

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

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15

16 **Abstract**

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

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

29

30 **Introduction**

31 It is well-established that death rates vary throughout the year, and in temperate climates there
32 tend to be more deaths in winter than in summer (Campbell, 2017; Fowler et al., 2015; Healy,
33 2003; McKee, 1989). Therefore, it has been hypothesized that a warmer world may lower
34 winter mortality in temperate climates (Langford & Bentham, 1995; Martens, 1998). In a large
35 country like the USA, which possesses distinct climate regions, the seasonality of mortality
36 may vary geographically, due to geographical variations in mortality, localized weather
37 patterns, and regional differences in adaptation measures such as heating, air conditioning and
38 healthcare (Davis, Knappenberger, Michaels, & Novicoff, 2004; Ferreira Braga, Zanobetti, &
39 Schwartz, 2001; Kalkstein, 2013; Medina-Ramón & Schwartz, 2007). The presence and extent
40 of seasonal variation in mortality may also itself change over time, due to shifts in weather
41 regimes, lifestyle, adaptation technologies, and healthcare (Bobb, Peng, Bell, & Dominici,
42 2014; Carson, Hajat, Armstrong, & Wilkinson, 2006; Seretakis, 1997; Sheridan, Kalkstein, &
43 Kalkstein, 2009).

44

45 A thorough understanding of the long-term dynamics of seasonality of mortality, and its
46 geographical and demographic patterns, is needed to identify at-risk groups, plan responses at
47 the present time as well as under changing climate conditions. Although mortality seasonality
48 is well-established, there is limited information on how seasonality, including the timing of
49 minimum and maximum mortality, varies by local climate and how these features have

50 changed over time, especially in relation to age group, sex and medical cause of death (Rau,
51 2004; Rau, Bohk-Ewald, Muszyńska, & Vaupel, 2018).

52

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

60

61 **Results**

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

68

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

74

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

84

85 From 1980 to 2013, the proportional (percent) difference in all-cause death rates between peak
86 and minimum months declined little for people older than 45 years of age (non-significantly
87 and by less than eight percentage points) (Figure 4). In contrast, the difference between peak
88 (summer) and minimum (winter) death rates declined significantly in younger ages, by over 25
89 percentage points in males aged 5-14 years and 15-24 years, largely driven in the declining
90 difference between summer and winter injury deaths. Under five years of age, percent seasonal
91 difference in all-cause death rates declined by a statistically-significant 13 percentage points
92 (95% CI 8 to 18) for boys but only a statistically-non-significant 5 percentage points (-12 to 2)
93 for girls. These declines in seasonality of child deaths were a net effect of declining winter-
94 summer difference in cardiorespiratory deaths and increasing summer-winter difference in
95 injury deaths.

96

97 The subnational centre of gravity analysis shows that all-cause mortality peaks and minima in
98 different climate regions are consistent with the national ones (Figure 5), indicating the
99 seasonality is largely independent of geography. The relative homogeneity of the timing of

100 maximum and minimum mortality contrasts with the large variation in seasonal temperatures
101 among climate regions. For example, in men and women aged 65-74 years, all-cause mortality
102 peaked in February in the Northeast and Southeast, even though the average temperatures for
103 those regions were different by over 13 degrees Celsius (9.3 in the Southeast compared with -
104 3.8 in the Northeast). Furthermore, above 45 years of age, there was little inter-region variation
105 in the percent seasonal difference in all-cause mortality, despite the large variation in
106 temperature difference between the peak and minimum months (Figure 6). The only cause of
107 death with regional differences in seasonality was injuries in men aged 55-64 years and women
108 aged 65-74 years. Injury death rates in these age-sex groups seemed to peak in January in the
109 Northeast peak and in August in the (Supplementary Figure 1).

110

111 **Strengths and limitations**

112 The strengths of our study are its innovative methods of characterizing seasonality of mortality
113 dynamically over space and time, by age group and cause of death; using wavelet and centre
114 of gravity analyses; using ERA-Interim data output to compare the association between
115 temperature and seasonality of death across regions. A limitation of our study is that we used
116 broad causes of death so that we have sufficient number of deaths by age group, sex, year,
117 climate region and cause of death. Different diseases and injuries may be differentially affected
118 by environmental, behavioural and healthcare factors associated with season and hence differ
119 in their seasonal behaviour. For example, suicides have been found to peak in early spring
120 (Feinstein, 2002), and cardiovascular disease mortality may peak earlier in the winter than that
121 from respiratory conditions (Mackenbach, Kunst, & Looman, 1992). Interventions have been
122 attempted for diseases such as influenza which may explain changes in seasonality over time,
123 although it is noted that there were no significant changes in seasonality for older age groups
124 (Simonsen et al., 2005). In addition, investigating how seasonality of mortality has changed by

125 socioeconomic characteristics or urban and rural place of residence may help with
126 understanding its drivers and planning responses.

127

128 **Discussion**

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

137

138 Prior studies have noted seasonality of mortality for all-cause mortality and for specific causes
139 of death in the USA (Feinstein, 2002; Kalkstein, 2013; Rau, 2004; Rau et al., 2018;
140 Rosenwaike, 1966; Seretakis, 1997). Few of these studies have done consistent national and
141 subnational analyses, and none has done so over time, for a comprehensive set of age groups
142 and causes of death, and in relation to regional temperature differences. Our results on strong
143 seasonality of cardiorespiratory deaths and weak seasonality of cancer deaths, restricted to
144 older ages, are broadly consistent with these studies (Feinstein, 2002; Rau et al., 2018;
145 Rosenwaike, 1966; Seretakis, 1997), which had limited analysis on how seasonality changes
146 over time and/or geography (Feinstein, 2002; Rau et al., 2018; Rosenwaike, 1966). Similarly,
147 our results on seasonality of injury deaths are supported by a few prior studies (Feinstein, 2002;
148 Rau et al., 2018; Rosenwaike, 1966), but our subnational analysis over three decades revealed

149 heterogeneities spatial variations in timing of peak and changes in the seasonal difference in
150 injury deaths not reported before.

151

152 The observed geographical similarity in seasonal mortality variation in the USA, also seen in
153 a study of 36 cities using deaths aggregated across age groups and over time (Kinney et al.,
154 2015), contrasts from the pattern observed across Europe, where the difference between winter
155 and summer mortality tends to be lower in the colder Nordic countries than in warmer southern
156 European nations (Fowler et al., 2015; Healy, 2003; McKee, 1989). The absence of association
157 between the magnitude of mortality seasonality and seasonal temperature difference indicates
158 that different regions in the USA are similarly adapted to temperature seasonality, whereas
159 Nordic countries may have better environmental (e.g., housing insulation and heating) and
160 health system measures to counter the effects of cold winters than those in southern Europe.

161

162 The cause-specific analysis showed that the substantial decline in seasonal mortality
163 differences in adolescents and young adults was related to the diminishing seasonality of
164 injuries, especially from road traffic crashes, which are more likely to occur in the summer
165 months (Centers for Disease Control and Prevention (CDC)., 2016; National Highway Traffic
166 Safety Administration, 2005) and are more common in men. The weakening of seasonality in
167 boys under five years of age was related to the reduction of seasonality of death from other
168 causes, from the significant reduction in cardiorespiratory seasonality mortality and decreasing
169 seasonality of other causes of death, as well as the increasing proportion of deaths during the
170 perinatal period (Centers for Disease Control and Prevention (CDC)., 2016; Mathews,
171 Macdorman, & Thoma, 2015; National Center for Health Statistics, 1993).

172

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

193

194 **Materials and methods**

195 *Data*

196 We used data on all 77,771,264 deaths in the USA from 1980 to 2013 from the National Center
197 for Health Statistics (NCHS). Age, sex, state of residence, month of death, and underlying

198 cause of death were available for each record. Yearly population counts were available from
199 NCHS for 1990 to 2013 and from the US Census Bureau prior to 1990 (Ingram et al., 2003).
200 We calculated monthly population counts through linear interpolation, assigning each yearly
201 count to July. We also subdivided the national data geographically by climate regions used by
202 the National Oceanic and Atmospheric Administration (Figure 1) (Karl & Koss, 1984). The
203 underlying cause of death was coded according to the international classification of diseases
204 (ICD) system (9th revision of ICD from 1980 to 1998 and 10th revision of ICD thereafter).

205

206 Data were divided by sex and age in the following 10 age groups: 0-4, 5-14, 25- 34, 35-44, 45-
207 54, 55-64, 65-74, 75-84, 85+ years. We calculated monthly death rates for each age and sex
208 group, both nationally and for sub-national climate regions. Death rate calculations accounted
209 for varying length of months, by multiplying each month's death count by a factor that would
210 make it equivalent to a 31-day month. For analysis of seasonality by cause of death, we mapped
211 each ICD-9 and ICD-10 codes to the following four disease categories:

212

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

217

218 Cardiorespiratory diseases and cancers accounted for 56.4% and 21.2% of all deaths in the
219 USA, respectively, in 1980, and 40.9% and 23.5%, respectively, in 2013. Deaths from
220 cardiorespiratory diseases have been associated with cold and warm temperatures (Basu, 2009;
221 Basu & Samet, 2002; Bennett, Blangiardo, Fecht, Elliott, & Ezzati, 2014; Braga, Zanobetti, &
222 Schwartz, 2002; Gasparrini et al., 2015). Injuries, which accounted for 8% of all deaths in the

223 USA in 1980 and 7.5% in 2013, may have seasonality that is distinct from so-called natural
224 causes. We did not further divide other causes because the number of deaths could become too
225 small to allow stable estimates when divided by age group, sex and climate region.

226

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

231

232 *Statistical methods*

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

247

248 We identified age-sex groups whose wavelet power spectra differed from that of a white noise
249 spectrum, which represents random fluctuations, at 5% significance level, for the entire study
250 period (1980-2013). For age-sex groups which had statistically significant power spectra for
251 1980-2013, we calculated the centre of gravity and the negative centre of gravity of monthly
252 death rates. These parameters show when in the year, on average, maximum and minimum
253 death rates occur, respectively. For calculating centre of gravity, each month was weighted by
254 its death rate; for negative centre of gravity, each month was weighted by the difference
255 between its death rate and the year's maximum death rate. In taking the weighted average, we
256 allowed January (month 1) to neighbour December (month 12), a technique called circular
257 statistics. Along with each circular mean, a 95% confidence interval (CI) was calculated by
258 using 1000 bootstrap samples. The R package CircStats (version 0.2.4) was used for this
259 purpose.

260

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

268

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272

273 **Author contributions**

274 All authors contributed to study concept, analytical approach, and interpretation of results. RP,
275 KF and ME collated and organised mortality files. RP performed the analysis, with input from
276 JB. RP and ME wrote the first draft of the paper; other authors contributed to revising and
277 finalising the paper.

278

279 **Competing financial interests**

280 The authors declare no competing financial interests.

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

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

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

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

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

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

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