Atmospheric Administration: <https://www.ncdc.noaa.gov/cag/county/time-series>, respectively. The Met Office provides the most accurate and reliable providers of this information in the UK, with a geospatial resolution of 1 km×1 km.<sup>26</sup>

Minimum SAT was used as a proxy for nocturnal SAT.<sup>15</sup> Since air pollution (ie, through particulate matter 2.5 (PM<sub>2.5</sub>)) can influence local CVD events,<sup>27</sup> we included

United States Environmental Protection Agency (EPA): <https://www.epa.gov/outdoor-air-quality-data/download-daily-data>. PM<sub>2.5</sub> data averaged for June and July of each year in our models for the smaller region of King County.

### CVD mortality data

In this population-based study, England and Wales sex-specific and age-specific deaths attributed to CVD and mental and behavioural disorders occurring in June and July (in Europe, mental and behavioural disorders are an established strong risk factor for CVD death among adults over 60 years of age<sup>28</sup>) for the years 2001–2015 were extracted from Office for National Statistics (ONS, reference #: 007957) data: <https://www.ons.gov.uk/peoplepopulationandcommunity/birthsdeathsandmarriages/deaths/adhocs/007957deathsbymonthofoccurrenceaged60andoverbysingleyearofagesexandspecifiedcausesenglandandwales2001to2015>. CVD death was defined as per the International Classification of Diseases (ICD), 10th revision (ICD-10: I00–I99) criteria, whereas deaths due to 'mental and behavioural disorders' were defined as ICD-10: F00–F99. For King County, sex-specific and age-specific CVD mortality for June and July for the years 2001–2015 were extracted from Centers for Disease Control and Prevention WONDER data.<sup>24</sup>

Sex-specific analyses were partitioned into two age groups: 60–64 years and 65–69 years. We elected to exclude from analysis younger adults, due to their lower CVD event rates and older adults, since in England the cause of death of individuals ≥75 years of age is likely to be misclassified, due to their higher prevalence of comorbid conditions.<sup>29</sup> Numerators of region-specific CVD deaths were based on the presence of one or more ICD-10 codes listed on each death record in a given month of the year, with denominators established on mid-year annual population estimates for the sum of England plus Wales and similarly for King County. Data were stratified by sex and age group. Monthly summer CVD and mental and behavioural mortality rates were computed by region-specific, sex-specific and age-specific deaths occurring each month of the year and were reported as the number of men and women deaths per 100 000 persons.

### Statistical analysis

Since atmospheric systems act on long time-scales, our primary exposures (June and July nocturnal SAT) were standardised as monthly anomalies from a reference period.<sup>22</sup> For the purpose of the present analysis, SAT anomalies were defined as deviations from a 30-year (1981–2010) baseline average.<sup>22</sup> For each year of the exposure period (2001–2015), June and July nocturnal SAT anomalies were computed separately for England and Wales and for King County by subtracting these regions' months' averages from their respective 1981–2010 average nocturnal SAT.

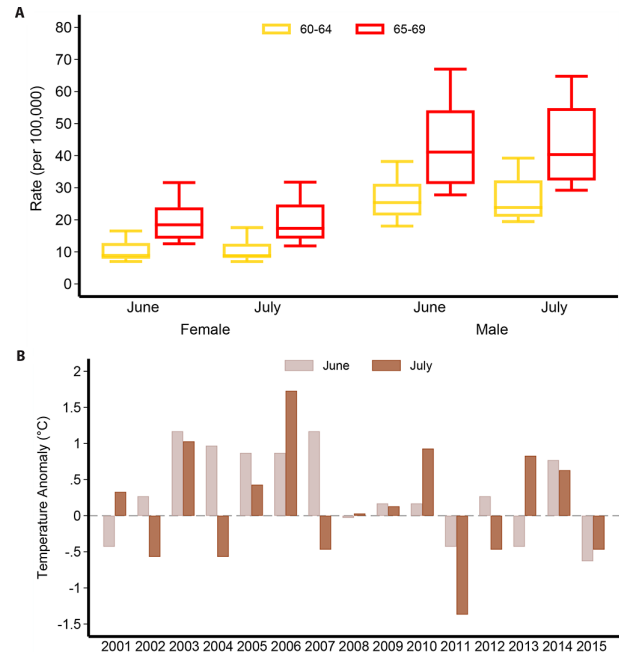
CVD mortality rates were found to be autocorrelated (ie, rates in the prior and subsequent years were significantly

correlated). Additionally, the outcome variable's variance was much greater than its mean, leading to overdispersion of data.<sup>22 30</sup> Moreover, a previous study showed that the incidence of mental health and behavioural distress in England and Wales has both increased over time and been identified as a strong risk factor for associations between diurnal SAT and cause-specific adult mortality.<sup>13</sup> To address these issues in our models, we used negative binomial regression with autocorrelated residuals of order one<sup>22</sup> to assess the association between sex-specific and age-specific CVD mortality rates to summer nocturnal SAT for England and Wales from 2001 to 2015, while controlling for each of mental health and behaviour mortality rates, an increase or decrease in CVD mortality rates with respect to the annual calendar year (i.e. trend) and the summer month as our covariates. For King County, we used quasi-Poisson to assess all associations, while controlling for each of PM<sub>2.5</sub>, an increase or decrease in CVD mortality rates with respect to the annual calendar year (ie, trend), and the summer month as our covariates. Findings are reported as incidence rate ratios (RR) and interpreted as change for one-unit increase of the exposure variable.<sup>22 30</sup> CIs were evaluated at 95%, along with Student's two-sided t-tests. Microsoft Excel (V.2013), RStudio (V.4.1.1), and STATA (V.15) were used for computation, analyses and figure composition.

### RESULTS

Within the selected cohorts, over the years 2001–2015, there were 39 912 (68.9% men) CVD deaths recorded in England and Wales and 488 male CVD deaths (54.1% in the group aged 65–69 years) in King County. Over this time period, CVD rates declined substantially in both regions annually (table 1), and notably over the summer months (online supplemental figure 1).

For England and Wales, CVD mortality rates, categorised by sex, age and month, are illustrated in figure 1A. The older (65–69 years) men and women exhibited higher CVD mortality rates than during both summer



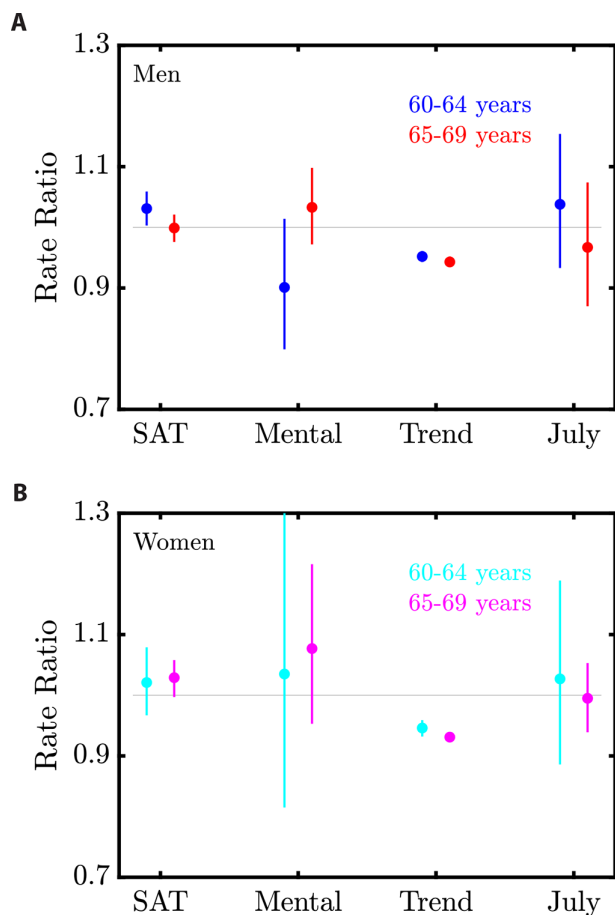
**Figure 1** (A) Data spread for sex-specific monthly summer (June–July) CVD mortality rates among middle-aged and older-aged adults in England and Wales from 2001 to 2015. (B) Month-specific summer (June–July) nocturnal SAT anomalies (based on deviations from the baseline period of 1981–2010) in England and Wales. CVD, cardiovascular disease; SAT, surface air temperatures.

months. CVD mortality rates were consistently higher among men than women. Summer nocturnal SAT anomalies are plotted in figure 1B. June anomalies ranged from  $-0.63^{\circ}\text{C}$  (2015) to  $1.17^{\circ}\text{C}$  (2003-corresponding to the notable western European heatwave). July anomalies ranged from  $-1.37^{\circ}\text{C}$  (2011) to  $1.73^{\circ}\text{C}$  (2006).

After adjusting for covariates, associations between exposure (a 1-unit increase in summer nocturnal SAT<sup>30</sup>) and CVD mortality rates, stratified by sex and age appear in figure 2. As shown in figure 2A, a  $+1^{\circ}\text{C}$  anomalous summer nocturnal SAT associated significantly with an

**Table 1** Total summer (June–July) sex-specific and age-specific cardiovascular disease deaths and their corresponding rates by British and US region for the years 2001 and 2015

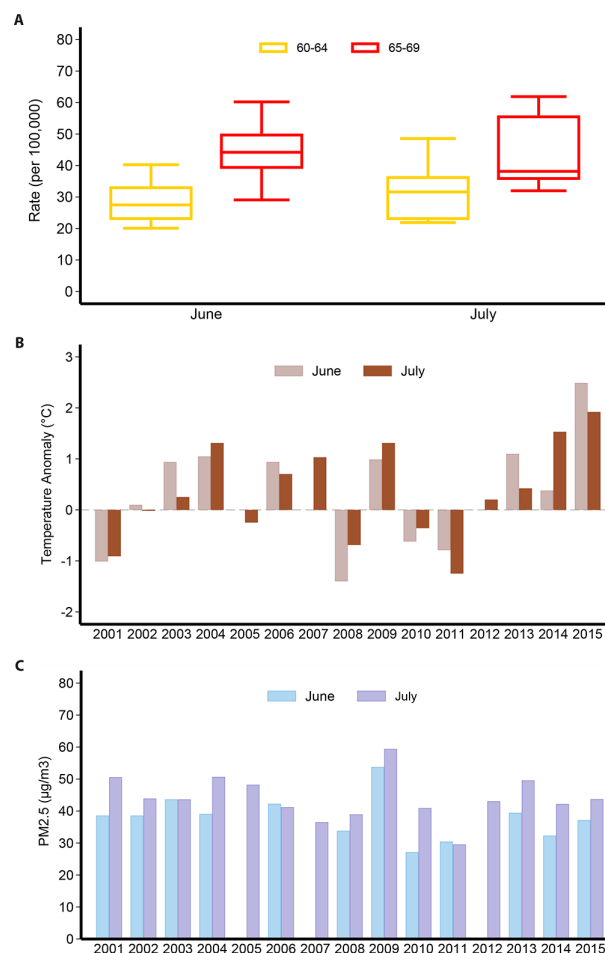
Region	Group	2001		2015		Rate (per 100 000)	
		No deaths	Population	No deaths	Population		
England and Wales	Men						
	60–64	969	1 251 730	77.4	590	1 512 948	39
	65–69	1451	1 104 859	131.3	938	1 560 546	60.1
	Women						
	60–64	403	1 297 331	31.1	234	1 576 695	14.8
	65–69	735	1 194 005	61.6	403	1 652 275	24.4
King County, Washington, USA	Men						
	60–64	27	29 824	90.5	37	58 227	63.5
	65–69	24	21 944	109.4	17	44 574	38.1



**Figure 2** (A) Plot depicting the association between summer CVD mortality rates and night SAT anomalies for middle-aged and older-aged men in England and Wales from 2001 to 2015. (B) Plot depicting the association between summer CVD mortality rates and night SAT anomalies for middle-aged and older-aged women in England and Wales from 2001 to 2015. Covariates include mental and behavioural mortality rates, trend and month (reference to June). CVD, cardiovascular disease; SAT, surface air temperatures.

increased risk of summer CVD mortality rates among men aged 60–64 (adjusted RR 1.031; 95% CI 1.003 to 1.059) but not in those aged 65–69 years (adjusted RR 0.999; 95% CI, 0.976 to 1.021), nor in adult women in either age group (figure 2B). There were no such associations with anomalous summer diurnal SAT as exposures in men or women of either age group (not shown).

For King County, summer CVD mortality rates were also higher within the older male cohort (figure 3A). Summer nocturnal SAT anomalies are plotted in figure 3B,C. June SAT anomalies ranged from  $-1.4^{\circ}\text{C}$  (2008) to  $2.49^{\circ}\text{C}$  (2015, a year when western North America recorded a record number of heatwaves and forest fires attributed to a strong El Niño event).<sup>22</sup> July anomalies ranged from  $-1.25^{\circ}\text{C}$  (2011) to  $1.92^{\circ}\text{C}$  (also in 2015). The smaller land mass of King County permits integration of  $\text{PM}_{2.5}$  into these models. King County  $\text{PM}_{2.5}$  levels generally were higher in July than in June, 2001–2015. After adjusting for covariates, a  $+1^{\circ}\text{C}$  anomalous summer nocturnal SAT associated significantly with an increased risk of summer



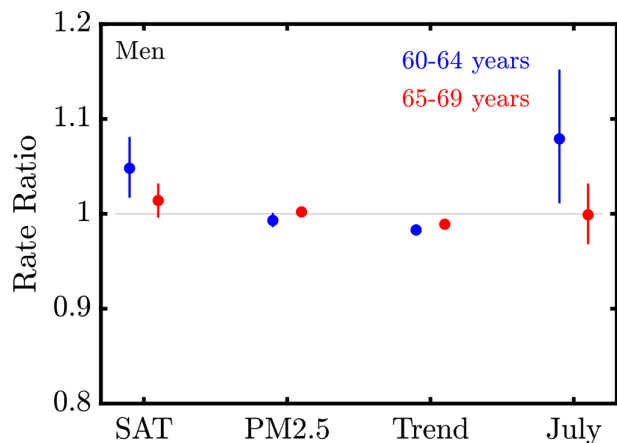
**Figure 3** (A) Data spread for sex-specific monthly summer (June–July) CVD mortality rates among middle-aged and older-aged adults in King County, Washington, USA from 2001 to 2015. (B) Month-specific summer (June–July) night SAT anomalies (based on deviations from the baseline period of 1981–2010) in King County. (C) Month-specific summer (June–July)  $\text{PM}_{2.5}$  values in King County. CVD, cardiovascular disease;  $\text{PM}_{2.5}$ , particulate matter 2.5; SAT, surface air temperatures.

CVD mortality rates among men aged 60–64 (adjusted RR 1.049; 95% CI, 1.017 to 1.081) but not in those aged 65–69 (adjusted RR 1.014; 95% CI 0.996 to 1.032) (figure 4).

## DISCUSSION

CVD mortality rates in both England and Wales and in King County, Washington state declined substantially between 2001 and 2015 (table 1) in parallel with greater population uptake of effective primary and secondary preventive therapies. Nonetheless, considerable residual risk persists and in England and Wales, event rates remain  $>50\%$  higher in adults aged 65–69 than in those aged 60–64 years.

High summer nocturnal SAT may be a source of such risk.<sup>6</sup> Such high summer SAT has been associated with increased cause-specific adult mortality in various high-income regions.<sup>3–8 10 13 16 18</sup> Importantly, in recent years



**Figure 4** Plot depicting the association between summer CVD mortality rates and nocturnal SAT anomalies for middle-aged and older-aged men in King County, Washington, USA from 2001 to 2015. Covariates include PM<sub>2.5</sub>, trend and month (reference to June). CVD, cardiovascular disease; PM<sub>2.5</sub>, particulate matter 2.5; SAT, surface air temperatures.

populous mid-latitude to high-latitude regions have experienced a proportionately rise in nocturnal than in daytime summer heat intensity.<sup>15</sup> The present work is one of few investigating potential associations between summer nocturnal SAT and CVD mortality rates. Our finding of significant associations, in men aged 60–64 residing in England and Wales or in King County, Washington, USA, between +1°C summer nocturnal SAT anomalies and summer CVD mortality rates, support this concept.

An association between summer nocturnal SAT and CVD mortality is biologically plausible hypothesis. The incidence and severity of CVD events can be exacerbated by temporal dys-synchrony between cardiovascular circadian clock gene rhythms and exogenous or endogenous homeostatic stresses.<sup>31</sup> One such stress is warmer nocturnal SAT, which also amplifies self-reported sleep-deprivation, itself a risk factor for adult heart disease mortality.<sup>21</sup> Waking itself, whether concordant with normal cardiovascular circadian rhythms or due to interrupted sleep, triggers increases in heart rate, vascular resistance, and blood pressure and predisposes to thrombosis.<sup>32</sup>

No significant association was detected in English and Welsh women, but their event rates were <50% of men of comparable age (table 1). Thus, there may have been insufficient statistical power to appreciate a qualitatively similar association in women, if present. On the other hand, their generally larger sweat gland volume<sup>33</sup> predisposes men exposed to heat to greater insensible fluid loss and intravascular volume depletion. However, the authors of a recent systematic review of 36 studies attributed the greater male susceptibility to heat-attributable illnesses to their psychology and behaviour rather than to any physiological dimorphism.<sup>34</sup>

Several studies<sup>4 15–18</sup> report a positive association between summer nocturnal SAT and either all-cause, heat-related or CVD mortality. In one focusing on

London, UK, night-time temperatures had a more potent influence than daytime exposure on all-cause mortality, ischaemic heart disease events and stroke, particularly in those ≤64 years of age; sex-specific risk was not reported.<sup>16</sup> A recent investigation of approximately 10 years' data for 11 southern European cities reported associations between the relative risk of cause-specific mortality and the magnitude and duration of nocturnal SAT exceeding 20°C.<sup>17</sup> Significant associations with CVD event rates were identified for Madrid, Lisbon, Porto and Rome.<sup>17</sup> However, sex-specific and age-specific associations were not reported, and our work, in contrast, considered monthly anomalies relative to a 30-year reference period as the thermal exposure of interest.

Other European studies also noted significant positive relationships between average or diurnal SAT and all-cause or CVD mortality in men <65 years or in working-age or middle-aged men.<sup>10–12</sup> An Australian group documented a significant association between ambient temperature in Queensland and the relative risk of CVD hospitalisation over a comparable time period (1995–2016); risk was greater in men than in women and in adults <70 years of age when compared with those 70 years and older.<sup>35</sup>

The non-significant trends observed for the older men in the present analysis and in these previous reports may reflect resilient survivor bias or signal the exponential accretion of coronary and peripheral vascular disease with age, resulting in more conventional than anomalous temperature-triggered cardiovascular events. Conversely, younger men may be more susceptible to increased summer nocturnal SAT. It has been noted<sup>35</sup> that endogenous testosterone, which declines with age, is in mice an heat-stress susceptibility factor.<sup>36</sup>

Nearly one-third of UK's population resides in south-east England.<sup>15</sup> This region's employment opportunities attract young and middle-aged men.<sup>37</sup> Urban design is also an important parameter, because majority of daytime summer heat is absorbed, then radiates locally at night.<sup>15</sup> Residential air conditioning is less common in both England and Wales and in Seattle, Washington, relative to other high-income mid-latitude to high-latitude nations such as the USA or Canada.<sup>14</sup> If uncomfortable warmth obliges individuals to open their bedroom windows, this action, in turn might increase CVD event risk by exposing sleepers to more intense outside nocturnal heat, atmospheric pollutants<sup>27</sup> and road and aircraft noise,<sup>29</sup> which in adult men increases the risk of developing hypertension.<sup>16 38</sup> Night-time noise-related stress<sup>38</sup> and warmer summer SAT also disrupt sleep, especially among vulnerable populations with lower socioeconomic status.<sup>21</sup> Sleep deprivation, in turn can increased central sympathetic outflow,<sup>39</sup> which over time can increase blood pressure and induce insulin resistance.<sup>40</sup> Dry air can exacerbate snoring<sup>41</sup>; in middle-aged men snoring is common, as is obstructive sleep apnea, which can trigger nocturnal CVD events.<sup>42</sup>

Although we cannot infer causality from our models, our age- and sex-specific analyses nonetheless represent



a novel contribution to the present literature. The principal strengths of this ecological study accrue from the large population sampled and its linkage with rigorous national mortality and meteorological data. The principal limitations are lack of access to 15-year sex-specific and age-specific granular monthly/weekly data (ie, district or city level) outcome and exposure data. The latter might have identified stronger associations between night-time summer heat and CVD mortality in populous urban regions, where ~90% of citizens are projected to reside within a few decades.<sup>15</sup> Nonetheless, in our online supplemental analysis of King County, the effect and direction of summer nocturnal SAT on CVD mortality among men aged 60–64 years were consistent with our primary analysis. The majority of adult men in England and Washington State retire at age 65. It is conceivable that the anxieties/mental health of men in their early sixties anticipating retirement and reduced income or benefits added to their risk for CVD death, as posited by a British study,<sup>13</sup> but this potential confounder was adjusted for, in our models. Lastly, we are not able to adjust for potential confounding factors such as local public health initiatives, or in secular trends in the discovery and implementation of effective primary and secondary CVD risk prevention strategies, cause of death misclassification or ICD coding error.

## CONCLUSION

Our observation of an association between warm summer night-time conditions and CVD mortality risk among men aged 60–64 years residing in England and Wales was replicated in our analysis of comparable American data from King County, Washington state. The present findings should stimulate similar investigation of exposure and event rates in other populous mid-latitude to high-latitude regions. Considering the growing likelihood of extreme summers in Western USA and UK,<sup>23</sup> our results invite preventive population health initiatives and novel urban policies aimed at reducing future risk of CVD events.

**Contributors** HM and JF contributed to the conception or design of the work. HM and JF contributed to the acquisition, analysis, or interpretation of data for the work. HM drafted the initial manuscript. JF critically revised the manuscript. Both authors gave final approval and agree to be accountable for all aspects of work ensuring integrity and accuracy. HM acts as a guarantor for the manuscript.

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**Data availability statement** All data relevant to the study are included in the article or uploaded as online supplemental information.

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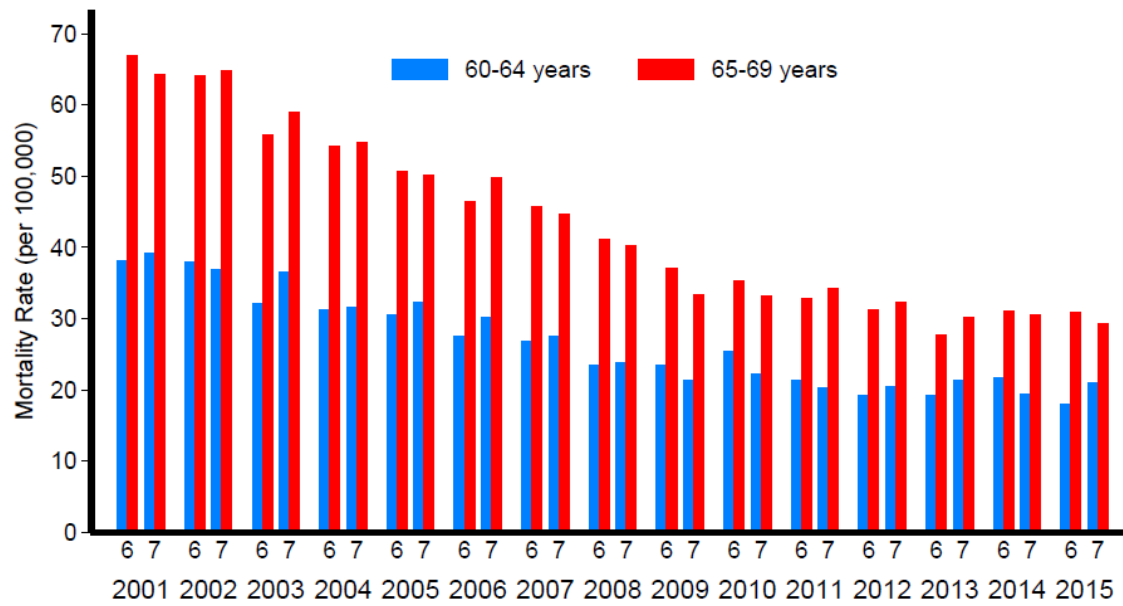
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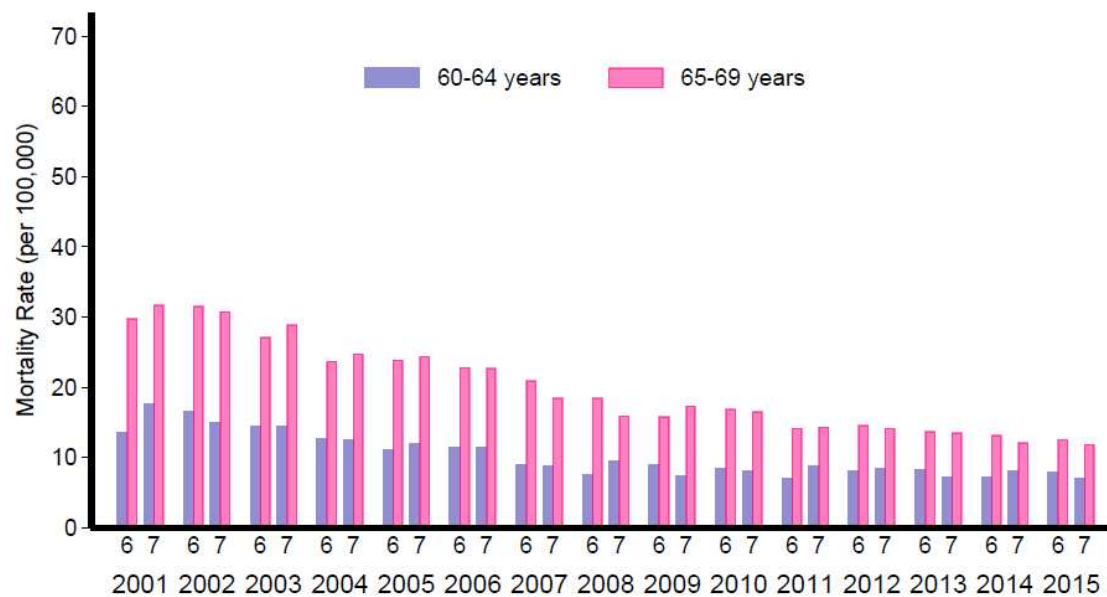
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## A) Men



## B) Women



**Supplementary Figure 1:** Monthly summer (6=June, 7=July) cardiovascular mortality trends by age-groups among (A) men and (B) women from 2001-2015 in England and Wales.