Seasonal dynamics of mortality in the United States from 1982 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

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

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

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

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

Robbie M Parks: robbie.parks@imperial.ac.uk

James E Bennett: j.e.bennett@imperial.ac.uk

Kyle Foreman: kfor@uw.edu

Ralf Toumi: r.toumi@imperial.ac.uk

Majid Ezzati: majid.ezzati@imperial.ac.uk

* Corresponding author:

Majid Ezzati

Imperial College London

Norfolk Place

London W2 1PG, UK

E-mail: majid.ezzati@imperial.ac.uk

Tel: +44 (0)20 7594 0767

It has been hypothesised that a warmer world may lower winter mortality in temperate climates.[1,2] There is however limited data to characterise the seasonality of mortality in relation to age, sex, and local climate, or to understand how it has changed over time. Here, we use geo-coded data on deaths in the USA and wavelet analytical techniques to comprehensively analyse the seasonality of mortality by age group and sex from 1982 to 2013, nationally and in subnational climatic regions. Death rates in men and women older than 45 years exhibit statistically significant seasonality with peak in January/February and minimum in June/July. Percent difference in death rates between peak and minimum months declined by less than seven percentage points from 1982 to 2013 nationally, and was independent of temperature difference between these two months in different climate regions. Under five years of age, seasonality of mortality largely disappeared after the 1990s. In adolescents and young adults, especially in males, death rates peak in June/July and are lowest in December/January, but the percent difference peak and minimum months shrank over time. The findings allow identifying at-risk groups, plan responses at the present time, and envision how changes in regional climate may influence seasonal mortality. Currently, all parts of USA are similarly adapted to temperature seasonality, although impacts on mortality depend on age.

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.[3-6] Less has been done on how the seasonal patterns of mortality vary in relation to age and sex.[7-9] Further, in a large country like the USA, which possesses distinct climate regions, not only do annual average death rates vary geographically, but also the seasonality of mortality may vary, due to both localised weather patterns and regional differences in adaptation measures such as heating, air conditioning, and healthcare.[10-13] 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.[14-16] 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.

Some studies, in one or more countries, have examined seasonality of mortality.[3-10,12,17-22] The length of time covered by these studies have ranged from a few years to over 50 years. Regardless of duration, the methods used in these works – ranging from simple trend moving average[8,17] to fitting periodic basis functions[7,18,20,22] – were unable to characterise how seasonality of mortality has changed over time; many also require a-priori assumptions on how frequently (e.g., every 12 months) the repeated death rate pattern occurs. Few of the previous studies have analysed seasonality by age and sex,[7-9] even though the main medical and behavioural causes of death vary for population subgroups, which may lead to different seasonal patterns. None has done so simultaneously by age, sex, and geography, even though seasonal temperatures vary geographically, as might their health effects.[10-12,23] Here, we comprehensively characterise the demographic, spatial and temporal patterns of mortality seasonality in the entire USA, through the application of wavelet analytical techniques that have been used to study the dynamics of weather phenomena[24] and infectious diseases[25] to over three decades of national mortality data.

All-cause male mortality had a statistically significant 12-month seasonality in all age groups except in ages 35-44 years, who displayed statistically significant periodicity at 6 months (Figure 1A). In females, there was no significant 12-month seasonality in ages 5 to 34 years

(Figure 1B); girls aged 5-14 years exhibited periodicity at 6 months for most of the analysis period. 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.

Death rates in men aged ≥45 years and women aged ≥35 years peaked in January and February, and were lowest in July and August (Figure 2). A similar temporal pattern was seen in children younger than five years of age, whose mortality was highest in February and lowest in August. In contrast, the peak and minimum of mortality in older boys and young men (ages 5-34 years) occurred in June/July and December/January, respectively.

Percent difference in death rates between mortality in peak and minimum months declined by less than seven percentage points for people older than 45 years of age from 1982 to 2013 (Figure 3). In contrast, the difference between peak (summer) and minimum (winter) declined significantly in younger ages, by nearly 25 percentage points in males aged 5-14 years and 15-24-years. Under five years of age, percent seasonal difference declined by a statistically-significant 13.2 percentage points (95% CI 8.1 to 18.2) for boys but only a statistically insignificant 5.0 percentage points (-12.0 to 2.0) for girls.

The sub-national centre of gravity analysis shows that mortality peaks and minima in different climate regions (Figure S1) are consistent with the national ones (Figure 4), indicating the seasonality is largely independent of geography. The relative homogeneity of the timing of maximum and mortality is evident, despite the large variation in temperatures that exist between climate regions during the same months. For example, in men and women aged 65-74 years, 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 is little inter-region variation in the percent seasonal difference, despite the large variation in temperature difference between the peak and minimum months (Figure 5; none of the associations with temperature difference were statistically significant above 45 years of age). The observed geographical consistency in seasonal mortality variation in the USA, also seen in a study of 36 cities using deaths aggregated across age groups and over time,[26] 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, possibly because the former have institutionalised environmental (e.g., housing insulation and heating) and health system measures to counter the effects of cold winters.[3,4,6] 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.

The main contribution of our study is a comprehensive analysis of seasonality over three decades in relation to age, sex, and geography. Analysing by these strata allowed us to identify distinct seasonal behaviours in relation to age and sex, including the higher summer mortality in young men which has rarely been reported,[8] and to establish that mortality seasonality is consistent sub-nationally in terms of both timing and magnitude. In a novel approach to mortality seasonality, we used wavelet and centre of gravity analyses, which allowed not only systematically identifying and characterising seasonality, but also examining how it changes or disappears over time. Insights of this kind would not have been possible analysing data averaged over time or fixed to pre-specified frequencies.

The main limitation of our study is that we have analysed all-cause mortality. Different diseases and injuries may be differentially affected by environmental and behavioural factors associated with season and hence differ in their seasonal behaviour. For example, suicides have been found to peak in early spring,[8] and cardiovascular disease mortality may peak earlier in the winter than that from respiratory conditions.[18] In contrast deaths from cancer show little or no seasonality.[17] All-cause mortality measures total mortality burden, and has the advantage of not being affected by errors and variations over time and space in assignment of cause of death. Nonetheless future work should apply our methods to specific causes of death that have public health importance or known interventions.

Our study framework and methods can also be applied to other countries with time- and geo-coded death records. Such data are available in high-income and some middle-income countries. It would be of further interest to compare seasonality by other population characteristics, e.g., between urban and rural areas or in relation to socio-economic status. Further, our analytical framework can be used to investigate the changing role of temperature and other environmental factors as determinants of the dynamics of mortality. It would be of interest, for example, to examine the coupling versus decoupling of temperature and mortality in younger and older age groups over time, using a wavelet coherence analysis of the bivariate time series. Further analyses can also examine the relationship between both average monthly temperature and its variability with death rates, to inform risk and adaptation assessment.

The substantial decline in seasonal mortality differences in adolescents and young adults may be related to diminishing role of injuries, especially from road traffic crashes, which are more likely to occur in the summer months,[27,28] and are more common in men. The weakening of seasonality in children under five years of age may be related to the reduction of deaths from respiratory causes, which have a strong seasonality, as well as the increase in the proportion of deaths that occur in the neonatal period, which do not vary noticeably throughout the year.[8,27,29,30] Further elucidation on the causes of deseasonalisation in these age groups requires analysing changes in the composition of causes of deaths, as well as shifts in seasonality of causes of death themselves.

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 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.[31] 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.[4,19,31] In many countries such services are increasingly under strain in an era of austerity. 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.[32] Such interventions are important today, and will remain so as the population ages and climate change increases the within- and between-season weather variability.

Methods

Data

We obtained data on all 73,804,561 deaths in the USA from 1982 to 2013 from the National Center for Health Statistics (NCHS). Age, sex, state of residence, and month 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.[33] We inferred 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 S1).[34]

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.

We obtained data on temperature from ERA-Interim, which combines predictions from a physical model with ground-based and satellite measurements.[35] 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,[36] 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. The resulting coefficients can be presented on a two-dimensional plot of time against frequency (Figure 1). Importantly, wavelet analysis is able to measure dynamic seasonal behaviour, in which the periodicity of death rates may disappear, emerge, or change over time. This is not possible in standard Fourier analysis or when fitting a statistical model with a period basis function. We used the R package WaveletComp (version 1.0) for the wavelet analysis. Before analysis, we logarithmically transformed death rates, detrended 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 (1982-2013), as well as in separate wavelet analyses for 1982-1997 and 1998-2013. For age-sex groups which had statistically significant power spectra for 1982-2013, as well as for both time sections (1982-1997 and 1998-2013), we calculated the centre of gravity and the negative centre of gravity of monthly death rates. These parameters estimate 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 1982 to 2013, reported as percentage point difference, as a quantitative measure of how the seasonality of death rates has changed over time.

References

1 Langford, I. H. & Bentham, G. The potential effects of climate change on winter mortality in England and Wales. *Int J Biometeorol* **38**, 141-147 (1995).

2 Martens, W. J. Climate change, thermal stress and mortality changes. *Soc Sci Med* **46**, 331-344 (1998).

3 McKee, C. Deaths in winter: can Britain learn from Europe? *European journal of epidemiology* **5**, 178-182 (1989).

4 Healy, J. D. Excess winter mortality in Europe: a cross country analysis identifying key risk factors. *Journal of epidemiology and community health* **57**, 784-789 (2003).

5 Campbell, A. Excess winter mortality in England and Wales: 2015/16 (provisional) and 2014/15 (final). *Statistical bulletin, Office for National Statistics* (2016).

6 Fowler, T. *et al.* Excess winter deaths in Europe: a multi-country descriptive analysis. *Eur J Public Health* **25**, 339-345, doi:10.1093/eurpub/cku073 (2015).

7 Gemmell, I., McLoone, P., Boddy, F. A., Dickinson, G. J. & Watt, G. C. M. Seasonal variation in mortality in Scotland. *International Journal of Epidemiology* **29**, 274-279, doi:10.1093/ije/29.2.274 (2000).

8 Feinstein, C. A. Seasonality of deaths in the US by age and cause. *Demographic Research* **6**, 469-486 (2002).

9 Rau, R. & Doblhammer, G. Seasonal mortality in Denmark: the role of sex and age. *Demographic Research* **9**, 197-222 (2003).

10 Davis, R. E., Knappenberger, P. C., Michaels, P. J. & Novicoff, W. M. Seasonality of climate-human mortality relationships in US cities and impacts of climate change. *Climate Research* **26**, 61-76 (2004).

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

12 Kalkstein, A. J. Regional similarities in seasonal mortality across the United States: an examination of 28 metropolitan statistical areas. *PloS one* **8**, e63971 (2013).

13 Braga, A. L., Zanobetti, A. & Schwartz, J. The time course of weather-related deaths. *Epidemiology* **12**, 662-667 (2001).

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

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

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

17 Rosenwaike, I. Seasonal variation of deaths in the United States, 1951–1960. *Journal of the American Statistical Association* **61**, 706-719 (1966).

18 Mackenbach, J., Kunst, A. & Looman, C. Seasonal variation in mortality in The Netherlands. *Journal of Epidemiology and Community Health* **46**, 261-265 (1992).

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

20 Nakaji, S. *et al.* Seasonal changes in mortality rates from main causes of death in Japan. *European journal of epidemiology* **19**, 905-913 (2004).

21 Brown, G., Fearn, V. & Wells, C. Exploratory analysis of seasonal mortality in England and Wales, 1998 to 2007. *Health Statistics Quarterly*, 58 (2010).

22 Marti-Soler, H. *et al.* Seasonal Variation of Overall and Cardiovascular Mortality: A Study in 19 Countries from Different Geographic Locations. *Plos One* **9**, 13, doi:10.1371/journal.pone.0113500 (2014).

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

24 Moy, C. M., Seltzer, G. O., Rodbell, D. T. & Anderson, D. M. Variability of El Nino/Southern Oscillation activity at millennial timescales during the Holocene epoch. *Nature* **420**, 162-165, doi:10.1038/nature01194 (2002).

25 Grenfell, B., Bjørnstad, O. & Kappey, J. Travelling waves and spatial hierarchies in measles epidemics. *Nature* **414**, 716-723 (2001).

26 Kinney, P. L. *et al.* Winter season mortality: will climate warming bring benefits? *Environmental Research Letters* **10**, doi:10.1088/1748-9326/10/6/064016 (2015).

27 National Center for Health Statistics. Leading causes of death and numbers of deaths, by sex, race, and Hispanic origin: United States, 1980 and 2010. *National Center for Health Statistics (NCHS)* (2012).

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

29 MacDorman, M. F. & Rosenberg, H. M. Trends in infant mortality by cause of death and other characteristics, 1960-88. *Vital Health Stat 20*, 1-57 (1993).

30 Matthews, T. J., MacDorman, M. F. & Thoma, M. E. Infant Mortality Statistics From the 2013 Period Linked Birth/Infant Death Data Set. *Natl Vital Stat Rep* **64**, 1-30 (2015).

31 Public Health England. The cold weather plan for England. *Public Health England* (2016).

32 Morris, M. E. *et al.* Smart-home technologies to assist older people to live well at home. *Journal of aging science* **1**, 1-9 (2013).

Methods

33 Ingram, D. D. *et al.* United States Census 2000 population with bridged race categories. *Vital and health statistics. Series 2, Data evaluation and methods research*, 1-55 (2003).

34 Karl, T. & Koss, W. J. Regional and national monthly, seasonal, and annual temperature weighted by area, 1895-1983. *National Climatic Data Center* (1984).

35 Dee, D. P. *et al.* The ERA-Interim reanalysis: configuration and performance of the data assimilation system. *Quarterly Journal of the Royal Meteorological Society* **137**, 553-597, doi:10.1002/qj.828 (2011).

36 Cazelles, B. *et al.* Wavelet analysis of ecological time series. *Oecologia* **156**, 287-304 (2008).

Correspondence and requests for materials should be addressed to ME.

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, with input from the other authors.

Competing interests

None

Figure 1. Wavelet power spectra for national time series data for 1982-2013, by age group for (A) men and (B) women. Wavelet power values increase from blue to red, with white contour lines indicating the 5% significance level against a white noise spectrum. Age groups with significant 12-month periodicity for the entire period and for both the 1982-1999 and 2000-2013 periods are highlighted with a bold black box (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 2. Mean timing of national maximum and minimum all-cause mortality, by sex and age group for 1982-2013. Red dots indicate the month of maximum mortality, and green dots that of minimum mortality. Vertical segments represent 95% confidence intervals. Only age-sex groups with statistically significant 12-month seasonality are included.

Figure 3. National percent difference in death rates between the maximum and minimum mortality months in 2013 versus 1982 by sex and age group. Age-sex groups with a statistically significant change at the 5% level are highlighted with a bold black outline.

Figure 4. Mean timing of (A) maximum and (B) minimum all-cause mortality, by climate region, sex and age group for 1982-2013. 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 Figure S1 for climate regions.

Figure 5. The relationship between percent difference in death rates and temperature difference between months in which mortality peaks versus troughs 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.