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# Unusually cold and dry winters increase mortality in Australia

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ABSTRACT

Seasonal patterns in mortality have been recognised for decades, with a marked excess of deaths in winter, yet our understanding of the causes of this phenomenon is not yet complete. Research has shown that low and high temperatures are associated with increased mortality independently of season; however, the impact of unseasonal weather on mortality has been less studied. In this study, we aimed to determine if unseasonal patterns in weather were associated with unseasonal patterns in mortality. We obtained daily temperature, humidity and mortality data from 1988 to 2009 for five major Australian cities with a range of climates. We split the seasonal patterns in temperature, humidity and mortality into their stationary and non-stationary parts. A stationary seasonal pattern is consistent from year-to-year, and a non-stationary pattern varies from year-to-year. We used Poisson regression to investigate associations between unseasonal weather and an unusual number of deaths. We found that deaths rates in Australia were 20–30% higher in winter than summer. The seasonal pattern of mortality was non-stationary, with much larger peaks in some winters. Winters that were colder or drier than a typical winter had significantly increased death risks in most cities. Conversely summers that were warmer or more humid than average showed no increase in death risks. Better understanding the occurrence and cause of seasonal variations in mortality will help with disease prevention and save lives.


## Introduction

Many studies have highlighted seasonal patterns in mortality, with high death rates in winter and low rates in summer (Gemmell et al., 2000; Kalkstein, 2013). A number of causes for the winter excess deaths have been suggested, including seasonal changes in environmental exposures (e.g., temperature, humidity, ultraviolet light, air pollution), diet, behaviour, infectious agents and light–dark cycles (Hales et al., 2012; Healy, 2003; Huang and Barnett, 2014). Understanding more clearly what factors influence seasonal patterns in mortality has implications for public health planning, as a better knowledge could be used to guide prevention programs (Lawlor, 2004; Naumova, 2006).

Epidemiological research has shown increased risks of death in cold and hot weather. Initial studies of temperature and mortality examined the temperature effects for individual cities. More recent large multi-city studies have provided evidence of temperature–mortality associations across a range of climates (Analitis et al., 2008; Anderson and Bell, 2009; Baccini et al., 2008; Barnett et al., 2012; McMichael et al., 2008). Humidity can also affect health through a variety of mechanisms, and mortality is usually highest on extremely hot and humid days (Davis et al., 2004). However, the effects of humidity on health have received less attention than the effects of temperature (Barreca, 2012; Schwartz et al., 2004).

Previous studies on weather and health are usually based on time-series designs that compare day-to-day changes in mortality with day-to-day changes in temperature while controlling for other time-varying risk factors such as season. The methods used have varied considerably, and estimates of the magnitude of temperature effects on mortality have differed substantially by location (Basu et al., 2005; O'Neill and Ebi, 2009). These differences may reflect actual differences in the effects of temperature on mortality due to variations in climate, but also the estimated effects of temperature could be confounded by seasonal patterns (Bhaskaran et al., 2013; Gasparrini and Armstrong, 2010; Welty and Zeger, 2005).

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In this study, we examined the seasonal patterns in death for five major cities in Australia and explored associations between mortality, season and weather. We did not examine the day-to-day changes in mortality and weather, but instead examined the pattern on a time-scale of months. We split the seasonal patterns in temperature, humidity and mortality into their stationary (seasonal) and non-stationary (unseasonal) parts. A stationary seasonal pattern is consistent from year-to-year, and a non-stationary pattern varies from year-to-year. We aimed to determine how unseasonal patterns in temperature and humidity in winter and summer were associated with unseasonal patterns in death.

## Methods

The cities studied were Sydney, Melbourne, Brisbane, Perth and Adelaide (in order of population size); five major capital cities in Australia. The study period was from 1988 to 2009. Winter was from June to August and summer from December to February.

We obtained daily mortality data from 1 January 1988 to 31 December 2009 for each city from the Australian Bureau of Statistics. Accidental deaths and deaths of individuals who were not residents of the city were excluded. We examined deaths in all ages.

Hourly measurements of daily ambient temperature and dew-point temperature (humidity) for the years 1988–2009 were obtained from the Australian Bureau of Meteorology. We used data from airport weather stations for all cities. Daily mean temperature and humidity were calculated as the average of the daily maximum and daily minimum values.

We aimed to separate the strong seasonal patterns in death and weather into their stationary and non-stationary parts. A stationary seasonal pattern is that which is consistent from year-to-year, and a non-stationary pattern is that which varies from year-to-year but is still recognizably seasonal.

To find the stationary seasonal pattern in deaths, we modelled the daily number of deaths in each city using Poisson regression:

$$death_t \sim Poisson\,(\mu_t),\ t = 1, \ldots, n,$$

$$\log(\mu_t) = \alpha + \mathrm{M}_t\boldsymbol{\gamma} + \mathrm{D}_t\boldsymbol{\beta} + s(t, 3),$$

where $\alpha$ is the intercept, $\mathrm{M}_t$ is an $n \times 11$ matrix of zeros and ones that corresponds to month (with a reference month of January) and $\boldsymbol{\gamma}$ is a vector of parameter estimates for the stationary seasonal pattern, $\mathrm{D}_t$ is an $n \times 6$ matrix of zeros and ones that corresponds to the day of the week (with a reference day of Monday) and $\boldsymbol{\beta}$ is a vector of parameter estimates for day of the week. The long-term trend in deaths was modelled by $s(t,3)$ which is a natural spline with 3 degrees of freedom.

We examined the deviance residuals of the model to look for patterns in deaths that were not explained by a stationary season. A positive residual means there were more deaths than predicted, and a negative residual means there were fewer deaths than predicted. We examined the deviance residuals for deaths rather than the raw residuals as they are more symmetric (when using Poisson regression) and are therefore more useful for diagnostic purposes (Dobson and Barnett, 2008).

We used the same process to examine temperature and humidity by fitting similar regression models. As temperature and humidity are continuous we used a Gaussian model and the raw residuals. We averaged the daily residuals into months as we are primarily interested in longer-term associations between weather and mortality. For temperature a positive temperature residual means an unusually warm month, and a negative residual means an unusually cold month. For humidity a positive residual means a wetter than average month, and a negative residual is a drier than average month. In order to look for long-term patterns in the residuals we smoothed them using local polynomial regression with a span of 0.5, and then plotted the smoothed residuals over time (Cleveland et al., 1992). We plotted the smoothed monthly temperature and humidity residuals next to the smoothed monthly death residuals to visually look for long-term associations between periods of unusual temperatures and periods of unusual deaths.

To look for statistical associations between unseasonal weather and an unusual number of deaths, we used the following Poisson regression model with the monthly number of deaths as the dependent variable:

$$death_m \sim Poisson\,(\mu_m),\ m = 1, \ldots, N,$$

$$\log(\mu_m) = \alpha + \log(o_m/30) + \mathrm{M}_m\boldsymbol{\gamma} + s(m, 3) + \mathrm{S}_m\bar{t}_m\boldsymbol{\delta} + \mathrm{S}_m\bar{h}_m\boldsymbol{\beta},$$

where $o_m$ is an offset of the number of days in month $m$ divided by 30, which adjusts for differences in month lengths (e.g., February being shorter) and standardizes the results to a common month of 30 days. As in the previous model, $\alpha$ is the intercept, the vector $\boldsymbol{\gamma}$ captures the stationary seasonal pattern, and the spline $s()$ captures the long-term trend using three degrees of freedom. The residual effect of temperature is estimated by the mean temperature residuals in each month ($\bar{t}_m$), where a warmer than average month has a positive residual. The effect of unusually low or high temperatures should be different in winter and summer. For example, lower than average winter temperatures are likely to increase the risk of death, whereas lower than average summer temperatures are likely to decrease risk. To capture this difference, $\mathrm{S}_m$ is an $N \times 4$ matrix of zeros and ones that corresponds to each season, so that $\boldsymbol{\delta}$ is a vector of parameter estimates that models an unusually warm or cold month for each of the four seasons. The vector of parameters $\boldsymbol{\beta}$ models the effect of humidity.

We presented results on an absolute scale by calculating the estimated mean number of deaths for seasons that were not unusual ($\bar{t}_m = 0$ and $\bar{h}_m = 0$). We then examined the difference in absolute death numbers for: a winter that was 1 °C colder ($\bar{t}_m = -1$) and a winter with a 1 °C decrease in humidity ($\bar{h}_m = -1$), a summer that was 1 °C warmer ($\bar{t}_m = 1$) and summer with a 1 °C increase in humidity ($\bar{h}_m = 1$). Our linear interaction means that we also test the effects of warmer or wetter winters and colder or drier summers, but we presented the results for the most plausible *a priori* scenarios. All results were presented as means with 95% confidence intervals (CIs). The R software (version 3.0.2) (R Development Core Team, Austria) was used for all analyses.

## Results

For the 22-year period, there were over 1.5 million deaths in the five major cities of Australia (Table 1). There was a strong seasonal pattern of mortality in every city, with far more deaths in winter (Fig. 1). The seasonal pattern was non-stationary, with much larger peaks in some winters.

Death rates were 20–30% higher in a winter than a summer (Fig. 2). Sydney had the largest seasonal pattern, and Melbourne the smallest. In Sydney there were 2353 deaths (95% CI: 2339–2367 deaths) in a typical winter month compared with 1817 deaths (95% CI: 1805–1829 deaths) in a typical summer month, an increase in winter of 536 deaths per month (Table 2).

We compared the residual patterns in deaths to the residual patterns in temperature and humidity. There was a striking similarity in the death residuals for Sydney, Melbourne, Brisbane and Perth (Fig. 3). So when deaths were unusually high (or low) in one of these cities they were also unusually high (or low) in the other