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# High resolution exposure modelling of heat and air pollution and the impact on mortality

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## ABSTRACT

*Background:* Elevated temperature and air pollution have been associated with increased mortality. Exposure to heat and air pollution, as well as the density of vulnerable groups varies within cities. The objective was to investigate the extent of neighbourhood differences in mortality risk due to heat and air pollution in a city with a temperate maritime climate.

*Methods:* A case-crossover design was used to study associations between heat, air pollution and mortality. Different thermal indicators and air pollutants ($PM_{10}$, $NO_2$, $O_3$) were reconstructed at high spatial resolution to improve exposure classification. Daily exposures were linked to individual mortality cases over a 15 year period.

*Results:* Significant interaction between maximum air temperature ($Ta_{max}$) and $PM_{10}$ was observed. During "summer smog" days ($Ta_{max} > 25$ °C and $PM_{10} > 50$ μg/m$^3$), the mortality risk at lag 2 was 7% higher compared to the reference ($Ta_{max}$ 15 °C and $PM_{10}$ 15 μg/m$^3$). Persons above age 85 living alone were at highest risk.

*Conclusion:* We found significant synergistic effects of high temperatures and air pollution on mortality. Single living elderly were the most vulnerable group. Due to spatial differences in temperature and air pollution, mortality risks varied substantially between neighbourhoods, with a difference up to 7%.

## 1. Introduction

Elevated (Basu and Samet, 2002) temperatures are associated with increased mortality (Basu and Samet, 2002; Basu et al., 2008; Basu, 2009; Yu et al., 2012; Guo et al., 2014), with air pollution acting as a confounder or effect modifier (Basu, 2009; Fischer et al., 2004; Stafoggia et al., 2008). However, the threshold and severity of heat effects varies by country and latitude, which can be explained by differences in various physiological as well as behavioural factors (Guo et al., 2014; Keatinge et al., 2000). Examples of these factors are acclimatisation to hot weather and the ability to thermoregulate the body, as well as time spent indoors, and the use of air conditioning (Yu et al., 2012). These factors may also differ within a population, which makes certain subgroups more susceptible to heat effects than others (Basu and Samet, 2002; Basu, 2009; Schwartz, 2005; Stafoggia et al., 2006).

Regarding heat exposure it is known that urban areas typically have higher temperatures than suburban or surrounding areas, a phenomenon known as the Urban Heat Island (UHI) effect (Oke, 1987). The UHI effect is influenced by urban characteristics such as building height, material and orientation as well as the amount of green space and water, which all vary between urban areas. Generally, the dry and dark urban surfaces will become hotter compared to lighter, moist or shaded surfaces because of easier absorption of sunlight (Voogt, 2004). Besides differences in heat exposure, there are also differences in exposure to air pollution, and density of potentially vulnerable groups within a city. Hence, substantial differences in heat-mortality risks between urban neighbourhoods are expected.

The objective and novelty of this study was to investigate the extent of effect modification between heat and air pollution, and if spatial differences in exposure within a city lead to discernible differences in mortality risk between neighbourhoods. This was done using thermal, air pollution and mortality data on the city of Rotterdam, a Dutch city with a maritime temperate climate and a multi-ethnic and socioeconomic diverse population. We used a case-crossover design in combination with high resolution exposure modelling to calculate associations and to examine possible interactions between heat, air pollution and natural-cause mortality. We also investigated if certain subgroups,

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determined by sex, age, ethnicity, marital status and household income, were more susceptible to heat-related mortality than the urban population as a whole.

## 2. Material and methods

### 2.1. Study population

The associations between heat, air pollution and mortality were studied in Rotterdam over the period 1995–2009. Rotterdam is a city with around 600,000 inhabitants in The Netherlands, located in Northern Europe close to the North Sea, and therefore benefits from relatively cool and clean sea breezes. Rotterdam consists of 90 neighbourhoods with an average size of 2.3 km$^2$, and has a large port and industrial area.

The study population consisted of natural-cause mortality cases in Rotterdam during this period, which were retrieved from the mortality database of Statistics Netherlands (in Dutch: Centraal Bureau voor de Statistiek (CBS)). Natural-cause mortality cases were selected according to the International Classification of Disease (ICD) codes 9th (for the year 1995) and 10th revision (1996–2009), excluding death due to all external causes such as accidents, suicides, and poisoning. Information about age, sex, marital status, ethnicity and household income (defined as a standardised measure for the prosperity of a household and corrected for differences in household size and composition) (CBS Statistics Netherlands, 2014) of these cases were available from the same database. This database is protected by strict privacy regulations, so the analysed data were completely anonymous. The Dutch Code of Conduct for Medical Research allows the use of anonymous data for research purposes without an explicit informed consent (Dutch Code of Conduct for Medical Research, 2014).

Daily, neighbourhood specific exposure data on heat and air pollution for the study period were merged to the mortality dataset, and matched by neighbourhood of residence and date of death of the cases in our study. Exposure was averaged on neighbourhood level because the exact home addresses of the mortality cases were not accessible due to privacy regulations.

### 2.2. Heat exposure assessment

Besides temperature, other meteorological factors such as humidity, wind speed and solar radiation, are also important in determining the outdoor thermal environment. Therefore, daily exposure to heat was assessed using three indices: daily maximum air temperature (Ta), mean radiant temperature (Tmrt) (Lindberg and Grimmond, 2011; Thorsson et al., 2014), and the Universal Thermal Comfort Index (UTCI) (Jendritzky et al., 2012).

Tmrt is a parameter that influences the energy balance and thermal comfort (heat load) of humans, and therefore useful when assessing the impact of heat on people's health (Lindberg and Grimmond, 2011). Tmrt is directly influenced by urban geometry and surface material, and therefore also a good measure to identify urban hot spots. Tmrt can be calculated from the total radiation flux density absorbed by the body, which is the sum of all short- and longwave radiation fluxes (both direct and reflected) to which a human body is exposed, the emissivity of the human body, and the Stefan–Boltzmann constant according to the Stefan–Boltzmann law formulas described in the paper of Thorsson et al. (2014). Total radiation flux densities can be modelled using inputs of global shortwave radiation, air temperature and relative humidity (Thorsson et al., 2014).

The UTCI is an indicator sensitive to changes in radiation, humidity and wind speed in both cold and warm conditions, and is often applied in public weather services, public health services, urban planning and design (Jendritzky et al., 2012).

Meteorological data were retrieved from the Royal Netherlands Meteorological Institute (KNMI) station at Rotterdam Airport, located north of Rotterdam (approximately 3 km distance from city centre). Air temperature, relative humidity, wind speed and global radiation were used as input for the models that constructed the various daily heat indices for the different neighbourhoods in Rotterdam during the study period.

Neighbourhood-specific daily air temperature was modelled according to the method of Klok et al. (2012). The Urban Heat Island effect in the city centre of Rotterdam (UHI_city centre) was estimated as the annual mean difference in air temperature between a weather station in the city centre (near Central Station) and Rotterdam Airport. This was found to be 1.2 °C. Differences in the surface temperature (Ts) between each neighbourhood and the airport and city centre (derived from satellite images) were used to scale this 1.2 °C to UHI effect values for each neighbourhood (Klok et al., 2012). Hourly air temperatures measured at Rotterdam Airport (Ta_airport) were corrected with this value to calculate hourly air temperatures for each neighbourhood (Ta_neighb). From this we could retrieve neighbourhood-specific daily maximum air temperatures ($Ta_{max}$) during the study period.

Neighbourhood-specific daily Tmrt and UTCI were both calculated using the SOLWEIG 1D (Solar and Longwave Environmental Irradiance Geometry) model (Lindberg and Grimmond, 2011; Lindberg, 2013). Technical details of the exposure assessment using this model are described in the online supplement.

### 2.3. Air pollution exposure assessment

Daily exposure to particulate matter with a diameter of ≤10 μm ($PM_{10}$), nitrogen dioxide ($NO_2$) and ozone ($O_3$) were estimated for the study period, using dispersion modelling in combination with air quality measurements (Keuken et al., 2011). Because home addresses were not available, we determined daily population weighted average (PWA) concentrations per neighbourhood instead. These were calculated from the daily average concentrations for three different 'exposure situations' in each neighbourhood and calibrated with daily measurement data. These 'exposure situations' were: streets with more than 10,000 vehicles per day (Zone 1), areas up to 100 m from urban motorways (Zone 2) and the rest of the urban area in a neighbourhood (Zone 3). Subsequently, the PWA concentration for a given neighbourhood was computed taking into account the number of people (#) living in each of these zones:

$$\mathrm{PWA}(\mu g/m^3) = ((C*\#)\mathrm{Zone}1 + (C*\#)\mathrm{Zone}2 + (C*\#)\mathrm{Zone}3) / (\#\mathrm{Zone}1 + \#\mathrm{Zone}2 + \#\mathrm{Zone}3) \quad (1)$$

with C the daily average concentration of a pollutant in μg/m$^3$ in each zone per neighbourhood.

Concentrations of $PM_{10}$, $NO_2$ and $O_3$ for Zone 3 in a neighbourhood were derived from background concentrations at 1 ∗ 1 km spatial resolution grids. These background concentrations are based on a combination of modelling and measurements in the National Air Quality Monitoring Network (Velders et al., 2013). The contribution of road traffic emissions from streets and motorways is added to the urban background in each neighbourhood (Zone 3 concentration) to obtain Zone 1 and 2 concentrations. More details on modelling of the traffic contributions are described in the online supplement.

The uncertainty involved in modelling the annual averages of regulated air pollutants at a certain location in The Netherlands has been estimated as 20% (Mathijssen and Visser, 2006). In this study, the modelled daily averages were calibrated by daily measurements and therefore a similar uncertainty is assumed for $PM_{10}$, $NO_2$ and $O_3$.

### 2.4. Study design and data analysis

The case-crossover design was used to assess the relations between heat, air pollution and mortality. This design is a modification of the matched case–control design in which each case acts as his/her own