National and regional seasonal dynamics of all-cause and cause-specific mortality in the USA from 1980 to 2013

Robbie M Parks[1,2], James E Bennett[1,2,3], Kyle J Foreman[1,2,4], Ralf Toumi[5], Majid Ezzati[1,2,3*]

[1] MRC-PHE Centre for Environment and Health, Imperial College London, London, United Kingdom, W2 1PG

[2] Department of Epidemiology and Biostatistics, School of Public Health, Imperial College London, London, United Kingdom, W2 1PG

[3] WHO Collaborating Centre on NCD Surveillance and Epidemiology, Imperial College London, London, United Kingdom, W2 1PG

[4] Institute for Health Metrics and Evaluation, University of Washington, Seattle, USA, WA 98121

[5] Space and Atmospheric Physics, Imperial College London, London, United Kingdom, W7 2AZ

Address correspondence to Majid Ezzati (majid.ezzati@imperial.ac.uk)

Abstract

It has been hypothesized that a warmer world may lower winter mortality in temperate climates, where winter deaths exceed summer ones. We used geo-coded mortality data and wavelet analytical techniques to analyse the seasonality of all-cause and cause-specific mortality by age group and sex from 1980 to 2013 in the USA, nationally and in subnational climatic regions. Death rates in men and women ≥45 years exhibited statistically significant seasonality with peak in January/February and minimum in June/July, driven by seasonality of cardiorespiratory diseases and injuries. In these ages, percent difference in death rates between peak and minimum months did not vary across climate regions, and was largely unchanged from 1980 to 2013. Under five years of age, seasonality of all-cause mortality largely

disappeared after the 1990s. In adolescents and young adults, especially in males, death rates peaked in June/July and were lowest in December/January, driven by seasonality of injury deaths.

Introduction

It is well-established that death rates vary throughout the year, and in temperate climates there tend to be more deaths in winter than in summer (Campbell, 2017; Fowler et al., 2015; Healy, 2003; McKee, 1989). Therefore, it has been hypothesized that a warmer world may lower winter mortality in temperate climates (Langford & Bentham, 1995; Martens, 1998). In a large country like the USA, which possesses distinct climate regions, the seasonality of mortality may vary geographically, due to geographical variations in mortality, localized weather patterns, and regional differences in adaptation measures such as heating, air conditioning and healthcare (Davis, Knappenberger, Michaels, & Novicoff, 2004; Ferreira Braga, Zanobetti, & Schwartz, 2001; Kalkstein, 2013; Medina-Ramón & Schwartz, 2007). The presence and extent of seasonal variation in mortality may also itself change over time, due to shifts in weather regimes, lifestyle, adaptation technologies, and healthcare (Bobb, Peng, Bell, & Dominici, 2014; Carson, Hajat, Armstrong, & Wilkinson, 2006; Seretakis, 1997; Sheridan, Kalkstein, & Kalkstein, 2009).

A thorough understanding of the long-term dynamics of seasonality of mortality, and its geographical and demographic patterns, is needed to identify at-risk groups, plan responses at the present time as well as under changing climate conditions. Although mortality seasonality is well-established, there is limited information on how seasonality, including the timing of minimum and maximum mortality, varies by local climate and how these features have changed over time, especially in relation to age group, sex and medical cause of death (Rau, 2004; Rau, Bohk-Ewald, Muszyńska, & Vaupel, 2018).

In this paper, we comprehensively characterize the spatial and temporal patterns of all-cause and cause-specific mortality seasonality in the USA by sex and age group, through the application of wavelet analytical techniques, which have been used to study the dynamics of weather phenomena (Moy CM, Seltzer GO, Rodbell DT, 2002) and infectious diseases (Grenfell, Bjørnstad, & Kappey, 2001), to over three decades of national mortality data. We also used centre of gravity analysis and circular statistics methods to understand the timing of mortality minimum and maximum where seasonality has been identified.

Results

All-cause mortality in males had a statistically significant 12-month seasonality in all age groups, except in those aged 35-44 years, for whom there was statistically significant periodicity at 6 months (Figure 2). In females, there was significant 12-month seasonality in all groups except 5-14 and 25-35 years (Figure 2). While seasonality persisted throughout the entire analysis period in older ages, it largely disappeared after late 1990s in children aged 0-4 years in both sexes and in women aged 15-24 years.

Mortality from all four cause groups was seasonal above 75 years of age (Figure 2). Seasonality in cancer deaths only appeared after 55 years of age, whereas deaths from cardiorespiratory causes exhibited statistically significant seasonality throughout the life-course. In addition to older ages, injuries were also seasonal from childhood through 44 years in women and 64 years in men.

Death rates in men aged ≥45 years and women aged ≥35 years peaked in January and February and were lowest in June-August, for all-cause mortality as well as for causes of death with statistically significant seasonality, including injuries (Figure 3). A similar temporal pattern was seen for all-cause mortality in children younger than five years of age, whose all-cause death rate was highest in February and lowest in August. These months also represented maximum and minimum mortality of children for non-injury causes. In contrast injury deaths in children, adolescents and young and middle-aged adults peaked in June/July and were lowest in December/January. Among older boys and young men, not only did injury mortality peak in in June/July, but all-cause mortality also.

From 1980 to 2013, the proportional (percent) difference in all-cause death rates between peak and minimum months declined little for people older than 45 years of age (non-significantly and by less than eight percentage points) (Figure 4). In contrast, the difference between peak (summer) and minimum (winter) death rates declined significantly in younger ages, by over 25 percentage points in males aged 5-14 years and 15-24 years, largely driven in the declining difference between summer and winter injury deaths. Under five years of age, percent seasonal difference in all-cause death rates declined by a statistically-significant 13 percentage points (95% CI 8 to 18) for boys but only a statistically-non-significant 5 percentage points (-12 to 2) for girls. These declines in seasonality of child deaths were a net effect of declining winter-summer difference in cardiorespiratory deaths and increasing summer-winter difference in injury deaths.

The subnational centre of gravity analysis shows that all-cause mortality peaks and minima in different climate regions are consistent with the national ones (Figure 5), indicating the seasonality is largely independent of geography. The relative homogeneity of the timing of maximum and minimum mortality contrasts with the large variation in seasonal temperatures among climate regions. For example, in men and women aged 65-74 years, all-cause mortality peaked in February in the Northeast and Southeast, even though the average temperatures for those regions were different by over 13 degrees Celsius (9.3 in the Southeast compared with -3.8 in the Northeast). Furthermore, above 45 years of age, there was little inter-region variation in the percent seasonal difference in all-cause mortality, despite the large variation in temperature difference between the peak and minimum months (Figure 6). The only cause of death with regional differences in seasonality was injuries in men aged 55-64 years and women aged 65-74 years. Injury death rates in these age-sex groups seemed to peak in January in the Northeast peak and in August in the (Supplementary Figure 1).

Strengths and limitations

The strengths of our study are its innovative methods of characterizing seasonality of mortality dynamically over space and time, by age group and cause of death; using wavelet and centre of gravity analyses; using ERA-Interim data output to compare the association between seasonality of death rates and regional temperature. A limitation of our study is that we used broad causes of death so that we have sufficient number of deaths by age group, sex, year, climate region and cause of death. Different diseases and injuries may be differentially affected by environmental, behavioural and healthcare factors associated with season and hence differ in their seasonal behaviour. For example, suicides have been found to peak in early spring (Feinstein, 2002), and cardiovascular disease mortality may peak earlier in the winter than that from respiratory conditions (Mackenbach, Kunst, & Looman, 1992). Similarly, the seasonality of influenza, and how it has changed over time, may be different than that of other respiratory diseases due to disease-specific interventions (Simonsen et al., 2005). Further, we did not investigate seasonality of mortality by socioeconomic characteristics which may help with understanding its determinants and planning responses.

Discussion

We used wavelet and centre of gravity analyses, which allowed not only systematically identifying and characterizing seasonality of total and cause-specific mortality in the USA, but also examining how seasonality has changed over time. We identified distinct seasonal behaviours in relation to age and sex, including the higher summer mortality in young men (Feinstein, 2002; Rau et al., 2018). Importantly, we also showed that all-cause and cause-specific mortality seasonality is largely similar in terms of both timing and magnitude across diverse climatic regions with substantially different summer and winter temperatures, with a notable exception of injuries in older ages. Insights of this kind would not have been possible analysing data averaged over time or nationally, or fixed to pre-specified frequencies.

Prior studies have noted seasonality of mortality for all-cause mortality and for specific causes of death in the USA (Feinstein, 2002; Kalkstein, 2013; Rau, 2004; Rau et al., 2018; Rosenwaike, 1966; Seretakis, 1997). Few of these studies have done consistent national and subnational analyses, and none has done so over time, for a comprehensive set of age groups and causes of death, and in relation to regional temperature differences. Our results on strong seasonality of cardiorespiratory deaths and weak seasonality of cancer deaths, restricted to older ages, are broadly consistent with these studies (Feinstein, 2002; Rau et al., 2018; Rosenwaike, 1966; Seretakis, 1997), which had limited analysis on how seasonality changes over time and/or geography (Feinstein, 2002; Rau et al., 2018; Rosenwaike, 1966). Similarly, our results on seasonality of injury deaths are supported by a few prior studies (Feinstein, 2002; Rau et al., 2018; Rosenwaike, 1966), but our subnational analysis over three decades revealed variations in when injury deaths peaked and in how seasonal differences in these deaths have changed over time which had not been reported before.

The observed geographical similarity in seasonal mortality variation in the USA, also seen in a study of 36 cities using deaths aggregated across age groups and over time (Kinney et al., 2015), contrasts from the pattern observed across Europe, where the difference between winter and summer mortality tends to be lower in the colder Nordic countries than in warmer southern European nations (Fowler et al., 2015; Healy, 2003; McKee, 1989). The absence of association between the magnitude of mortality seasonality and seasonal temperature difference indicates that different regions in the USA are similarly adapted to temperature seasonality, whereas Nordic countries may have better environmental (e.g., housing insulation and heating) and health system measures to counter the effects of cold winters than those in southern Europe.

The cause-specific analysis showed that the substantial decline in seasonal mortality differences in adolescents and young adults was related to the diminishing seasonality of injuries, especially from road traffic crashes, which are more likely to occur in the summer months (National Highway Traffic Safety Administration, 2005) and are more common in men. The weakening of seasonality in boys under five years of age was related to two phenomena: first, the seasonality of death from cardiorespiratory diseases declines, and second, the proportion of deaths during the perinatal period, which have limited seasonality, increased (MacDorman & Gregory, 2015).

In contrast to young and middle ages, mortality in older ages, where death rates are highest, maintained persistent seasonality over a period of three decades (we note that although the percent seasonal difference in mortality has remained largely unchanged in these ages, the absolute difference in death rates between the peak and minimum months has declined because total mortality has a declining long-term trend). This finding demonstrates the need for environmental and health service interventions targeted towards this group irrespective of geography and local climate. Examples of such interventions include enhancing the availability of both environmental and medical protective factors, such as better insulation of homes, winter heating provision and flu vaccinations, for the vulnerable older population (Public Health England, 2017). Social interventions, including regular visits to the isolated elderly during peak mortality periods to ensure that they are optimally prepared for adverse conditions, and responsive and high-quality emergency care, are also important to protect this vulnerable group (Healy, 2003; Lerchl, 1998; Public Health England, 2017). Emergent new technologies, such as always-connected hands-free communications devices with the outside world, in-house cameras, and personal sensors also provide an opportunity to enhance care for the older, more vulnerable groups in the population, especially in winter when the elderly have fewer social interactions (Kimberly Miller, 2013). Such interventions are important today, and will remain so as the population ages and climate change increases the within- and between-season weather variability.

Materials and methods

Data

We used data on all 77,771,264 deaths in the USA from 1980 to 2013 from the National Center for Health Statistics (NCHS). Age, sex, state of residence, month of death, and underlying cause of death were available for each record. Yearly population counts were available from NCHS for 1990 to 2013 and from the US Census Bureau prior to 1990 (Ingram et al., 2003). We calculated monthly population counts through linear interpolation, assigning each yearly count to July. We also subdivided the national data geographically by climate regions used by the National Oceanic and Atmospheric Administration (Figure 1) (Karl & Koss, 1984). The underlying cause of death was coded according to the international classification of diseases (ICD) system (9th revision of ICD from 1980 to 1998 and 10th revision of ICD thereafter).

Data were divided by sex and age in the following 10 age groups: 0-4, 5-14, 25- 34, 35-44, 45-54, 55-64, 65-74, 75-84, 85+ years. We calculated monthly death rates for each age and sex group, both nationally and for sub-national climate regions. Death rate calculations accounted for varying length of months, by multiplying each month's death count by a factor that would make it equivalent to a 31-day month. For analysis of seasonality by cause of death, we mapped each ICD-9 and ICD-10 codes to the following four disease categories:

- Cancers: ICD-9 140.0 – 239.9 and ICD-10 C00 – D48
- Cardiorespiratory diseases: ICD-9 390.0 – 519.9 and ICD-10 I00 – J99
- Injuries (external causes): ICD-9 800.0 – 999.9 and ICD-10 S00 – Z99
- Other causes: ICD-9 and ICD-10 codes not in the above three categories

Cardiorespiratory diseases and cancers accounted for 56.4% and 21.2% of all deaths in the USA, respectively, in 1980, and 40.9% and 23.5%, respectively, in 2013. Deaths from cardiorespiratory diseases have been associated with cold and warm temperatures (Basu, 2009; Basu & Samet, 2002; Bennett, Blangiardo, Fecht, Elliott, & Ezzati, 2014; Braga, Zanobetti, & Schwartz, 2002; Gasparrini et al., 2015). Injuries, which accounted for 8% of all deaths in the USA in 1980 and 7.5% in 2013, may have seasonality that is distinct from so-called natural causes. We did not further divide other causes because the number of deaths could become too small to allow stable estimates when divided by age group, sex and climate region.

We obtained data on temperature from ERA-Interim, which combines predictions from a physical model with ground-based and satellite measurements (Dee et al., 2011). We used gridded four-times-daily estimates at a resolution of 80km to generate monthly population-weighted temperature by climate region throughout the analysis period.

Statistical methods

We used wavelet analysis to investigate seasonality, both nationally and sub-nationally, for each age-sex group. Wavelet analysis uncovers the presence, and frequency, of repeated maxima and minima in each age-sex-specific death rate time series. In brief, a Morlet wavelet, described in detail elsewhere (Cazelles et al., 2008), is equivalent to using a moving window on the death rate time series and analysing periodicity in each window using a short-form Fourier transform, hence generating a dynamic spectral analysis, which allows measuring dynamic seasonal behaviour, in which the periodicity of death rates may disappear, emerge, or change over time. In addition to coefficients that measure the frequency of periodicity, wavelet analysis gives an indication of statistical significance of results compared with random fluctuations that can be represented with white (an independent random process) or red (autoregressive of order 1 process) noise. We used the R package WaveletComp (version 1.0) for the wavelet analysis. Before analysis, we logarithmically transformed death rates, de-trended using a polynomial regression, and rescaled each all-cause mortality death rate time series so as to range between 1 and -1.

We identified age-sex groups whose wavelet power spectra differed from that of a white noise spectrum, which represents random fluctuations, at 5% significance level, for the entire study period (1980-2013). For age-sex groups which had statistically significant power spectra for 1980-2013, we calculated the centre of gravity and the negative centre of gravity of monthly death rates. These parameters show when in the year, on average, maximum and minimum death rates occur, respectively. For calculating centre of gravity, each month was weighted by its death rate; for negative centre of gravity, each month was weighted by the difference between its death rate and the year's maximum death rate. In taking the weighted average, we allowed January (month 1) to neighbour December (month 12), a technique called circular statistics. Along with each circular mean, a 95% confidence interval (CI) was calculated by using 1000 bootstrap samples. The R package CircStats (version 0.2.4) was used for this purpose.

For each age-sex group and year, we used a Poisson model to estimate the percentage difference in death rates between the maximum and minimum mortality months for each year, and its standard error which accounts for population size. We then fitted a linear regression to the time series of seasonal differences for each age and sex group, weighting each by the inverse of the square of its standard error. We calculated change in the fitted values from 1980 to 2013, reported as percentage point difference, as a quantitative measure of how the seasonality of death rates has changed over time.

Acknowledgments

Robbie Parks is supported by a Wellcome Trust ISSF Studentship. Work on the US mortality data is supported by a grant from US Environmental Protection Agency.

Author contributions

All authors contributed to study concept, analytical approach, and interpretation of results. RP, KF and ME collated and organised mortality files. RP performed the analysis, with input from

JB. RP and ME wrote the first draft of the paper; other authors contributed to revising and finalising the paper.

Competing financial interests

The authors declare no competing financial interests.

References

Basu, R. (2009). High ambient temperature and mortality: a review of epidemiologic studies from 2001 to 2008. *Environmental Health*, *8*(1), 40. https://doi.org/10.1186/1476-069X-8-40

Basu, R., & Samet, J. M. (2002). Relation between elevated ambient temperature and mortality: A review of the epidemiologic evidence. *Epidemiologic Reviews*. https://doi.org/10.1093/epirev/mxf007

Bennett, J. E., Blangiardo, M., Fecht, D., Elliott, P., & Ezzati, M. (2014). Vulnerability to the mortality effects of warm temperature in the districts of England and Wales. *Nature Climate Change*, *4*(4), 269–273. https://doi.org/10.1038/nclimate2123

Bobb, J. F., Peng, R. D., Bell, M. L., & Dominici, F. (2014). Heat-related mortality and adaptation to heat in the United States. *Environmental Health Perspectives*, *122*(8), 811–816. https://doi.org/10.1289/ehp.1307392

Braga, A. L. F., Zanobetti, A., & Schwartz, J. (2002). The effect of weather on respiratory and cardiovascular deaths in 12 U.S. cities. *Environmental Health Perspectives*, *110*(9), 859–863. https://doi.org/10.1289/ehp.02110859

Campbell, A. (2017). Excess winter mortality in England and Wales: 2016 to 2017 (provisional) and 2015 to 2016 (final). *Statistical Bulletin, Office for National Statistics*.

Carson, C., Hajat, S., Armstrong, B., & Wilkinson, P. (2006). Declining vulnerability to temperature-related mortality in London over the 20th century. *American Journal of Epidemiology*, *164*(1), 77–84. https://doi.org/10.1093/aje/kwj147

Cazelles, B., Chavez, M., Berteaux, D., Ménard, F., Vik, J. O., Jenouvrier, S., & Stenseth, N. C. (2008). Wavelet analysis of ecological time series. *Oecologia*. https://doi.org/10.1007/s00442-008-0993-2

Davis, R. E., Knappenberger, P. C., Michaels, P. J., & Novicoff, W. M. (2004). Seasonality of climate-human mortality relationships in US cities and impacts of climate change. *Climate Research*, *26*(1), 61–76. Retrieved from internal-pdf://32.0.35.211/paper.pdf

Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., … Vitart, F. (2011). The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society*, *137*(656), 553–597. https://doi.org/10.1002/qj.828

Feinstein, C. A. (2002). Seasonality of deaths in the U.S. by age and cause. *Demographic Research*, *6*, 469–486. https://doi.org/10.4054/DemRes.2002.6.17

Ferreira Braga, A. L., Zanobetti, A., & Schwartz, J. (2001). The time course of weather-related deaths. *Epidemiology*, *12*(6), 662–667. https://doi.org/10.1097/00001648-200111000-00014

Fowler, T., Southgate, R. J., Waite, T., Harrell, R., Kovats, S., Bone, A., … Murray, V. (2015). Excess winter deaths in Europe: A multi-country descriptive analysis. *European Journal of Public Health*, *25*(2), 339–345. https://doi.org/10.1093/eurpub/cku073

Gasparrini, A., Guo, Y., Hashizume, M., Lavigne, E., Zanobetti, A., Schwartz, J., … Armstrong, B. (2015). Mortality risk attributable to high and low ambient temperature: A multicountry observational study. *The Lancet*, *386*(9991), 369–375. https://doi.org/10.1016/S0140-6736(14)62114-0

Grenfell, B. T., Bjørnstad, O. N., & Kappey, J. (2001). Travelling waves and spatial hierarchies in measles epidemics. *Nature*, *414*(6865), 716–723. https://doi.org/10.1038/414716a

Healy, J. D. (2003). Excess winter mortality in Europe: A cross country analysis identifying key risk factors. *Journal of Epidemiology and Community Health*, *57*(10), 784–789. https://doi.org/10.1136/jech.57.10.784

Ingram, D. D., Parker, J. D., Schenker, N., Weed, J. A., Hamilton, B., Arias, E., & Madans, J. H. (2003). United States Census 2000 population with bridged race categories. *Vital and Health Statistics. Series 2, Data Evaluation and Methods Research*, (135), 1–55. Retrieved from internal-pdf://103.99.132.94/paper.pdf

Kalkstein, A. J. (2013). Regional Similarities in Seasonal Mortality across the United States: An Examination of 28 Metropolitan Statistical Areas. *PLoS ONE*, *8*(5). https://doi.org/10.1371/journal.pone.0063971

Karl, T. R., & Koss, W. J. (1984). Regional and national monthly, seasonal, and annual temperature weighted by area, 1895-1983.

Kimberly Miller, A. A. (2013). Smart-Home Technologies to Assist Older People to Live Well at Home. *Journal of Aging Science*, *1*(1). https://doi.org/10.4172/2329-8847.1000101

Kinney, P. L., Schwartz, J., Pascal, M., Petkova, E., Tertre, A. Le, Medina, S., & Vautard, R. (2015). Winter season mortality: Will climate warming bring benefits? *Environmental Research Letters*, *10*(6). https://doi.org/10.1088/1748-9326/10/6/064016

Langford, I. H., & Bentham, G. (1995). The potential effects of climate change on winter mortality in England and Wales. *Int J Biometeorol*, *38*(3), 141–147. Retrieved from internal-pdf://189.27.88.183/art%253A10.1007%252FBF01208491.pdf

Lerchl, A. (1998). Changes in the seasonality of mortality in Germany from 1946 to 1995: the role of temperature. *International Journal of Biometeorology*, *42*(2), 84–88. https://doi.org/10.1007/s004840050089

MacDorman, M. F., & Gregory, E. (2015). Fetal and Perinatal Mortality: United States, 2013. *National Vital Statistics Reports*, *64*(8), 1–24.

Mackenbach, J. P., Kunst, A. E., & Looman, C. W. N. (1992). Seasonal variation in mortality in The Netherlands. *Journal of Epidemiology and Community Health*, *46*(3), 261–265. https://doi.org/10.1136/jech.46.3.261

Martens, W. J. (1998). Climate change, thermal stress and mortality changes. *Soc Sci Med*, *46*(3), 331–344. Retrieved from internal-pdf://57.13.130.132/1-s2.0-S0277953697001627-main.pdf

McKee, C. M. (1989). Deaths in winter: Can Britain learn from Europe? *European Journal of Epidemiology*, *5*(2), 178–182. https://doi.org/10.1007/BF00156826

Medina-Ramón, M., & Schwartz, J. (2007). Temperature, temperature extremes, and mortality: A study of acclimatisation and effect modification in 50 US cities. *Occupational and Environmental Medicine*, *64*(12), 827–833. https://doi.org/10.1136/oem.2007.033175

Moy CM, Seltzer GO, Rodbell DT, & A. D. (2002). Variability of El Nino/Southern Oscillation activity at millennial timescales during the Holocene epoch. *Nature*, *420*(November). https://doi.org/10.1038/nature01163.1.

National Highway Traffic Safety Administration. (2005). Trend and Pattern Analysis of Highway Crash Fatality By Month and Day. *National Center for Statistics and Analysis (NCHS)*, (March).

Public Health England. (2017). The Cold Weather Plan for England. *Public Health England*, (October).

Rau, R. (2004). Seasonality in Human Mortality. A Demographic Approach. *Wirtschafts-Und Sozialwissenschaftlichen Fakultät*, *PhD*, 361. https://doi.org/10.1007/978-3-540-44902-7

Rau, R., Bohk-Ewald, C., Muszyńska, M. M., & Vaupel, J. W. (2018). *Visualizing Mortality Dynamics in the Lexis Diagram*. https://doi.org/10.1007/978-3-319-64820-0

Rosenwaike, I. (1966). Seasonal Variation of Deaths in the United States, 1951–1960. *Journal of the American Statistical Association*, *61*(315), 706–719.

https://doi.org/10.1080/01621459.1966.10480899

Seretakis, D. (1997). Changing Seasonality of Mortality From Coronary Heart Disease. *JAMA: The Journal of the American Medical Association*, *278*(12), 1012. https://doi.org/10.1001/jama.1997.03550120072036

Sheridan, S. C., Kalkstein, A. J., & Kalkstein, L. S. (2009). Trends in heat-related mortality in the United States, 1975-2004. *Natural Hazards*, *50*(1), 145–160. https://doi.org/10.1007/s11069-008-9327-2

Simonsen, L., Reichert, T. A., Viboud, C., Blackwelder, W. C., Taylor, R. J., & Miller, M. A. (2005). Impact of influenza vaccination on seasonal mortality in the US elderly population. *Archives of Internal Medicine*, *165*(3), 265–272. https://doi.org/10.1001/archinte.165.3.265

390 **Figure 1**: Climate regions of the USA.

Figure 2: Wavelet power spectra for national time series of all-cause and cause-specific death rates for 1980-2013, by age group and cause of death for (A) males and (B) females. Wavelet power values increase from blue to red, with white contour lines indicating the 5% significance level against a white noise spectrum (the same age groups would remain significant if significance had been measured against a red noise spectrum). The shaded regions at the left and right edge of each box indicate the cone of influence, where spectral analysis is less robust.

Figure 3: Mean timing of national maximum and minimum all-cause and cause-specific mortality, by sex and age group for 1980-2013. Red arrows indicate the month of maximum mortality, and green arrows that of minimum mortality. The size of the arrow is inversely proportional to its respective 95% confidence interval. Only age-sex groups with statistically significant 12-month seasonality are included.

Figure 4: National percent difference in death rates between the maximum and minimum mortality months in 2013 versus 1980 by sex and age group. Only age-sex groups with statistically significant 12-month seasonality are included. Age-sex groups with a statistically significant change at the 5% level are highlighted with a bold pink outline.

Figure 5: Mean timing of (A) maximum and (B) minimum all-cause mortality, by climate region, sex and age group for 1980-2013. Only age-sex groups with significant 12-month seasonality in the national analysis are included. Average temperatures (in degrees Celsius) are included in white for the corresponding month of maximum and minimum mortality for each climate region. See Supplementary Figure 1 for results by cause of death.

Figure 6: The relationship between percent difference in death rates and temperature difference between months with maximum and minimum mortality across climate regions, by sex and age group in 2013. Only age-sex groups with significant 12-month seasonality in the national analysis are included.

Supplementary Figure 1: Mean timing of (A) maximum and (B) minimum cause-specific mortality, by climate region, sex and age group for 1980-2013. Only age-sex groups with significant 12-month seasonality in the national analysis are included. Average temperatures (in degrees Celsius) are included in white for the corresponding month of maximum and mortality for each climate region.