Impacts of Temperature and its Variability on Mortality in New England

5 authors, including:

Liuhua Shi
Harvard University
25 PUBLICATIONS **251** CITATIONS

SEE PROFILE

Itai Kloog
Harvard University
116 PUBLICATIONS **2,996** CITATIONS

SEE PROFILE

Antonella Zanobetti
Harvard University
277 PUBLICATIONS **15,449** CITATIONS

SEE PROFILE

Pengfei Liu
Harvard University
69 PUBLICATIONS **1,198** CITATIONS

SEE PROFILE

Some of the authors of this publication are also working on these related projects:

Veterans Affairs (VA) Normative Aging Study View project

Pollution Health effects View project

Impacts of temperature and its variability on mortality in New England

Liuhua Shi[1], Itai Kloog[2], Antonella Zanobetti[1], Pengfei Liu[3] and Joel D. Schwartz[1,4]*

Rapid build-up of greenhouse gases is expected to increase Earth's mean surface temperature, with unclear effects on temperature variability[1-3]. This makes understanding the direct effects of a changing climate on human health more urgent. However, the effects of prolonged exposures to variable temperatures, which are important for understanding the public health burden, are unclear. Here we demonstrate that long-term survival was significantly associated with both seasonal mean values and standard deviations of temperature among the Medicare population (aged 65+) in New England, and break that down into long-term contrasts between ZIP codes and annual anomalies. A rise in summer mean temperature of 1 °C was associated with a 1.0% higher death rate, whereas an increase in winter mean temperature corresponded to a 0.6% decrease in mortality. Increases in standard deviations of temperature for both summer and winter were harmful. The increased mortality in warmer summers was entirely due to anomalies, whereas it was long-term average differences in the standard deviation of summer temperatures across ZIP codes that drove the increased risk. For future climate scenarios, seasonal mean temperatures may in part account for the public health burden, but the excess public health risk of climate change may also stem from changes of within-season temperature variability.

Emissions of greenhouse gases will change the Earth's climate, most notably by changing temperature and temperature variability[1]. The Intergovernmental Panel on Climate Change (IPCC), in its newly released Fifth Assessment Report, forecasts a rise in world average temperature ranging from 0.2–5.5 °C by 2100 (ref. 1). This has increased interest in the impact of temperature on health.

Although many studies have reported associations between short-term temperature changes and increased daily deaths[4-11], evidence on the association between annual mortality and changes in seasonal temperature averages is scarce[12,13]. As such impacts by definition cannot be short-term mortality displacement (we are looking at annual averages and displacement of deaths by a few weeks will not influence these), these results can imply important public health effects of the changing climate. In addition to the seasonal mean temperature, its variability may also play a significant role in raising the risk of mortality[12,14]. There is evidence that people adapt to the usual temperature in their city[14,15]. For these reasons, this study focused on both mean temperature, and temperature variability for summer and winter.

Conventionally, ambient temperature (T_a) was obtained from monitors near airports, and analysed at the city or county level[16]. Overlooking the temporal and spatial variation of T_a may

introduce an exposure measurement error and may bias health effect estimates[17]. We recently presented new hybrid models for assessing high-resolution spatio-temporal T_a for epidemiological studies, based on surface temperature (T_s) measured by satellite. This approach allows prediction of daily T_a at 1×1 km spatial resolution throughout the New England area[18]. We also showed that using high-resolution T_a predicted from the hybrid models better captured the associations between T_a and adverse health outcomes than temperature data from existing monitoring stations[19].

Using temporally and spatially resolved T_a estimates, the present study aims to tease apart the associations of annual all-cause mortality with seasonal mean temperature and temperature variability for both summer and winter, among the Medicare population in New England during 2000–2008, and to further separate these into long-term spatial differences and annual anomalies. Temperature variability is represented by the standard deviation of daily mean temperature within season.

The results, presented as percentage increases in mortality, are shown in Fig. 1 for spatial contrasts, annual anomalies, and the overall effect estimates. Both seasonal mean temperatures and their standard deviations were significantly associated with all-cause mortality for summer and winter ($p < 0.05$). A rise of 1 °C in summer mean temperature corresponded to an overall estimated 1.0% increase in mortality (95% CI: 0.6, 1.5%). This was entirely due to yearly anomalies; living in a location with long-term warmer summer temperatures in New England was associated with lower mortality rates, suggesting acclimatization. A 1 °C increase in winter mean temperature was observed to lower mortality by 0.6% (95% CI: 0.3, 0.9%). Here, it was the spatial contrast that was associated with lower mortality, and the anomalies with higher mortality, suggesting little acclimatization to cold. For each 1 °C increase in standard deviation of temperature, 1.3% (95% CI: 0.2, 2.4%) and 4.1% (95% CI: 3.0, 5.2%) increases in annual deaths were seen in summer and winter, respectively. The observed associations in summer and winter were respectively attributable to spatial contrasts and yearly anomalies.

A key result of this study is that increases in temperature variability can have similar estimated effects on mortality as increases in mean temperature. This makes understanding the effect of climate change on seasonal temperature variability important for assessing health risks. In addition, we found that small area variations in long-term average temperature and its standard deviation across New England are associated with differences in mortality rates, which are quite different from the associations with anomalies. In particular, they suggest that even within New England, places with typically warmer summers have lower annual mortality
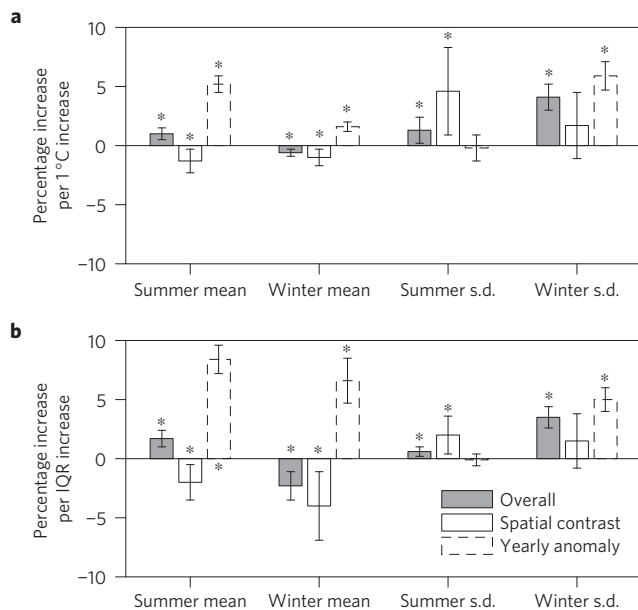
Figure 1 | Changes in mortality due to seasonal mean temperature and temperature variability across New England, 2003–2008. Percentage increase in mortality for per 1°C (**a**) and per interquartile range (IQR) (**b**). A sensitivity analysis controlling for the number of heat waves in each ZIP code in each year found essentially identical results. Error bars stand for 95% confidence intervals. s.d. is standard deviation. *$p < 0.05$.

Figure 2 | Modifications of the effect for annual anomalies of different temperature indices by population density, age, sex and race. Percentage increases in mortality (95% CI) for each 1°C increase in summer mean temperature annual anomaly (**a**), winter mean temperature annual anomaly (**b**), summer temperature standard deviation (s.d.) annual anomaly (**c**) and winter temperature standard deviation (s.d.) annual anomaly (**d**) in each subgroup, respectively. Red indicates increased risk of death and blue stands for decreased risk of death. Error bars stand for 95% confidence intervals. The dashed lines indicate the effect estimates for all groups. *$p < 0.05$, indicates significantly different estimates versus the first subgroup.

rates whereas anomalies are associated with higher annual mortality rates in that year. Hence, the negative health impacts of climate change may stem from the increase in year-to-year fluctuations of temperature from a level that people have been acclimated to for a long time, or an increase in daily variability within season, rather than the warmer temperature itself.

Short-term associations between daily temperature and mortality have been reported to be greater in locations with larger seasonal temperature variability[9,14]. Several recent studies suggested that a large change in temperature between neighbouring days can elevate daily mortality[10,11]. Hence, temperature variability emerges as an important risk factor for both short-term and long-term survival.

Subjects exercising in hot conditions for 12 days doubled their endurance time, whereas subjects alternately exercising in mild and hot conditions did not[20]. This suggests that more temperature variability in the summer can impede adaptation, which is consistent with our associations with seasonal standard deviation. However, the underlying mechanisms for the observed relationship with seasonal mean temperature remain unresolved. That more people die when summers are warmer or when winters are colder than normal for their ZIP code may be due to accumulating effects over the season on the changes in blood pressure associated with short-term change in temperature, or lack of behavioural response.

Our results also suggest that living in warmer ZIP codes in New England reduced long-term mortality in both summer and winter, but living in ZIP codes with more variable temperature in either summer or winter increased mortality. In addition, higher annual anomalies were significantly associated with increased long-term mortality, although insignificantly for the standard deviation of summer temperature.

We also examined effect modifications (Figs 2 and 3). For seasonal mean temperature anomalies, consistent increases in mortality rates for positive anomalies were seen across the groups (see Fig. 2). Although some differences were statistically significant (for example, between males and females for summer mean), the differences in effects were not large, except for some noise in smaller
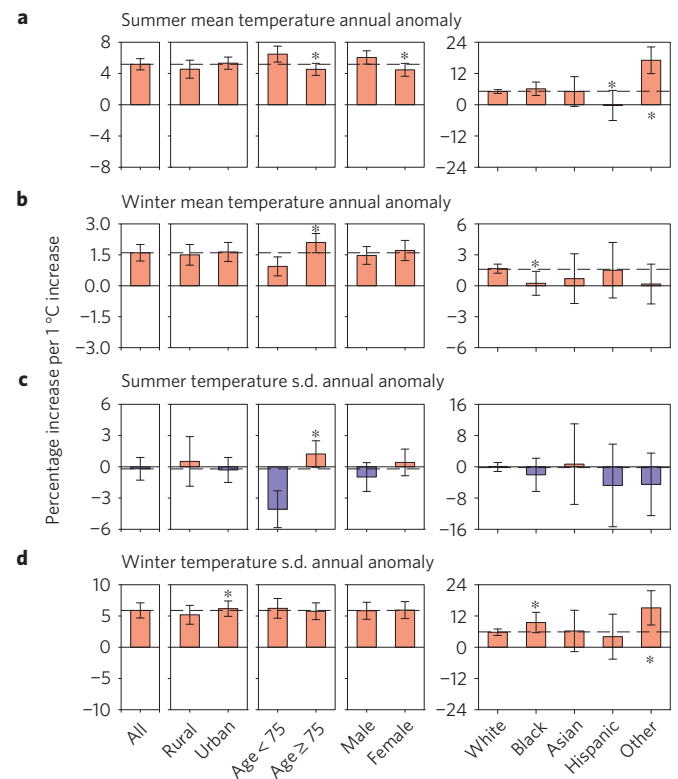
racial groups. Anomalies for the standard deviation of temperature within winter also showed consistently positive associations across groups. Summer temperature standard deviation anomalies showed no association with mortality overall, but opposite effects by age, with higher mortality rates in persons 75+, and lower rates in 65–75.

For ZIP code differences in the long-term means of the temperature parameters, more heterogeneity was seen across population groups (see Fig. 3). Higher effect estimates were found in less dense areas for both mean and standard deviation of summer temperature. This is consistent with a recent study suggesting that subjects in rural counties were more vulnerable to heat[21]. We also found that subjects in urban areas benefited more from living in regions with warmer winters, but were at higher risk for elevated winter temperature variability. In addition, the relatively younger age group (65–74 yr) was more sensitive to the changes of most temperature indices. This may be due to their having more outdoor activities than the older age group. A similar reason may also explain why, in summer, higher effect estimates were found for subjects living in rural areas. However, in the cold and snowy winter of New England, possibly outdoor activities of studied subjects in rural areas were limited, therefore winter mean temperature and its standard deviation had lower effect estimates for subjects in rural areas than that in urban areas. Females were more sensitive to increased mean temperature in summer and winter, but less sensitive to increased standard deviation of summer temperature
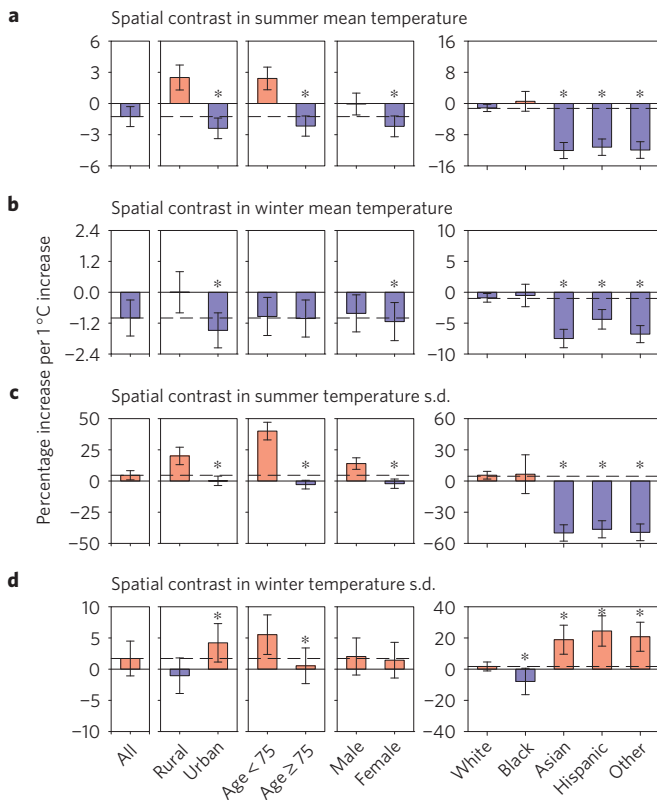
Figure 3 | Modifications of the effect for spatial variability in different temperature indices by population density, age, sex and race. Percentage increases in mortality (95% CI) for each 1 °C increase in spatial contrasts of summer mean temperature (**a**), spatial contrasts of winter mean temperature (**b**), spatial contrasts of summer temperature standard deviation (s.d.) (**c**) and spatial contrasts of winter temperature standard deviation (s.d.) (**d**) in each subgroup, respectively. Red indicates increased risk of death and blue stands for decreased risk of death. Error bars stand for 95% confidence intervals. *$p < 0.05$.

than males. We saw a number of interactions by race that are not always easy to understand. It is possible that the decreased risk of death in locations with higher summer mean temperatures in Asian, Hispanic and 'other' race group is because elderly subjects in these groups immigrated from warm areas, such as South China, Southeast Asia, India and Mexico. These subjects were more acclimated to a warmer summer. This could also explain why Asian, Hispanic and 'other' race groups significantly benefited more from a warmer winter, but were more adversely impacted by greater winter standard deviation. However, we note that the percentage of the population over 65 in New England that is not white is only 5.9%, and for 4.3% of ZIP codes was zero, so some of the observed variability across race may result from unstable estimates.

A potential limitation of the present study is that there is still a possible residual unknown resulting from the lack of individual level risk factors for mortality. In addition, bias could also be induced by spatial or temporal auto-correlation, which can lead to spuriously narrow standard errors and CIs.

Implications for future climate research

Scientific understanding of how mean surface temperature responds to the increasing anthropogenic emission of GHGs has been greatly improved in recent decades[1]. Considering the comparable increments of both summer and winter mean temperatures predicted for the future 50 years, the benefit of warmer winters may be largely compensated by the harm of hotter summers. However,

for annual anomalies, warmer winter temperature actually increases annual mortality. The degree of temperature variability, such as the within-season standard deviation, which is influenced by many factors, such as the intensity and pattern of atmospheric circulations, remains highly uncertain for future climate scenarios[22,23]. For example, Petoukhov and Semenov proposed that the weakening of the polar vortex may bring about an increased frequency of very cold winters in northern America[24]. However, Huntingford and co-authors suggested that there is no significant change in global temperature variability in spite of changing regional patterns[3]. That study assessed variability across the entire year, including seasonal variability, and it is not clear whether variability changed within some seasons[3]. This uncertainty can be propagated into the projection of temperature-related health risk.

This study, by estimating impacts of both mean temperature and temperature variability in summer and winter simultaneously, adds considerable strength to the evidence of a significant association between mortality and prolonged exposures to temperatures, especially temperature variability. In addition to the within-season variability we also showed that between-year variability (anomalies) increased mortality risks. Hence, the variability of atmospheric temperature emerges as a key factor of the potential health impacts of climate change.

This work provides an important example of how temperature may affect human health in a temperate climate region. We would expect that the health effects of seasonal mean temperature and temperature variability can vary greatly among different climate zones[12]. Such variation may also exist across areas with distinct socio-economical status, which can convey vulnerability to the changing climate. A quantitative assessment of the projected risk of human health associated with future climate change can be estimated globally by incorporating more comprehensive epidemiological studies and projected climate scenario data for different climate zones. However, as an important environmental stressor emphasized in this study, the uncertainty of the projected changes in the temperature variability can induce significant errors in such estimates. Hence, better climate projections on temperature variability at multiple scales are important in assessing the risks to human health.

Methods

Methods and any associated references are available in the online version of the paper.

References

1. IPCC *Climate Change 2013: The Physical Science Basis* (eds Stocker, T. *et al.*) (Cambridge Univ. Press, 2013).
2. Alexander, L. & Perkins, S. Debate heating up over changes in climate variability. *Environ. Res. Lett.* **8,** 041001 (2013).
3. Huntingford, C., Jones, P. D., Livina, V. N., Lenton, T. M. & Cox, P. M. No increase in global temperature variability despite changing regional patterns. *Nature* **500,** 327–330 (2013).
4. Schwartz, J., Samet, J. M. & Patz, J. A. Hospital admissions for heart disease: The effects of temperature and humidity. *Epidemiology* **15,** 755–761 (2004).
5. Goodman, P. G., Dockery, D. W. & Clancy, L. Cause-specific mortality and the extended effects of particulate pollution and temperature exposure. *Environ. Health Perspect.* **112,** 179–185 (2004).
6. Barnett, A. G. Temperature and cardiovascular deaths in the US elderly: Changes over time. *Epidemiology* **18,** 369–372 (2007).
7. Anderson, B. G. & Bell, M. L. Weather-related mortality: How heat, cold, and heat waves affect mortality in the United States. *Epidemiology* **20,** 205–213 (2009).
8. Yu, W. *et al.* Daily average temperature and mortality among the elderly: A meta-analysis and systematic review of epidemiological evidence. *Int. J. Biometeorol.* **56,** 569–581 (2012).

9. Braga, A. L., Zanobetti, A. & Schwartz, J. The effect of weather on respiratory and cardiovascular deaths in 12 US cities. *Environ. Health Perspect.* **110,** 859–863 (2002).

10. Guo, Y. *et al.* A large change in temperature between neighbouring days increases the risk of mortality. *PLoS ONE* **6,** e16511 (2011).

11. Lin, H. *et al.* Temperature changes between neighboring days and mortality in summer: A distributed lag non-linear time series analysis. *PLoS ONE* **8,** e66403 (2013).

12. Zanobetti, A., O'Neill, M. S., Gronlund, C. J. & Schwartz, J. D. Summer temperature variability and long-term survival among elderly people with chronic disease. *Proc. Natl Acad. Sci. USA* **109,** 6608–6613 (2012).

13. Rehill, N., Armstrong, B. & Wilkinson, P. Clarifying life lost due to cold and heat: A new approach using annual time series. *BMJ Open* **5,** e005640 (2015).

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

15. McGeehin, M. A. & Mirabelli, M. The potential impacts of climate variability and change on temperature-related morbidity and mortality in the United States. *Environ. Health Perspect.* **109,** 185–189 (2001).

16. Basu, R. High ambient temperature and mortality: A review of epidemiologic studies from 2001 to 2008. *Environ. Health* **8,** 40–52 (2009).

17. Thomas, D., Stram, D. & Dwyer, J. Exposure measurement error: Influence on exposure-disease relationships and methods of correction. *Annu. Rev. Public Health* **14,** 69–93 (1993).

18. Kloog, I., Nordio, F., Coull, B. A. & Schwartz, J. Predicting spatiotemporal mean air temperature using MODIS satellite surface temperature measurements across the Northeastern USA. *Remote Sens. Environ.* **150,** 132–139 (2014).

19. Kloog, I., Melly, S. J., Coull, B. A., Nordio, F. & Schwartz, J. D. Using satellite-based spatiotemporal resolved air temperature exposure to study the association between ambient air temperature and birth outcomes in Massachusetts. *Environ. Health Perspect.* http://dx.doi.org/10.1289/ehp.1308075 (2015).

20. Nielsen, B. *et al.* Human circulatory and thermoregulatory adaptations with heat acclimation and exercise in a hot, dry environment. *J. Physiol.* **460,** 467–485 (1993).

21. Lippmann, S. J., Fuhrmann, C. M., Waller, A. E. & Richardson, D. B. Ambient temperature and emergency department visits for heat-related illness in North Carolina, 2007–2008. *Environ. Res.* **124,** 35–42 (2013).

22. Zorita, E. & González-Rouco, F. Disagreement between predictions of the future behavior of the Arctic Oscillation as simulated in two different climate models: Implications for global warming. *Geophys. Res. Lett.* **27,** 1755–1758 (2000).

23. Riddle, E. E., Butler, A. H., Furtado, J. C., Cohen, J. L. & Kumar, A. CFSv2 ensemble prediction of the wintertime Arctic Oscillation. *Clim. Dynam.* **41,** 1099–1116 (2013).

24. Petoukhov, V. & Semenov, V. A. A link between reduced Barents–Kara sea ice and cold winter extremes over northern continents. *J. Geophys. Res.* **115** (2010).

Author contributions

J.D.S. designed the research and directed its implementation; A.Z. and I.K. prepared the data set; L.S., P.L. and J.D.S. analysed data; L.S., P.L. and J.D.S. wrote the paper; all authors contributed to revision of the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to J.D.S.

Competing financial interests

The authors declare no competing financial interests.

Methods

Study population. We constructed a cohort using Medicare data for all residents aged 65 and older for the years 2000–2008 in New England (see Supplementary Table 1 in Supplementary Methods). This was an open cohort, including eligible persons from 1999, or at the year when they subsequently turned 65. Subjects entered the cohort for survival if they were still alive on 1 January of the year following the year that they enrolled in Medicare, and follow-up years (our time metric) were calendar years. As a national social insurance programme administered by the US federal government since 1966, Medicare guarantees Americans aged 65 and older access to health insurance[25]. The Medicare beneficiary denominator file from the Centers for Medicare and Medicaid services (CMS) lists all beneficiaries enrolled in the Medicare Fee-for-service (FFS), and contains information on beneficiaries' eligibility and enrolment in Medicare, as well as the date of death.

Exposure data. The present study uses 1×1 km ambient temperature (T_a) data estimated from surface temperature (T_s) measured by satellites[18]. Specifically, we started by calibrating the $T_s - T_a$ relationship for each day using grid cells with both T_a and T_s measurements (model 1). This daily calibration was then used to predict T_a in grid cells in the study domain without T_a measurements, but with available T_s measurements. To fill in cells or days when no T_s measurements were available, a generalized additive mixed model was fitted with a smooth function of latitude and longitude of the grid-cell centroid (model 2). The performance of the estimated T_a was validated by tenfold cross-validation. Out-of-sample R^2 was found to be very high ($R^2 = 0.947$, yearly variation 0.933–0.958 for the years 2000–2011) for days with available satellite T_s measurements. Excellent performance was also observed, even in days with no available T_s data ($R^2 = 0.940$, yearly variation 0.902–0.962 for the years 2000–2011). More details are published[17].

By linking the ZIP code centroid to the nearest temperature grid, we assigned the grid-cell temperature exposures to each ZIP code. The predicted daily ambient temperatures allow us to calculate, for each year and each ZIP code, the mean temperature for summer (June–August), the mean temperature for winter (December–February), the standard deviation of daily mean summertime temperature, and the standard deviation of daily mean wintertime temperature. We refer to these as summer mean temperature, winter mean temperature; summer temperature variability and winter temperature variability, respectively (see Supplementary Table 2 in Supplementary Methods). Supplementary Table 2 also presents the distribution of the spatial and temporal variations for the temperature variables. Supplementary Table 3 in Supplementary Methods gives the correlation coefficients between these explanatory variables.

Covariates. Medicare provides information on age, race and sex of all individuals. From the US Census Bureau 2000, we obtained tabulated ZIP-code-level socio-economic variables, including population density, percentage of green space, percentage of the population (age $\geq$ 65) in poverty status, and median value for owner-occupied housing units. In addition, based on ZIP-code-level primary and secondary hospital admissions for lung cancer, we calculated the long-term average hospital admission rate for lung cancer in each ZIP code as a surrogate for smoking experience. The census data were merged with individuals based on their ZIP code of residence. County-level percentage of diabetes and percentage of lack of physical activity, obtained from the CDC Behavioral Risk Factor Surveillance survey for the entire country, were adjusted as well.

Statistical methods. In our data set, one observation is created for each Medicare participant for each year of follow-up, using the Andersen–Gill formulation of survival analysis. Survival times were calculated from enrolment date until death or 31 December 2008 (censoring), whichever came first.

We considered the following possible exposure indices: summer mean temperature, winter mean temperature, summertime standard deviation of temperature and wintertime standard deviation of temperature in each follow-up year. To separate the independent associations of mortality with mean temperature and temperature variability, all temperature-related indices were entered into the models simultaneously and treated as time-varying exposures.

We applied extended Cox proportional hazard models (Proc PHREG, SAS 9.3), which allow for time-varying covariates in survival analysis. The models were adjusted for individual risk factors, including age, sex, race, and ZIP-code-level covariates such as population density, percentage of green space, percentage of the population below poverty level, median value for owner-occupied housing units, and hospital admission rate for lung cancer (a surrogate for smoking experience), as well as county-level percentage of diabetes and percentage of lack of physical activity. To adjust for time trend, we entered an indicator for each year of follow-up. To allow for possible non-proportionality of hazard, participants were stratified by sex, five-year age groups, and race (white, black, and others), such that each sex/age/race group had its own baseline hazard.

We then assessed the association of mortality with the four exposure indices. The analyses were also repeated without mutual adjustment for seasonal mean temperatures and their standard deviation (see Supplementary Table 4 in Supplementary Methods). To separate the contribution of the spatial and temporal components of the temperature variables, we fit a model with two terms for each temperature variable. We defined each term as its mean in that ZIP code over the entire study period, plus the difference (anomaly) from that mean for the ith ZIP code in the tth follow-up year. With all eight terms put in the model, the mean for each ZIP code captures purely geographic contrasts, whereas the anomaly indicates the effects of yearly variations within each ZIP code.

The results are expressed as the percentage increase in mortality for each °C increase in an exposure index, for spatial contrasts, annual anomalies and the overall effect estimates. Percentage increases in mortality were also calculated for per IQR (Interquartile Range; IQR = third quartile − first quartile) increase, to reflect the current distribution of these variables. For example, an 8.4% (95% CI: 7.3, 9.6%) increase of mortality was observed for per IQR increase of yearly anomaly of summer mean temperature. This result can be interpreted as that, within a ZIP code, the risk of death in a relatively warm summer (third quartile in the studied period) was 8.4% higher than in a relatively cold summer (first quartile). A sensitivity analysis controlling for the number of heat waves in each ZIP code in each year was performed as well.

We also examined age (defined as $\geq$75 yr and 65–74 yr), sex, race (white, black, Asian, Hispanic, and other) and population density (less than 33rd percentile, rural, and otherwise urban) as effect modifiers for both spatial contrasts and temperature anomalies, respectively, by adding interaction terms between such variables and each of the eight temperature indices in the model.

References

25. Kloog, I., Coull, B. A., Zanobetti, A., Koutrakis, P. & Schwartz, J. D. Acute and chronic effects of particles on hospital admissions in New-England. *PLoS ONE* **7,** e34664 (2012).