ABSTRACT

Objectives This study was conducted to examine modification in heat-related mortality in the Netherlands by sociodemographic and geographical factors including socioeconomic position and population density (PD).

Design This observational study applied time series analysis on daily mortality counts according to mean daily temperature (°C).

Setting Statistics Netherlands.

Participants Death registrations in 2006, 2018 and 2019 from residents registered at the Dutch Personal Records Database, restricted to deaths in the period between April and October.

Main outcome measures Assuming a V-like relation between temperature and mortality, a segmented linear model was used to estimate the temperature effects on mortality. In order to estimate the effects of severe heat, a second model including a heat threshold of 22°C was included in the model. We stratified by sociodemographic groups, calendar year and the five main causes of death (cardiovascular, respiratory, neoplasm, psychological and nervous system, and other) and controlled for time trend and seasonality.

Results The effect of 1°C increase in temperature whereby the mean daily temperature exceeded 16°C was a 1.57% (95% CI 1.51% to 1.63%) increase in mortality among the total population. In temperature segments whereby the mean daily temperature exceeded 22°C, this effect was 2.84% (95% CI 2.73% to 2.93%). Low-income groups were at higher risk of heat-related mortality, compared with high-income groups. Areas with a high PD show relatively weak effects within both the warm and heat segments.

Conclusion Results of this study highlight the variation in terms of heat vulnerability among the Dutch population, whereby poor living conditions specifically may increase the effect on high temperature on mortality.

INTRODUCTION

The relation between heat and mortality is well documented across numerous studies in high-income countries, including the Netherlands.1–4 This relation has been observed during several main heat events, such as the European heatwave of 2003 and 2006.5 6 During the summer of 2003, an estimated excess mortality was observed of up to 2200 deaths in the Netherlands and up to 45 000 heat-related deaths across the whole of Europe. Again in 2018 and 2019, extreme temperatures have been repeatedly measured across Europe.7

Health impacts of heat exposure are likely to be heterogeneous across populations with different sociodemographic characteristics.8 According to the European WHO guidance of heat health action plan,9 elderly, infants, persons with chronic conditions and persons with lower socioeconomic position (SEP) are more vulnerable to heat. Research conducted in the USA and across Europe highlighted the vulnerability to heat of low SEP persons.10–14 Socioeconomic disparities in heat vulnerability could possibly partly be explained by a lower heat risk perception and fewer adaptation measures available to persons with a lower SEP.15–17 Besides, multimorbidity is more prevalent in lower socioeconomic groups.18

Rapid urbanisation and its consequential impact on residents’ health may also contribute to disparities in heat effects.19 The extent of population density (PD) could...
have consequences on local climate due the so-called ‘Urban Heat Island’ (UHI) effect. This effect occurs in an urbanised environment with a high PD. However, consistent evidence is still limited.12,23

Admittedly, a heatwave is still a rare event in the Netherlands and most evidence has been gathered in regions with warmer summers. Therefore, research into heat-related mortality in a country with a relatively mild climate, such as the Netherlands, might well reveal striking differences compared with the results of aforementioned studies. Since heat events in Europe are likely to recur more often, studies into heat vulnerability in European populations are becoming more important.24 Additionally, as the impact of the 2006 heatwave in the Netherlands motivated the initiation of a national heat plan which was implemented in 2007 by the Ministry of Health,25 current heat effects may be expected to be different than those in 2006. The study will focus on the years 2006, 2018 and 2019, as these years are the only years after 2000 that were comparable in terms of extreme heat.

This study will build on previous studies conducted in the Netherlands,2,4 but it will be the first Dutch study to link registries with multiple geographic and sociodemographic variables to every single death registration. Using these data, we performed a time series analysis into the short-term association between temperature and mortality. The objectives of this analysis were twofold: (1) to examine modification in heat-related mortality by SEP and PD, and (2) to compare the current situation (2018/2019) with the year 2006. The study will focus on both ‘warm’ and ‘heat’ temperature segments, which provide a more complete picture of the temperature–mortality relation.

METHODS

Study area and population

The Netherlands, with an average PD of 508 inhabitants per km² in 2019, has a temperate maritime climate influenced by the North Sea. The study population includes all death registrations in 2006, 2018 and 2019 from residents registered at the Dutch Personal Records Database, restricted to deaths in the period between April and October.

Data collection

Patient and public involvement

This study used mortality data which could be obtained from Statistics Netherlands (CBS) for the years 2006, 2018 and 2019. There was no patient and decedent involvement in the presented study.

Mortality data

Using the CBS registries, we measured daily count of deaths as registered among the resident population of the Netherlands. We classified each death according to the underlying causes of death. We were particularly interested in causes of death for which previous studies have documented relatively large heat effects, as socioeconomic differences might be particularly visible for those causes. For the sake of statistical power, we distinguished broad groups of causes of death. These include three groups with relatively heat large effects (cardiovascular, respiratory, and psychological and nervous system diseases), a contrasting group with generally smaller effects (neoplasms) and a rest group of other causes. The groups were defined according to the corresponding chapters of the International Classification of Diseases 10th Revision.

Meteorological data

Meteorological variables were retrieved from the database of The Royal Netherlands Meteorological Institute, which is publicly accessible. Daily mean temperature (24-hour averages) for the study period was obtained as this temperature indicator represents exposure throughout day and night.26 Local weather stations were selected to represent all 12 provinces. Missing values were replaced with data from nearby weather stations. These meteorological data were matched to the residential province of each deceased person. A national temperature indicator was estimated by obtaining the weighted mean daily temperature.

Modifiers

SEP is measured by standardised household income as this factor affects access to preventive resources such as air conditioning most directly.27 Data on household income were obtained by linkage to tax registries as available through CBS and corrected for the size and composition of the household. Household income was obtained for the deceased 1 year prior to year of death. In the case of institutionalised persons (ie, those living in long-term residential care; living in nursing homes, rehabilitation centres, etc), income was obtained 5 years prior to the year of death, as income data were not available for institutionalised residents. Missing income data were replaced with income data from registered partner, if available. Levels on income were based on the income distribution of the Dutch population aged ≥65 years in 2006 and 2018 (highest=>70th, mid-high=50th–70th, mid=40th–50th, mid-low=20th–40th, lowest=<20th percentile). Housing tenure (whether the dwelling is owner occupied or rented) was used as an additional indicator of SEP.28 Data on housing tenure have been annually updated on the first of January in the CBS register by linkage to tax registries, whereby house ownership is divided into ‘rented house’ and ‘owned house’ for non-institutional residents.

PD was measured as the number of addresses within a radius of 1 km around a specific address. These were
obtained from a 1 km\(^2\) surface throughout the entire country for all studied periods and linked to the address of residence of every single deceased person. The mean density was 1794 per km\(^2\). PD was divided into five categories (lowest=0–600, mid-low=601–1200, mid=1201–1800, mid-high=1801–2600, highest=2601–12 450 addresses/km\(^2\)).

In order to measure regional place of residence, the 12 provinces were categorised into three groups based on the geographical location versus the North Sea (Noord-Holland, Zuid-Holland, Zeeland, Friesland, Groningen and Flevoland=coastal area; Utrecht, Gelderland, Overijssel and Drenthe=mid-east inland; Noord-Brabant and Limburg=south-east inland). Other modifiers were age in years (≤64, 65–69, 70–74, 75–79, 80–84, 85–89 and ≥90 years), sex (male/female) and type of household (non-institutionalised/institutionalised).

Data analysis

Temperature effects on mortality were modelled by a multivariate segmented Poisson regression model, where the dependent variable was daily death count. This model included a robust SE estimation allowing for overdispersion (ie, the variance of the count outcome is higher than predicted under a Poisson distribution). All models assumed a V-shaped relation. We manually compared all break points between 0°C and 30°C and selected the break point with the model with the lowest Akaike information criterion (AIC). The break point with the lowest AIC was estimated at 16.0°C, which is in line with findings from Huynen et al.\(^4\) We arrived at this temperature by investigating the death count for every degree Celsius interval ranging from 0°C to 30°C.

In this study, two segmented lag models were used to analyse temperature effects on mortality. One model (with two segments) was built to estimate effects of all ‘warm’ temperatures on mortality and the second model (with three segments) to focus on ‘hot’ temperatures. The first model estimated temperature effects using two temperature segments (cold respectively warm). In order to estimate temperature effects on mortality associated with severe heat, the second model included three linear segments representing cold temperature (<16.0°C), warm temperature (≥16.0°C and <22.0°C) and severe heat (≥22.0°C). The threshold for severe heat (22.0°C) was between the 90th and 95th temperature percentiles; thresholds in this range are widely used to estimate heat effects.\(^29\)

The number of daily deaths depends on the current day average temperature, plus contributions from temperatures of preceding days. As it is well documented that temperature effects can last for multiple days,\(^26\)\(^30\) lag structures between 0 and 7 days prior to the day of death were modelled. To overcome issues of collinearity, the averages of mean temperatures were calculated for three combined lag periods (lag 0–1, lag 2–4 and lag 5–7). Thus, lag structure 0–1 is the average temperature of the current and one preceding day. All lagged variables were transformed into the linear segments corresponding to cold, warm and hot days. The ‘hot’ model only included the current day and four preceding days (lag 0–1 and lag 2–4, but not lag 5–7), as heat effects are mostly immediate and are followed by negative estimates consistent with an expected decrease in mortality (mortality displacement).\(^31\)

To summarise, the resulting Poisson models, with daily death count as the dependent variable, include the following independent variables. The model with two segments includes:

Poisson model (with two segments) was built to estimate effects of all ‘warm’ between 16°C and 22°C and ‘Cold’ below 16°C. The model with three segments includes:

In order to obtain the cumulative effects of warm and hot days, respectively, we summed the estimated effects over the lag periods. These cumulative effects are presented as the percentage change in mortality for every 1°C increase in temperature in all relevant days, whereby the threshold exceeded 16°C (first model, two segments) and 22°C (second model, three segments).

To control for time-varying influences such as seasonal patterns and long-term trends, categorical variables for year, month and day of week were included in the model as covariates.

First, we investigated the current situation (years 2018/2019). In this analysis, we stratified by sociodemographic groups (age, sex, type of household, household income, housing tenure, PD and geographic region). We ran the model independently for each sociodemographic group. Subsequent analyses were performed for different causes of death, with stratification by income, housing tenure and PD. Lastly, the recent situation (2018/2019) was compared with 2006. All analyses were performed in STATA V.16 using Poisson models.

RESULTS

Descriptive statistics of mortality data

During 2006, 2018 and 2019, a total of 440 421 number of deaths occurred in the Netherlands. Restrictions to the warm period (April to October) led to a total count of 243 499 deaths (online supplemental figure S1). Table 1 summarises the number of total deaths and mean daily deaths for each temperature segment. The mean number of daily deaths was highest on days with a mean daily temperature exceeding 22°C. Among 8% of all deaths occurred during these ‘hot’ days.
The mortality distribution is relatively constant among temperature segments and sociodemographic groups. Highest death numbers are observed in persons aged ≥90 years. Thereby, females show a slightly higher death count, and a quarter of deaths are among the institutionalised. Looking at levels of SEP, the mid-low level shows the highest number of deaths (about one-third). Among non-institutionalised persons, rented house tenure has a somewhat higher death number compared with owned house tenure. Deaths are more or less equally distributed according to levels of PD. Almost half of all deaths occurred among residents of coastal provinces.

Table 1  Total death numbers and mean daily deaths stratified by cold, warm and hot days between April and October in the Netherlands

| Sociodemographic groups | N (% of death counts) | Mean daily deaths (% of total deaths per group) |
|-------------------------|-----------------------|-----------------------------------------------|
|                         | Total days (n=642)    | Cold days (<16°C) (n=338)                     | Warm days (≥16°C and <22°C) (n=255) | Hot days (≥22°C) (n=49) |
| Total death counts      | 243499                | 378                                           | 377                                    | 402                      |
| Age group (years)       |                       |                                               |                                        |                          |
| 0–64                    | 38497                 | 60                                            | 60                                     | 64                       |
| 65–74                   | 43477                 | 87                                            | 68                                     | 68                       |
| 75–79                   | 31458                 | 49                                            | 48                                     | 52                       |
| 80–84                   | 39860                 | 62                                            | 61                                     | 68                       |
| 85–89                   | 43634                 | 67                                            | 68                                     | 73                       |
| ≥90                     | 46573                 | 72                                            | 72                                     | 78                       |
| Sex                     |                       |                                               |                                        |                          |
| Female                  | 124658                | 193                                           | 193                                    | 210                      |
| Male                    | 118841                | 185                                           | 184                                    | 192                      |
| Type of household       |                       |                                               |                                        |                          |
| Non-institutionalised   | 182487                | 285                                           | 282                                    | 293                      |
| Owned house             | 80870                 | 131                                           | 128                                    | 128                      |
| Rented house            | 97081                 | 153                                           | 151                                    | 162                      |
| Unknown                 | 4536                  | 9                                             | 9                                      | 11                       |
| Institutionalised       | 61012                 | 93                                            | 95                                     | 110                      |
| Socioeconomic position  |                       |                                               |                                        |                          |
| High                    | 36554                 | 57                                            | 56                                     | 59                       |
| Mid-high                | 46104                 | 72                                            | 71                                     | 78                       |
| Mid                     | 50596                 | 79                                            | 78                                     | 80                       |
| Mid-low                 | 78256                 | 120                                           | 122                                    | 130                      |
| Low                     | 30112                 | 46                                            | 47                                     | 52                       |
| Unknown                 | 1877                  | 3                                             | 3                                      | 3                        |
| Population density      |                       |                                               |                                        |                          |
| Low                     | 46437                 | 72                                            | 72                                     | 77                       |
| Mid-low                 | 51979                 | 81                                            | 81                                     | 85                       |
| Mid                     | 46729                 | 50                                            | 50                                     | 53                       |
| Mid-high                | 46431                 | 81                                            | 81                                     | 83                       |
| High                    | 48544                 | 88                                            | 88                                     | 96                       |
| Unknown                 | 3379                  | 5                                             | 5                                      | 8                        |
| Region                  |                       |                                               |                                        |                          |
| Coastal areas           | 114794                | 178                                           | 177                                    | 192                      |
| Mid-east inland         | 73606                 | 115                                           | 113                                    | 121                      |
| South-east inland       | 55099                 | 85                                            | 86                                     | 89                       |

d: 4
Association between temperature and mortality by sociodemographic groups stratified by cold, warm and hot segments during 2018/2019

Table 2 shows the results of the multivariate segmented Poisson regression stratified by cold, warm and hot temperature segments. The cumulative effect within the warm segment is a 1.57% increase in mortality per 1°C increase in temperature among the total population. Within the hot segment, this effect almost doubled, with a 2.84% increase in mortality per 1°C increase. In general, temperature effects on mortality increase by age group. In addition, females show a higher change rate in mortality within the warm and hot segments (1.83% and 2.91%, respectively) when compared with males (1.29% and 2.61%). Furthermore, institutionalised residents (3.41% and 4.86%) show a notably larger excess risk compared with non-institutionalised residents (rented house=1.13% and 3.00%, owned house=0.72% and 0.86%).

Figure 1 visualises patterns in relation to SEP (income, housing tenure) and PD. The temperature effects for warm and hot segments show a general increase from highest to lowest level of income. The lowest income group has a substantial higher excess risk in mortality in...
the warm segment (2.60%), compared with the highest income group (0.77%). Variations in effects in the hot segment are less marked but still observable, with an excess risk of 3.72% for the lowest income groups, compared with 2.07% in high-income groups. Variations in housing tenure correspond to these patterns, as effects on mortality of both temperature segments are largest among those with rented house.

The strongest effects on mortality of warm and hot are observed in mid-low level of PD (1.80% for warm and 4.09% for heat). In general, there is no consistent pattern according to PD. Areas with a high PD show relatively low effects within both the warm and hot segments. Additionally, coastal areas show the highest increase in mortality (1.75%) by the warm segment. However, mid-east inland areas show a relatively large effect of heat (3.66%).

In table 3, the analyses of income and PD are stratified by type of household. Among institutionalised persons, there is little difference between low and high-income groups in heat-related mortality. On the other hand, the effect of income level on heat-related mortality is enhanced among non-institutionalised residents. Among the latter, the effect of warm is 0.78% vs 1.17% for low versus high-income groups, while the effect of severe heat is 1.62% vs 2.64%.

Variations between causes of death in the effect of SEP and PD on heat-related mortality are small or lack consistency due to low counts (online supplemental table S1).

Mortality differences between levels of household income and PD and housing tenure; current situation (2018/2019) compared with the year 2006

Table 4 shows differences over time in the association of mortality with warm temperature and heat. Nationally, the effect of temperature on mortality within the warm segment declined from 4.09% (95% CI 4.00% to 4.16%)
in 2006 to 1.57% (95% CI 1.51% to 1.63%) in 2018/2019. The effects within the hot segment declined from 4.69% (95% CI 4.56% to 4.82%) in 2006 to 2.84% (95% CI 2.73% to 2.94%) in 2018/2019. Changes over time occurred for most levels of SEP and PD. Particularly large is the drop in heat-related mortality rate in the lowest level of income and in mid-high and high levels of PD. However, for ‘hot’, no reduction is observed for tenants, those with the mid-high level of income and those with intermediate level of PD.

DISCUSSION

Our results showed socioeconomic differences in the effect of temperature on mortality within the Dutch population. A much higher effect was found for the lowest level of income compared with the highest level, indicating that heat-related mortality is higher in low-income groups. Additionally, we found moderate differences according to housing tenure, with a somewhat higher effect of high temperature on mortality among tenants as compared with house owners.

Our main findings are in line with previous studies from other countries that reported that persons with low socioeconomic conditions were more vulnerable to heat.\textsuperscript{11,13} Yet, according to results in this study, SEP modified heat vulnerability among non-institutionalised residents, but much less among institutionalised residents. Immobilisation, multimorbidity and psychogeriatric disorders are frequent in institutionalised residents. These factors might contribute to heat susceptibility, regardless of income.\textsuperscript{32} Moreover, residential care institutions in the Netherlands are financially accessible to all residents and characterised by a highly regulated environment, which may eliminate the presumed protective role of income.

No consistent pattern was observed in relationships to PD. The most densely populated areas showed no larger temperature effect on mortality as compared with the other areas. Other reviews reported weak evidence as well, thereby, investigation into PD as effect modifier in heat-related mortality has been limited.\textsuperscript{12} Also, there has been a wide set of different approaches in the investigation of PD, which makes it difficult to compare studies. According to Van Hove \textit{et al}, in the Netherlands, the UHI is substantial in both cities and smaller settlements, where comparable with other European cities.\textsuperscript{33} Most likely, the effect in the Netherlands is not strong enough to determine rural-urban differences in heat-related mortality. The percentage of impervious surface and other characteristics of the physical environment may be more relevant in terms of the UHI effect than PD. In-depth research including exploration of the built environment and green space in relation to heat mortality could possibly provide a better picture of the UHI effect.\textsuperscript{34-36} Our results imply that, despite the UHI effect, populations that are most vulnerable to heatwaves can be found in semirural areas as well as inner cities.

| Table 3 | Mortality differences whereby the mean daily temperature exceeds 16°C (model 1) and 22°C (model 2) between levels of socioeconomic position and population density stratified by type of household with multivariate segmented Poisson regression controlled for seasonality and time trend |
|---------|---------------------------------------------------------------------------------------------------------------|
| Mortality risk | % change in mortality by 1°C change in temperature |
| Type of household | Non-institutionalised | Institutionalised |
| | % change (95% CI) | % change (95% CI) |
| Warm (model 1) | | |
| Total population | 0.93 (0.87 to 1.01) | 3.41 (3.24 to 3.61) |
| Household income* | | |
| Higher income | 0.78 (0.65 to 0.88) | 3.65 (3.21 to 4.10) |
| Lower income | 1.17 (1.01 to 1.33) | 3.20 (2.89 to 3.49) |
| Population density* | | |
| Low density | 0.84 (0.74 to 0.95) | 3.40 (3.10 to 3.70) |
| High density | 1.17 (0.96 to 1.40) | 3.44 (2.88 to 3.99) |
| Hot (model 2) | | |
| Total population | 2.01 (1.88 to 2.14) | 4.86 (4.60 to 5.12) |
| Household income* | | |
| Higher income | 1.62 (1.45 to 1.79) | 6.01 (5.37 to 6.64) |
| Lower income | 2.64 (2.38 to 2.90) | 4.17 (3.83 to 4.49) |
| Population density* | | |
| Low density | 2.49 (2.23 to 2.76) | 5.49 (5.08 to 5.89) |
| High density | 1.61 (1.43 to 1.79) | 4.08 (3.48 to 4.67) |

Models 1 and 2 ran independently for non-institutionalised and institutionalised persons and level of income and population density (PD). *High, mid-high and mid levels are merged and mid-low and low levels are merged.
Mortality effects of warm and hot segments were much higher in 2006 compared with the other years. The introduction of a heat health warning system (HHWS) by the government in 2007 might have contributed to this decrease. However, there is no strong evidence on effectiveness of HHWS internationally. An evaluation of the Dutch national heat plan among long-term care institutions identified several barriers with implementation by healthcare personnel. A generally downward trend in mortality risks could also be attributable to

Table 4  Mortality differences whereby the mean daily temperature exceeds 16°C (model 1) and 22°C (model 2) between levels of socioeconomic position and population density stratified by year with multivariate segmented Poisson regression controlled for seasonality and time trend

| Mortality risk | % change in mortality by 1°C change in temperature |
|---------------|---------------------------------------------------|
|                | 2006 % change (95% CI) | 2018/2019 % change (95% CI) | Difference 2006–2018/2019 |
| Warm (model 1) |                                    |                                |                           |
| Total population | 4.09 (4.00 to 4.16) | 1.57 (1.51 to 1.63) | 2.52                      |
| Socioeconomic position |                                |                                |                           |
| Household income |                                    |                                |                           |
| High | 1.76 (1.32 to 2.20) | 0.77 (0.32 to 0.50) | 0.99                      |
| Mid-high | 2.83 (2.46 to 3.20) | 1.37 (1.15 to 1.61) | 1.46                      |
| Mid | 4.05 (3.65 to 4.45) | 1.68 (1.46 to 1.89) | 2.37                      |
| Mid-low | 4.90 (4.65 to 5.15) | 1.63 (1.47 to 1.78) | 3.27                      |
| Low | 6.68 (6.10 to 7.26) | 2.60 (2.27 to 2.93) | 4.08                      |
| Housing tenure |                                    |                                |                           |
| Owned house | 1.79 (1.54 to 2.04) | 0.54 (0.42 to 0.68) | 1.25                      |
| Rented house | 3.35 (3.17 to 3.54) | 1.05 (0.92 to 1.19) | 2.30                      |
| Institutionalised | 7.63 (7.29 to 7.99) | 3.41 (3.24 to 3.61) | 4.22                      |
| Population density |                                    |                                |                           |
| Low | 3.94 (3.60 to 4.28) | 1.80 (1.55 to 2.06) | 2.14                      |
| Mid-low | 2.71 (2.33 to 3.08) | 1.50 (1.26 to 1.75) | 1.21                      |
| Mid | 3.17 (2.62 to 3.71) | 1.69 (1.36 to 2.02) | 1.48                      |
| Mid-high | 4.98 (4.58 to 5.40) | 0.96 (0.77 to 1.16) | 4.02                      |
| High | 4.68 (4.35 to 5.02) | 1.99 (1.77 to 2.20) | 2.69                      |
| Hot (model 2) |                                    |                                |                           |
| Total population | 4.69 (4.56 to 4.82) | 2.84 (2.73 to 2.94) | 1.85                      |
| Socioeconomic position |                                |                                |                           |
| Household income |                                    |                                |                           |
| High | 2.85 (2.14 to 3.57) | 2.07 (1.47 to 2.67) | 0.78                      |
| Mid-high | 2.10 (1.53 to 2.68) | 2.12 (1.85 to 2.41) | −0.02                     |
| Mid | 4.71 (4.11 to 5.32) | 3.18 (2.88 to 3.48) | 1.53                      |
| Mid-low | 5.95 (5.56 to 6.34) | 3.10 (2.86 to 3.33) | 2.85                      |
| Low | 8.19 (7.32 to 9.08) | 3.72 (3.31 to 4.13) | 4.47                      |
| Housing tenure |                                    |                                |                           |
| Owned house | 1.34 (0.92 to 1.75) | 0.76 (0.56 to 0.95) | 0.58                      |
| Rented house | 1.80 (1.55 to 2.06) | 2.93 (2.72 to 3.14) | −1.13                     |
| Institutionalised | 11.35 (10.81 to 11.88) | 4.86 (4.60 to 5.12) | 6.49                      |
| Population density |                                    |                                |                           |
| Low | 2.61 (2.11 to 3.11) | 1.56 (1.23 to 1.89) | 1.05                      |
| Mid-low | 5.55 (4.93 to 6.18) | 4.84 (4.45 to 5.23) | 0.71                      |
| Mid | 2.72 (1.91 to 3.52) | 3.05 (2.56 to 3.55) | −0.33                     |
| Mid-high | 4.36 (3.73 to 5.00) | 0.84 (0.56 to 1.14) | 3.52                      |
| High | 5.66 (5.18 to 6.12) | 3.57 (3.28 to 3.87) | 2.09                      |

Models 1 and 2 ran independently for each year and level of socioeconomic position (SEP) and population density (PD).
general improvements in housing and living conditions, and healthcare services.39 The potential role of living conditions is suggested by our finding that excess risk in heat-related mortality mainly declined over time among persons with low income.

Major strengths of this study are its national coverage of all deaths in the Netherlands, which in addition could be linked to registries with several geographic and individual-level variables. However, some limitations of this study are acknowledged. First, the present study estimated an optimum mean daily temperature of 16.6°C to determine the V-shaped temperature–mortality association. This optimum temperature might differ according to SEP or PD. Second, we took a standardised approach for the entire study period, thus foregoing particularities of individual heatwaves. Closer inspection of our data suggested that apparently similar heatwaves had different mortality impacts, possibly due to factors such as the timing in the summer season, preceding temperature trends or correlated meteorological factors.40 Third, the number of deaths—although significant for the Netherlands as a whole—appeared too small to determine with sufficient precision possible interactions with SEP and PD for broad causes of death groups such as all cardiovascular diseases.

Finally, we recognise that there are different ways to measure SEP and to represent the different dimensions through which SEP may influence heat vulnerability. For example, educational level may influence risk perception, while income may affect access to preventive resources such as air conditioning.27 The present study used income and housing tenure as indicators for SEP, as these most directly measure material circumstances that are considered a key factor in preventing heat-related mortality.

CONCLUSION
Overall, our results suggest important differences in heat vulnerability within the Dutch population, whereby socioeconomic factors are more relevant compared with geographic indicators such as PD. Also, current findings emphasise the importance of distinguishing between the non-institutionalised and institutionalised, and a particular attention to non-institutionalised people living on a low income and in poor housing conditions.

Contributors MdV cleaned and analysed the data and drafted the manuscript. AEK and MdV contributed to building the study design and interpreted the results. AEK and MF gave advice on statistical analysis. All authors contributed to revision of the manuscript. AEK is responsible for the overall content as guarantor.

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Patient consent for publication Not applicable.

Ethics approval Dutch law allows the use of electronic health records without informed consent of patients and without approval by a medical ethics committee for observational studies, like ours, that do not use directly identifiable data (Dutch Civil Law, Article 7:458). The data were analysed within a secured environment at the CBS, which ensures strict adherence to privacy regulations and laws.

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