Impacts of extreme temperatures on the mortality of a sample of insured lives in South Africa

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ABSTRACT

Background Extreme temperatures are among the most serious environmental health hazards associated with climate change. Life insurers, with their exposure to mortality risk, must understand potential material impacts of climate change on the mortality experience of their policyholders. Other financial institutions with exposure to mortality and longevity risk can also be affected by changes in the frequency or severity of extreme temperatures. To date, however, limited evidence exists on the relationships between climate change hazards, such as heat stress, and the mortality of insured lives in South Africa, and, indeed, in other developing countries.

Objective We investigated whether any significant relationship exists between the excess mortality of South African insured lives and extreme temperatures and temperature volatility for a sample of pensioners and a sample of lives covered under a life insurer's funeral book.

Methodology We collected daily time series of all-cause mortality from two data sources pertaining to South African insured lives (a pensioner dataset from 1 January 2012 to 1 January 2019 and a funeral insurance dataset from 1 June 2021 to 31 July 2024) and hourly temperatures for all parts of South Africa for the same periods, from which we calculated minimum and maximum daily temperatures. Individual standardised deviations for mortality rates relative to their average monthly levels ("mortality residuals") were calculated across all age groups. Similarly standardised

deviations for daily temperature relative to monthly average temperatures ("temperature residuals") across the whole country were calculated. The relationship between these residuals were analysed through visual mapping of excess mortality events against temperature, quantile regression and non-parametric copula fitting to model their joint behaviour.
Findings We observed a significant positive correlation between temperature residuals and excess mortality among the pensioner book but no such relationship in the funeral book. While overall concordance between excess deaths and excess temperature as measured by the respective residuals was weak for both datasets (tau = 0.014 for pensioner book; tau = –0.093 for funeral book), there was some weak association in the upper tail of the joint distribution for pensioners as well as between low temperature residuals and high mortality residuals for the funeral book.
Discussion Our analysis presented in this paper suggests that insurers need to pay close attention to the impact that extreme temperatures have on mortality. The results show possible evidence of heat-related excess mortality in the pensioner book and cold-related excess mortality in the funeral book. The results are consistent with well-documented heat-related excess mortality for older lives in general globally. The differences found between the pensioner and the funeral insurance datasets could be reflective of the different socio-economic circumstances of the two sets of lives and their relative vulnerability to heat- and cold-related excess mortality respectively. The initial findings warrant further analysis which could also contribute to development of temperature shocks to be incorporated into the ORSA and other applications of scenario analysis.

KEYWORDS
Climate change, temperature, mortality, South Africa, insured population, heat effects

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BACKGROUND

Climate impacts are already manifesting in South Africa (Pinto et al., 2022) and are projected to worsen in scenarios in which global temperatures rise, with heatwaves projected to become more extreme and more frequent even in scenarios where global warming is limited to 2°C (Johnston et al., 2024).

There are many ways in which climate change affects human health, but exposure to extreme temperature is among the most serious environmental health hazards (Murray et al., 2020), with heat having the most immediate and direct impact (Chen et al., 2024). In their study on South African lives, Scovronick et al. (2018) found that heat effects occur immediately after exposure, diminishing quickly, whereas cold effects are delayed but persistent. Non-optimal temperatures (i.e., temperatures both too hot and too cold) disrupt the body's ability to regulate its own temperature (i.e. thermoregulate), which leads to several health conditions and, in the case of extreme deviations in temperature, death (Ahima, 2020). Non-optimal temperatures account for more than 5 million deaths globally every year (2000–2019) – approximately 9.4% of the total global mortality burden – with cold-related deaths representing the largest contribution of non-optimal temperature-related mortality (8.5% vs. 0.9% of heat-related deaths) (Zhao et al., 2021). Current projections indicate that heat-related deaths will steeply increase under warmer climates, and will eventually outweigh current cold-related deaths, which will decline in most locations under high-emission scenarios (Gasparrini et al., 2017).

With mortality being a key risk in the life insurance industry, it is important that life insurers – and other financial institutions with exposure to mortality risks, such as pension funds – start considering the degree to which rising and volatile temperatures linked to climate change could affect their experience in this regard. Apart from scientific evidence of the increased mortality risk, South African insurers are also being faced with regulatory encouragement to appropriately manage all climate-related risks, including those posed to their mortality experience. South Africa's regulatory body for insurers, the Prudential Authority, has expressed its concern regarding the potential impacts of climate change on the safety and soundness of insurers and has urged insurers to take active steps to address climate-related risks (Prudential Authority, 2024).

While numerous studies have been conducted to assess the impacts of climate change on mortality (e.g. De Schrijver et al., 2022; Guo et al., 2023; Mazdiyasni et al., 2017), few have focused on the South African population and none (in the public domain, at least) have looked only at the insured South African population. This is notable because the manifestations and impacts of climate change are expected to vary widely by geographic region (Warren et al., 2006) and distinct demographic groups will be affected differently: infants, children, pregnant women, older people, chronically ill, outdoor workers, socio-economically disadvantaged and urban dwellers are the most heat vulnerable (Calleja-Agius et al., 2021; Islam & Winkel, 2017). Findings for foreign geographies, other populations or even the general South African population may, therefore, not be applicable to the insured South African population, which would make them not entirely useful to the South African long-term insurance industry.

To this end, a working party was established as part of the Actuarial Society of South Africa's Climate Change committee to investigate the impacts of climate change on mortality and morbidity. A subset of the working party was tasked with the statistical analysis of exposure and mortality data to understand and quantify potential impacts of extreme temperature on the mortality of South African insured lives. We believe that these initial results will be helpful for the insurance and retirement industries in other developing markets, not only in for the South African industry. The challenges of working with South African population-level mortality and exposure data are quite well known (Dorrington et al., 2004; Richman, 2017), thus, studies based on high quality data sources within South Africa may help inform likely impacts of climate change on the population-level experience.

This paper sets out the methodology and results of the research conducted by the working party that sought to investigate the relationship between extreme temperatures and temperature volatility on the mortality of South African insured lives. It aims to assist life insurers in quantifying the impacts of extreme temperatures and the volatility of temperature associated with climate change on the mortality of insured lives in South Africa. The approach presented is based on historical weather data and actual exposure and claims data of two distinct groups of policyholders from two insured populations: a set of approximately 92,000 pensioners (hereinafter referred to as the "pensioner data") and a set of approximately 700,000 lives covered under funeral policies (hereinafter referred to as the "funeral data"). These two sets were selected because their anonymised data were made available by two companies, a pension fund administrator and a life insurer. The two datasets represent two diverse groups of people in terms of age and socioeconomic status and both groups embody characteristics known to be particularly vulnerable to heat stress: the elderly and the economically disadvantaged. It was therefore expected that this dataset would yield relatively more significant results than those for the general insured population; we discuss whether this goal was achieved in the conclusions of our study.

Additionally, the proposed method and results presented may facilitate the assessment of the impact of future environmental scenarios on mortality outcomes, valuable for insurers conducting their risk and solvency assessments. The findings may also be used for other insurance functions, from underwriting, pricing and product design to financial reporting, business planning and basis setting.

SCOPE AND KNOWN LIMITATIONS

There are expected to be numerous direct and indirect impacts of climate change on human health and mortality. It is understood that there are multiple hazards associated with climate change that adversely affect human health, including increased air pollution, floods, droughts and vector-borne diseases (Calleja-Agius et al., 2021; Robben et al., 2024). This paper considers only the direct impact of temperature extremes, as measured by high deviation from expected values, on human mortality for two insured populations.

Findings are based on the data described in Section 4. We emphasise that these datasets may not be representative of the entire insured population of South Africa. Geographical concentration in the funeral book, for example, meant that the findings are restricted to a subset of South African provinces, where the life insurer had strong presence. We recommend that researchers using our results consider the extent to which these may generalise to other contexts.

The statistical techniques employed were selected for their simplicity, tractability and suitability for the purpose of the study and the data available. Nonetheless, we take the age of the population into account implicitly when calculating the mortality residuals. There are other techniques and methodologies that could be used for further work, even with the current datasets under study. For example, expected mortality can be calculated using a Poisson model of mortality with rates determined using several covariates as proposed by Robben et al. (2024). Other improvements to the statistical techniques could involve time-series analysis as an alternative way of dealing with seasonality as well as distributed lag non-linear models as demonstrated by Robben et al. (2024) and Gasparrini et al. (2010) respectively, and used for example by Chen et al. (2024) and Scovronick et al. (2018).

In this initial set of findings, we do not examine the findings by age which is a natural next step, especially if more industry data becomes available. In addition, temperature residuals are not calculated at provincial level, or lower, and are kept at national level for this study. This is another improvement that can be made once more granular location is obtained, or the geolocation information already present in the data properly analysed and decoded, which has not yet been done. The difference in temporal effect and duration of heat-related and cold-related excess mortality are not dealt with in this initial analysis. Furthermore, measures of heat and cold other than ambient air temperature, which are discussed in the literature review section, are not considered in this study.

We intend to use this initial work as a foundation for further work investigating other climate change hazards and their impacts on specific health conditions, such as cardiovascular disease, respiratory illnesses and mental health for a larger sample of the South African insured population.

LITERATURE REVIEW

A comprehensive description of some important work done on the relationship between climate change and mortality globally is contained in, for example, the work of Robben et al. (2024). They developed a mortality modelling framework to examine short-term associations between environmental factors and mortality in small European regions, finding that temperature-related factors, particularly extreme heat, were the most influential in explaining mortality deviations. A "harvesting effect", which occurs, for example, when environmental related excess mortality in the previous week leads to a mortality deficit in the current week (i.e. the deaths would have occurred within a few days in any case) (Schwartz, 2001), was observed during heat waves. These methods are highly relevant to our study on the effects of extreme temperatures on insured lives in South Africa (Robben et al., 2024).

While there may be significant differences in insured mortality compared to overall population mortality,[1] it is useful to examine work done to date to quantify the impact of extreme temperatures on South Africans in general to compare to methodology and results from this study.

Chen et al. (2024) assessed the impact of population aging on future temperature-related excess mortality at different levels of global warming in 50 countries, including South Africa. They did this by estimating the location-age-specific temperature-mortality

1 Quoted from ASSA's Continuous Statistical Investigation (CSI) Committee in Joubert (unpublished).

associations in a two-stage time-series analysis using quasi-Poisson regression with distributed lag nonlinear models and multivariate random meta-regression. They then derived excess temperature-mortality projections under three warming scenarios (1.5°C, 2°C, and 3°C of global warming above the preindustrial level). Finally, they quantified the impact of population aging as the difference in the change in temperature-related mortality fractions (percentage of all-cause deaths attributed to heat and cold over total mortality) between climate-only (i.e., not accounting for changes in population demographics) and climate-population scenarios.

They found that for heat-related mortality, climate change alone will result in an increased mortality burden in South Africa of around 0.02% at 1.5°C warming and of 0.03% at 2°C warming. At 3°C warming they found that mortality in South Africa is expected to decrease by –0.2%. From the supplementary information made available by the authors, it appears that this result is driven by a decrease in relative risk as temperatures increase for a number of regions in South Africa, including the City of Johannesburg. It is not clear why this would be the case, but it could be due to a low number of heatwaves during the study period, leading to fewer data points for higher temperatures.

Scovronick et al. (2018) conducted a time-series analysis using daily temperature data and a national dataset of all 8.8 million recorded deaths in South Africa between 1997 and 2013. Relationships between mortality and temperature data were estimated with a distributed lag non-linear model and pooled in a multivariate meta-analysis. They found that the relative risk for all-age all-cause mortality on very cold and hot days (1st and 99th percentile of the temperature distribution) was 1.14 (1.10,1.17) and 1.06 (1.03,1.09), respectively. They found a "U" shaped relationship for every age and cause group investigated, except for 25–44 year olds. The strongest associations were in the youngest (< 5) and oldest (> 64) age groups and for cardiorespiratory causes. Heat effects occurred immediately after exposure but diminished quickly whereas cold effects were delayed but persistent. Overall, 3.4% of deaths (~ 290,000) in South Africa were attributable to non-optimum temperatures over the study period.

Wichman (2017) investigated the relationship between heat exposure, as measured by apparent temperature,[2] and all-cause mortality in Cape Town, Durban and Johannesburg. Using a time-stratified case-crossover design, the study analysed mortality data from 2006 to 2010 and linked it to meteorological data, adjusting for confounders like air pollution and seasonality. The findings revealed that higher apparent temperatures were associated with an increased risk of mortality, particularly among the elderly and those with pre-existing health conditions, with varying heat effects across the cities due to differing climates.

The study revealed that in Cape Town, Durban and Johannesburg, mortality increased

2 *Ambient* air temperature may not be the best predictor of skin temperature, which is the main trigger of the body's cooling and warming mechanisms. *Apparent* temperature (Tapp) combines the effects of heat and cold with humidity to better capture the physiological response than temperature alone (Barnett et al., 2010).

by 0.9% for every 1°C increase in the 'daily apparent temperature' above 19°C (except for Durban, where the threshold was 25°C). For people older than 65 years, the mortality increase was 2.1% per degree of warming.

DATA

We obtained ethical clearance from the University of Johannesburg to conduct this study based on the secondary data used, which was anonymised by removing any personally identifiable policyholder information. Ethical clearance was predicated on compliance with the Protection of Personal Information Act (POPIA). In addition to the conditions required for ethical clearance, we set up safeguards around the data (access control and secure storage location) to secure confidentiality of the data and the intellectual property of the providers.

Exposure and mortality data

Pensioner data

We obtained postal code-level exposure and all-cause mortality from a pension administrator for a closed book of approximately 92,000 lives and 16,600 deaths for the study period 1 January 2012 to 1 January 2019. For each pensioner, monthly exposure was provided at each age.

Funeral data

We obtained country-level exposure for a life insurer's funeral book of business for approximately 100,000 funeral policies covering roughly 700,000 to one million lives and 23,000 deaths for the study period of 1 June 2021 to 31 July 2024. The high number of unique lives is due to reinstated policies being assigned new policy identifiers upon re-entry to the book. Furthermore, of the 23,000 deaths included in our initial dataset only 18,372 were included in the final analysis due to data quality issues identified with these claims upon reasonability checks on date of death and matching of death data and exposure data. It may well be the case that the excluded deaths were valid but their records could not be matched to the appropriate exposure period. This warrants further investigation.

Temperature data

ERA5 reanalysis data, the fifth generation of the European Centre for Medium-Range Weather Forecasts (ECMWF) atmospheric reanalysis of the global climate, were used. It is produced by the Copernicus Climate Change Service (C3S) at ECMWF and provides hourly estimates of a large number of atmospheric, land and oceanic climate variables.[3] We

3 https://www.copernicus.eu/en/access-data/copernicus-services-catalogue/reanalysis-era5-complete; Accessed 25 September 2024.

obtained temperature data over the land mass of South Africa once per hour for the period from 1 January 1981 until 30 August 2024.

Data limitations

The pensioner data contained exposure per month. A crude calculation of daily exposure was done, assuming constant exposure per month and taking death as the sole decrement. This crude calculation was deemed reasonable given the closed book nature of the dataset and the lack of other discontinuance options for pensioners. While postal code information was available for this dataset, the analysis conducted for this paper was done at country level.

The funeral data did not contain granular location information due to the rurality of certain areas in South Africa. Lives were mapped to a province in some cases where complete addresses or known landmarks near the policyholder's place of residence was captured. This dataset thus lends itself to possible future analysis at province level but the analysis conducted for this paper was done at country level. Further analysis at a more granular level will be considered once the quality of province-level data is considered.

STATISTICAL METHODOLOGY

Calculating daily exposure and daily death rates

For the pensioner dataset, we needed a more granular level of exposure than monthly exposure since we needed to calculate daily mortality rates. We first filtered the data to calculate the number of lives exposed for each month of the investigation. The number of deaths on each day of the investigation was then counted. Some reasonability checks were done on the observed number of deaths. These included checking whether overall deaths per year did not fluctuate unreasonably as well as checking whether expected seasonal effects were reflecting correctly in the data (e.g. higher death rates in winter months). Figures 1 and 2 show examples of the visual inspection done to check reasonable properties of death counts by year (after removing possibly erroneous death data in the funeral dataset).

Another important reasonability check was whether daily death rates calculated were higher for males than females and whether the seasonality effects, such as more deaths in winter months than summer months, were preserved when the data was split by sex. These aspects of the data can be seen by observing the overall pattern (on a log scale) for the different sexes over each calendar year shown in Figure 3 for the pensioner data. This analysis was not completed for the funeral due to incomplete sex data within the funeral dataset. Furthermore, for the pensioner dataset only, which represented a closed book, the expected trend of increasing mortality each year because of the aging of the book, is observed in Figure 3.

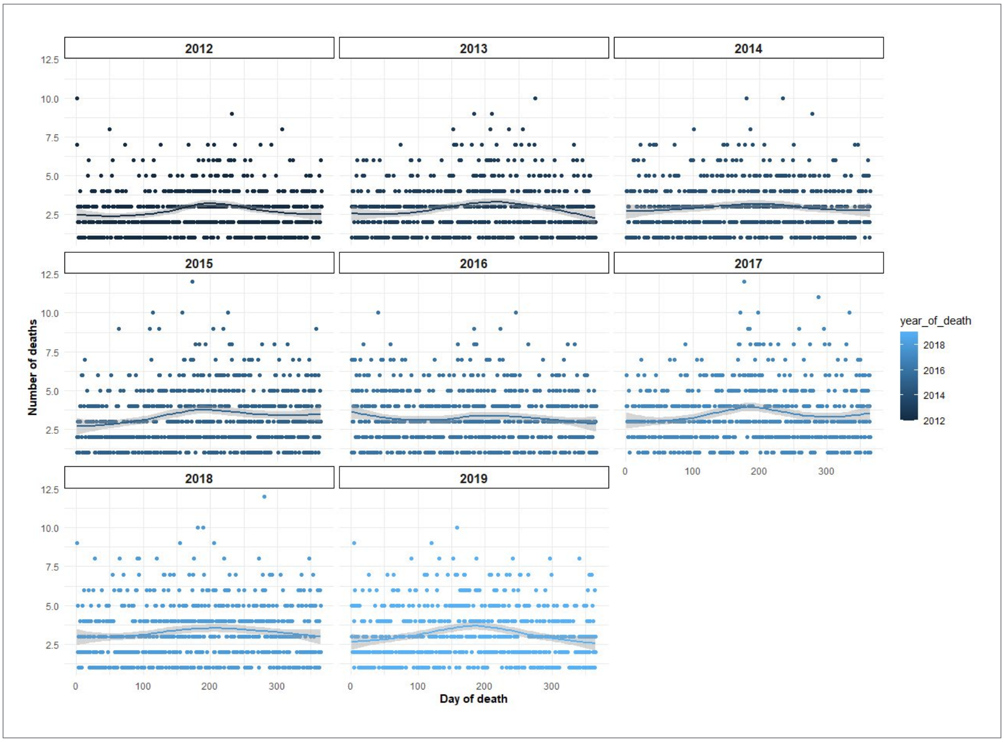

FIGURE 1. Count of deaths by day for each year (pensioner data)

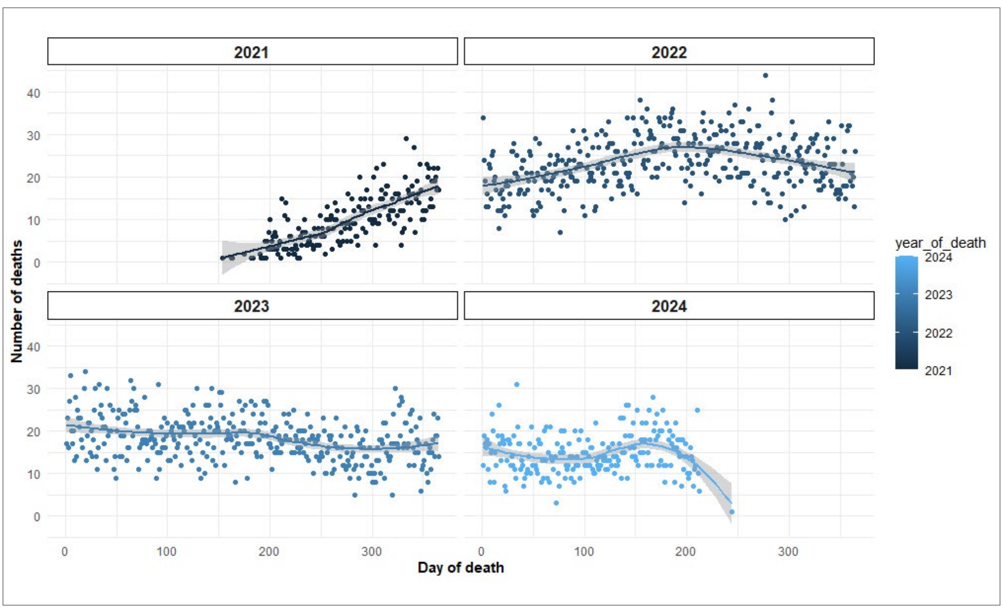

FIGURE 2. Count of deaths by day for each year (funeral data)

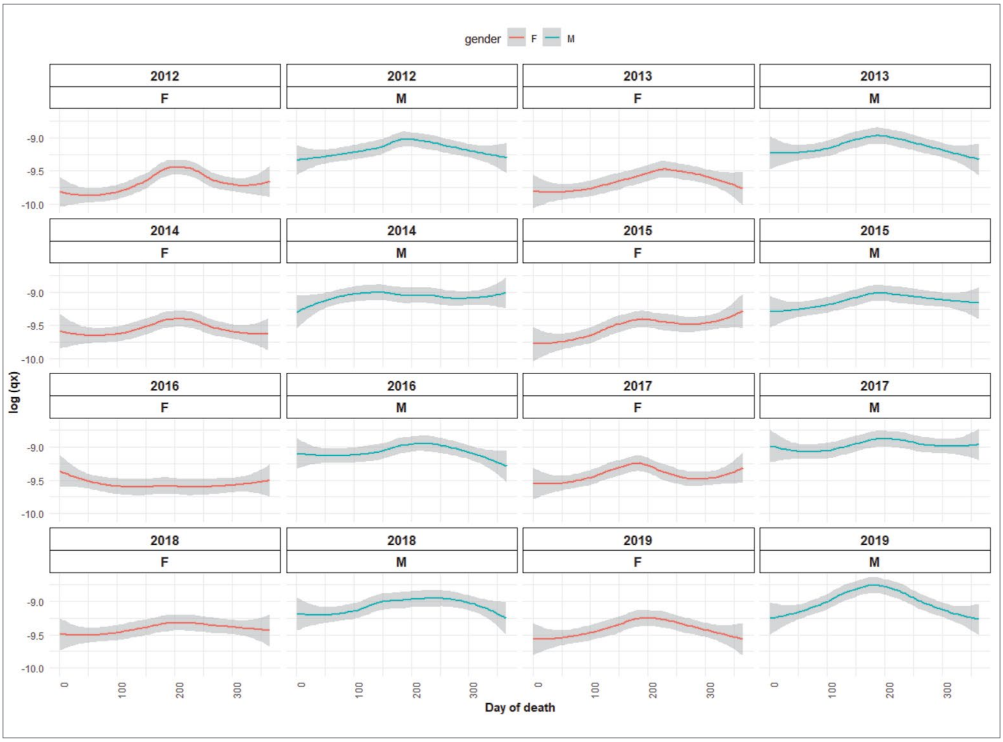

Figure 3. Summary of death rates by gender for each day of each calendar year (pensioner data)

Mortality and temperature residuals

Individual standardised deviations for mortality rates relative to their average monthly levels ("mortality residuals") were calculated at an overall level and not by age group for purposes of an initial crude overall analysis. This inherently assumes a constant age profile in the data. The reasonableness of this assumption deserves further consideration but a visual summary of the age profile of the pensioner data (shown in Figure 4) and that of the funeral data (shown in Figure 5) suggests that stratifying by age is important and needs to be considered. Achieving this level of homogeneity will compromise the credibility of the findings due to the low levels of exposure that will be available by age group and so this trade-off needs to be considered. This trade-off will lessen to the extent that more data becomes available. Nonetheless, we do not believe that the findings of the study are compromised by this methodological choice, due to the more extreme level of the mortality events considered below.

Similarly, standardised deviations for daily temperature relative to monthly average temperatures ("temperature residuals") across the whole country were calculated. Average, or expected, temperature was defined as the monthly average over a rectangular geospatial grid covering the whole country over all years. There is room to refine this crude average by restricting the GPS coordinates that are incorporated into the calculation even more precisely. The same method was used to calculate residuals within the funeral dataset.

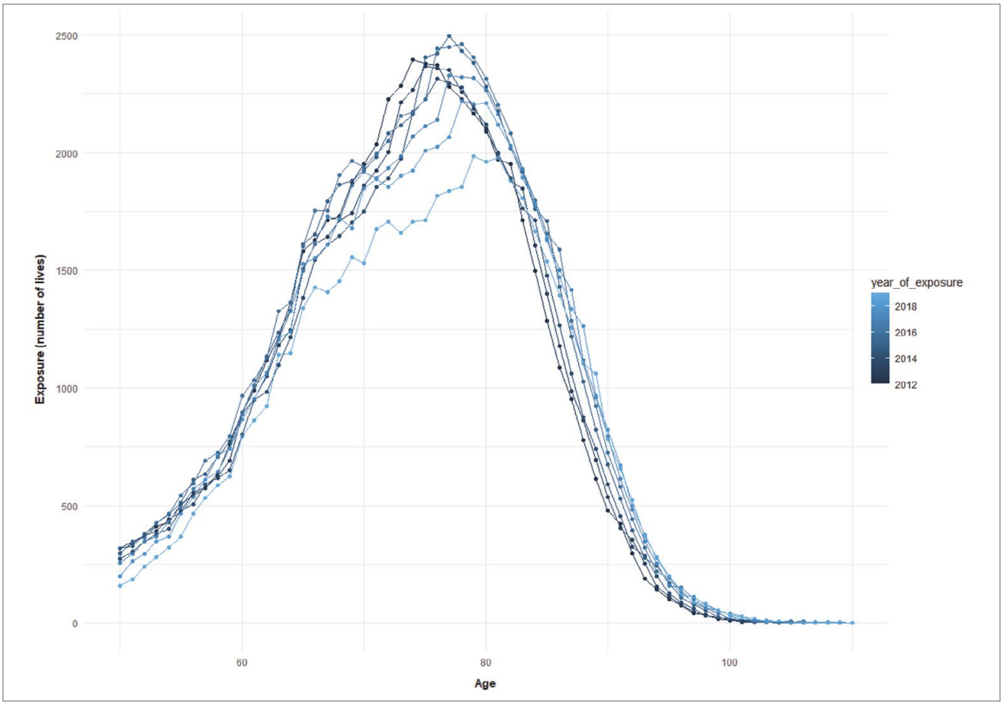

FIGURE 4. Age profile of the lives over time (pensioner data)

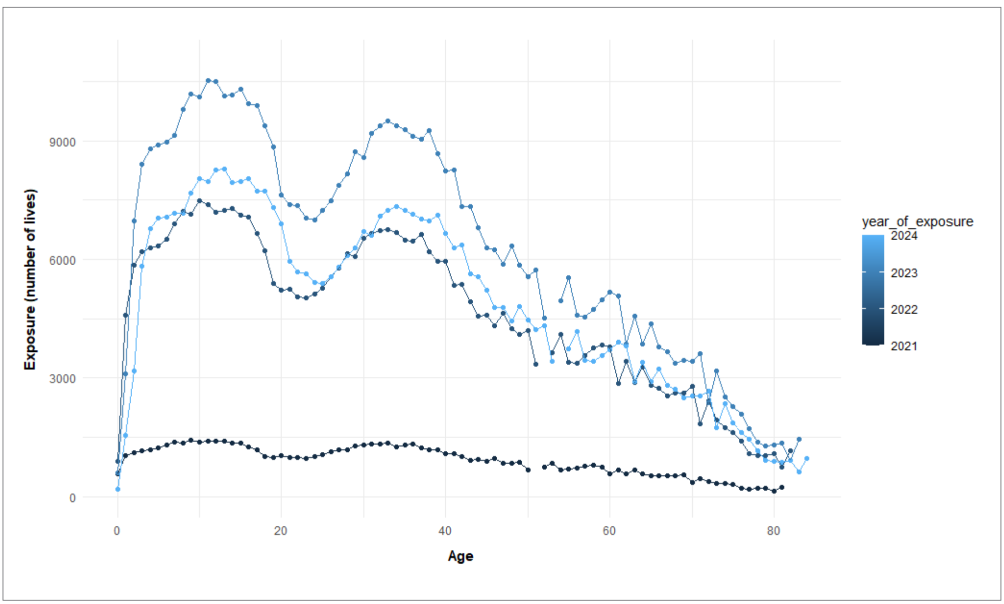

FIGURE 5. Age profile of the lives over time (funeral data) with extremely high values at ages 51 to 55 removed

Excess mortality events

To determine the extreme mortality events, daily death rates were calculated for each day of each calendar year. The daily mortality rates that fell in the 99th percentile of the distribution of mortality residuals represented the "1-in-100 years" extreme events ("excess mortality events"). Each sex was dealt with separately in the pensioner dataset but in the funeral dataset this was not possible given the granularity and quality of the covariates in the data.

Data preparation and initial descriptive analysis

Data visualisation was used to determine possible relationships between extreme values of daily temperature residuals and excess mortality events defined by daily mortality residuals lying in the 99th percentile of its distribution.

Quantile regression

To further investigate the relationship between temperature residuals and excess mortality events, three hypotheses were tested focusing on this association at the 95th, 99th and 99.5th percentiles of the mortality residuals distribution, i.e. at the upper tails of the mortality residuals distribution. We show only the results for the quantile regressions fitted for the 99th percentile but mention results of the other models where there are significant findings to report. This was done via a quantile regression analysis, using the "quantreg" package in R. First, a linear quantile regression line was fitted to the data. Thereafter a quadratic specification of quantile regression was fitted to ascertain whether a quadratic relationship was more appropriate to explain the impact of temperature residuals on the 99th percentile of mortality residuals for each dataset.

Copula fitting

Traditional correlation measures, such as Pearson's correlation coefficient and Kendall's tau, assess overall associations between variables but may fail to capture localised behaviours, such as the co-occurrence of extreme values. Copulas address this limitation by examining the joint distribution of the two variables of interest, mortality and temperature residuals, particularly in understanding tail dependencies. Kendall's tau and Spearman's rho are rank-based measures that assess the strength and nature of dependence between variables (Joe, 2014). Both coefficients range from –1 to +1, with values near +1 indicating strong positive dependence, values near –1 indicating strong negative dependence, and values around 0 suggesting minimal association (Joe, 2014). High values of these measures imply that the copula effectively captures the underlying dependencies, while low or negative values indicate a poor fit (Joe, 2014).

Copulas were fitted to temperature and mortality residuals using the non-parametric kernel approach known as Transformation Local Likelihood (TLL2nn) from the "kdecopula" package in R (Nagler, 2017). This method is robust and adapts to the local structure of the data, making it suitable for capturing complex dependencies without assuming a predefined parametric form.

FINDINGS

Pensioner data

Visualisation of excess mortality events and temperature residuals

An initial investigation was performed to determine whether there was a visible overlap between excess mortality events and extreme temperatures. This investigation was done by plotting, for each sex, the days on which excess mortality events occurred and examining what the temperature residuals were on those days (see Figure 6 where the dots represent excess mortality events). The same analysis was also done using actual levels of average daily temperature instead of temperature residuals to determine whether there were any cases where the absolute average temperature levels showed a more obvious impact on mortality as opposed to only considering temperature relative to its average level (shown in Figure 7).

This visualisation suggested some overlap between excess mortality events and days

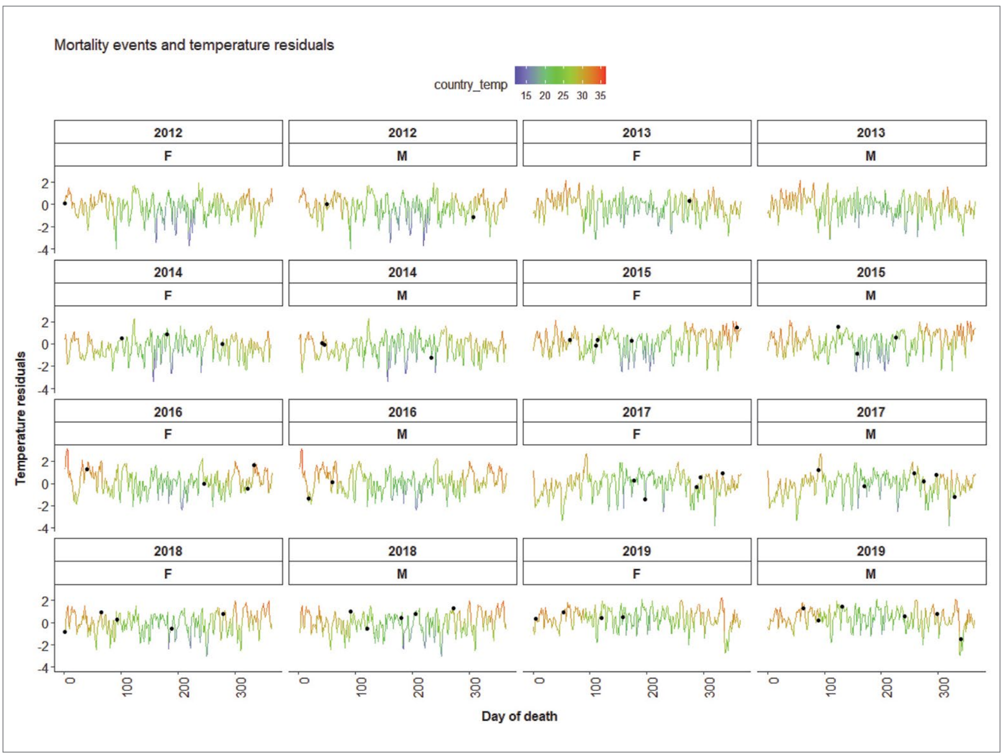

FIGURE 6. Line graph of daily temperature residuals overlaid with excess mortality events (dots) for pensioner data. Colour of the line is determined by the value of the temperature observed on the day.

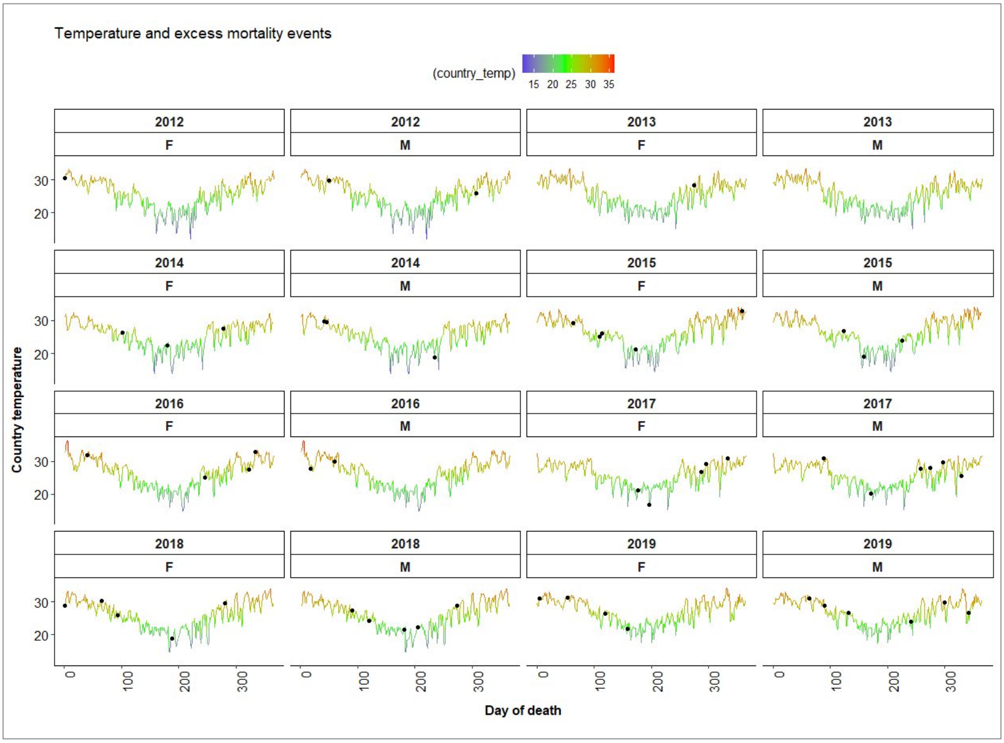

FIGURE 7. Line graph of daily temperature overlaid with excess mortality events (dots) for pensioner data. Colour of the line is determined by the value of the temperature observed on the day.

on which weather deviated significantly from the mean. From Figure 6, in 2016, all excess mortality events appear to have occurred at either peaks or negative peaks of temperature residuals. In 2017, excess mortality events for females appear to occur more frequently at peaks and negative peaks of temperature residuals (four out of five) but this was not the case for males (three out of six). In 2018, three out of five excess mortality events for females appeared at peaks and negative peaks of temperature residuals and this was the case for all male excess mortality events in that year. The results for other years do not appear to show an obvious visual relationship between excess mortality events and peaks and negative peaks of temperature residuals.

Figure 6 suggests that there may be an association between excess mortality events and extreme temperature events. Figure 7 suggests that it may be the peaks and negative peaks in actual temperature values that may be driving this. Further, this association appears to be skewed towards days where the temperature deviation is positive i.e., the day's temperature was hotter than the mean temperature for that month for all years included in the investigation. The increase in the excess mortality events over time is expected in the pensioner data because of the aging of a book that is closed to new entrants.

Quantile regression

To further investigate this relationship, a scatter plot of the residual daily deaths against residual temperatures was generated (Figure 8). The results of the linear quantile regression fitted for the 99th percentile of mortality residuals are shown in Table 1 and Figure 8.

TABLE 1. Quantile regression (99th percentile, linear specification) model summary for pensioner data

	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	2.92226	0.07671	38.09304	0.00000
Residual temperatures	0.17064	0.07671	2.22450	0.02616

The quantile regression model suggests that a positive linear relationship exists between temperature residuals and mortality rate residuals (p=0.03) at the 99th percentile (shown by the red line in Figure 8). This suggests that deviations above the mean monthly temperature have greater impacts on excess mortality events than deviations below the mean monthly temperature (see Figure 8 for a visual depiction).

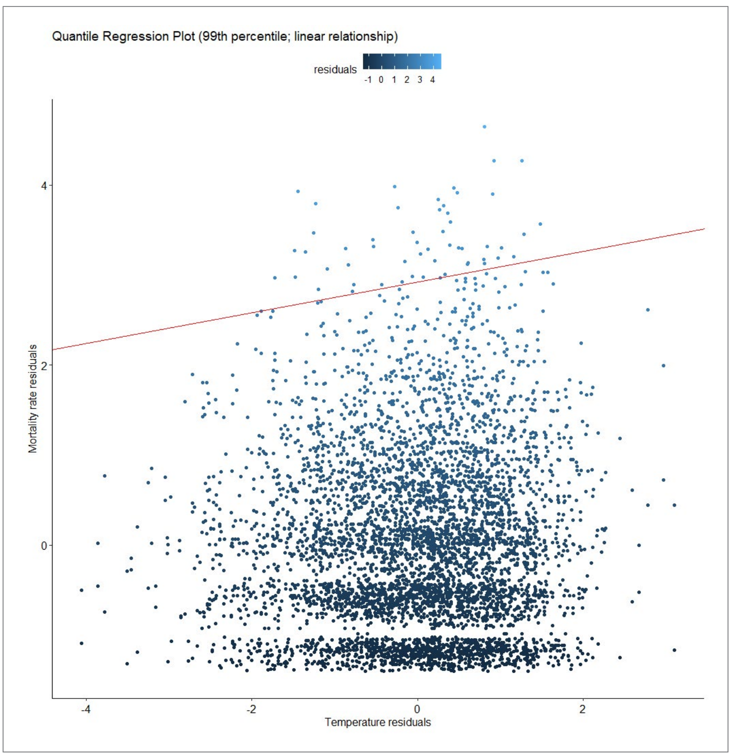

FIGURE 8. Scatter plot of daily standardised temperatures and death rates overlaid with a 99th percentile linear quantile regression model (p=0.03)

A further test conducted assessed whether a quadratic function would better fit the data, and therefore whether the data is symmetrical around a temperature residual of 0. This was done by fitting a quadratic quantile regression at the 99th percentile of mortality residuals. The fitted quantile regression model is summarised in Table 2.

TABLE 2. Quantile regression (99th percentile, quadratic specification) model summary for pensioner data

	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	2.98957	0.09326	32.05671	0.00000
Residual temperatures	0.10595	0.05830	1.81744	0.06921
(Residuals Temperatures)^2	–0.08704	0.03081	–2.82503	0.00475

In the quadratic quantile regression model for the pensioner data, the quadratic component is statistically significant ($p<0.01$), suggesting that a non-linear relationship between temperature residuals and extreme mortality events exists (shown in Figure 9).

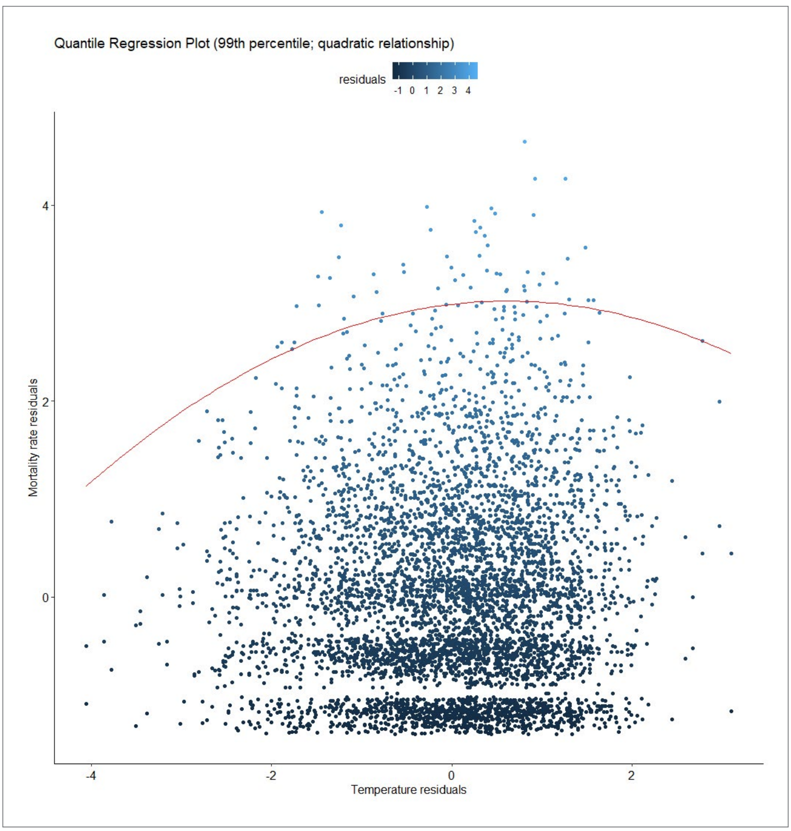

FIGURE 9. Scatter plot of daily standardised temperatures and death rates overlaid with a 99th percentile parabolic quantile regression model

Copula fitting

Figure 10 depicts a 2D-kernel density plot of the bivariate distribution of temperature residuals (x-axis) and mortality residuals (y-axis). The high-density region in the top left and the small high-density region in the top right corners are the ones we are particularly interested in. These indicate an overlap between extreme temperature residuals (hot and cold) and extreme mortality events. When the bivariate distributions are examined by year (Figure 11), there is some evidence to believe the pronounced association in the upper left and upper right quadrants are being driven by the later years of the study period.

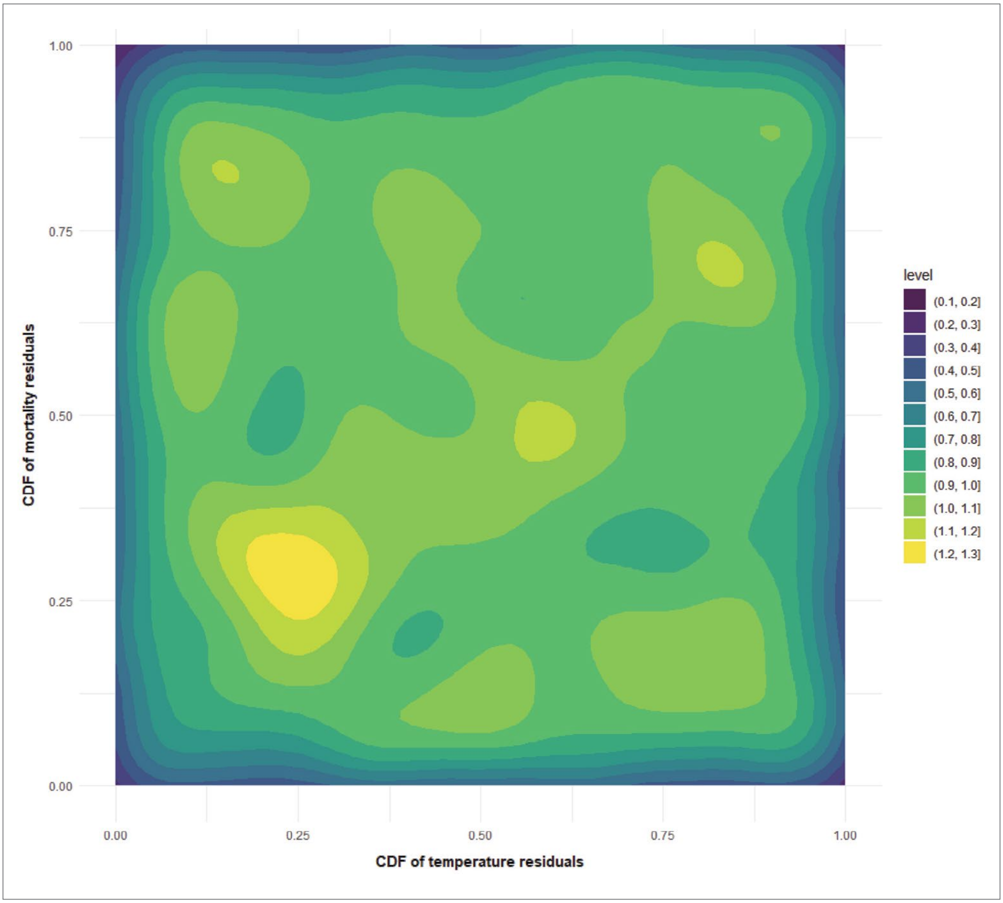

FIGURE 10. Bivariate distribution of residual mortality and temperature for pensioner data

A non-parametric copula was fitted to 5,411 paired observations of mortality and temperature residuals, providing a large dataset to estimate the copula. The results of the copula fitting procedure are summarised in Table 3 and Figure 12. The copula was fitted using 5,411 paired observations of excess deaths and temperature, providing a large dataset to estimate the copula.

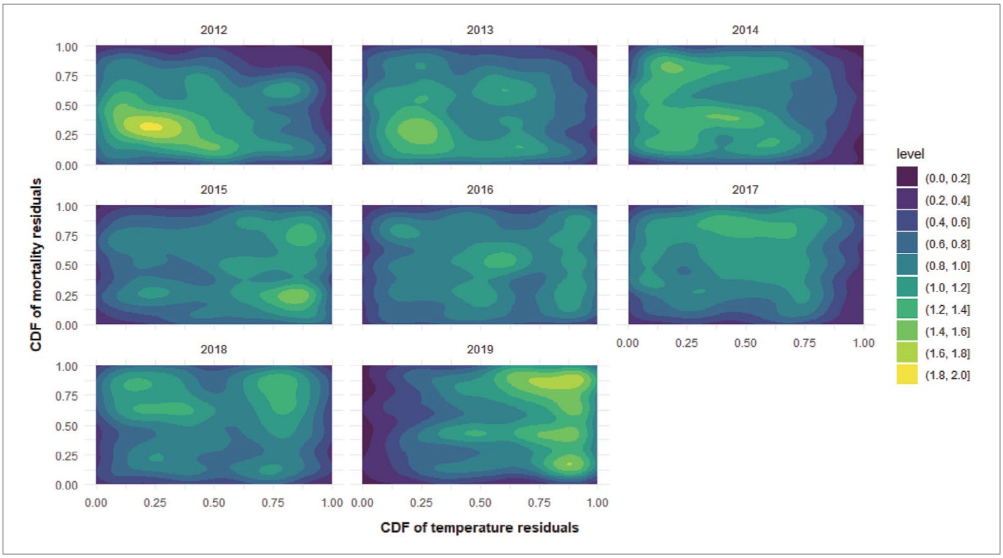

FIGURE 11: Bivariate distribution of residual mortality and temperature for pensioner data by year

TABLE 3. Non-parametric copula model summary for pensioner data

Summary of Kernel copula density estimate	Value
Kendall tau	0.014
Spearman rho	0.022
Observations	5411
Bandwidth (alpha)	0.4579485
Bandwidth (B)	matrix(c(0.74, -0.67, 0.67, 0.74), 2, 2)
Other model information: logLik: 14.73 AIC: 2.54 cAIC: 2.64 BIC: 108.06 Effective number of parameters: 16	

The value of Kendall's tau (0.014) and Spearman's rho (0.022) indicates a very weak positive dependence between excess deaths and excess temperature. This suggests that as one variable increases, the other variable tends to increase as well, but the strength of this association is minimal. This however does not mean that the correlation is weak at all points.

Funeral data

Visualisation of excess mortality events and temperature residuals

Figure 13 compares the excess mortality events of the funeral book with daily temperature residuals. There appears to be an association between extreme mortality and extreme heat events. Further, this association appears to be skewed towards days where the temperature deviation is positive i.e., the day's temperature was hotter than the mean temperature for

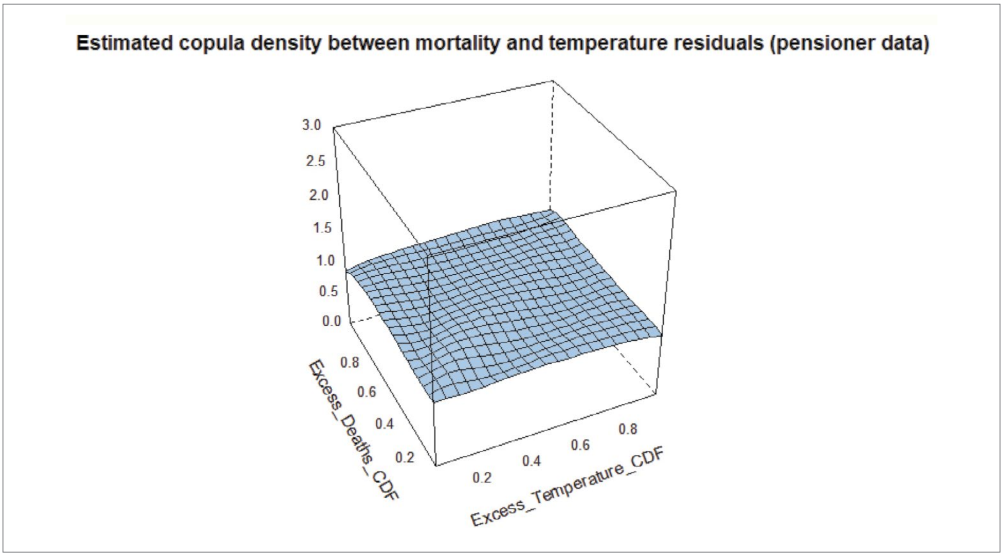

FIGURE 12: Non-parametric copula density of temperature residuals and mortality residuals

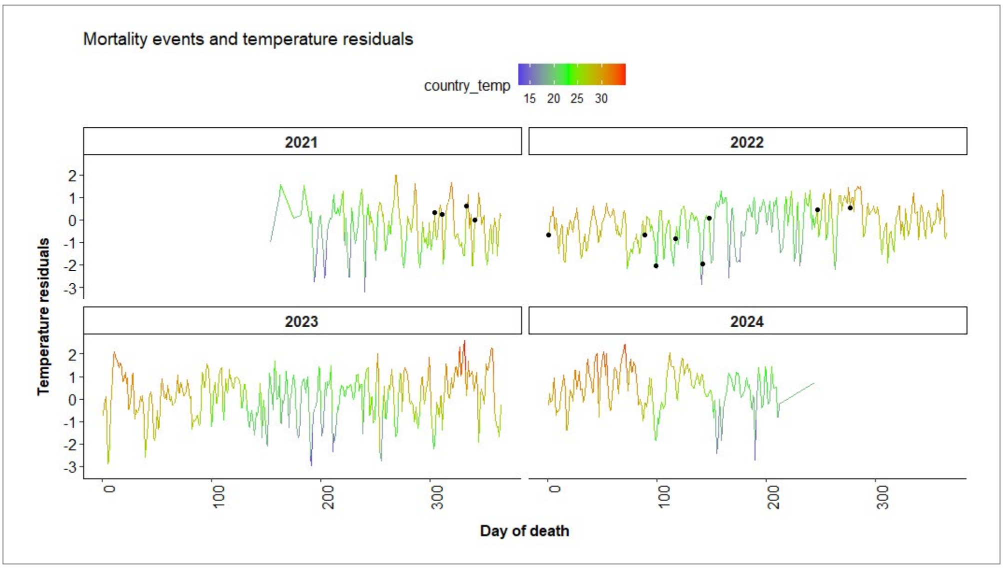

FIGURE 13. Line graph of daily temperature residuals overlaid with excess mortality events (dots) for pensioner data. Colour of the line is determined by the value of the temperature observed on the day.

that month for all years included in the investigation. However, we do see a concentration of extreme mortality days within the 2021 and 2022 calendar years, which could suggest that the mortality residuals have been skewed by the impact of COVID-19 within these years, which cannot be excluded due to the limited number of years for which we have data available. Many of the excess mortality events coincided with peaks of temperature residuals (five out of 12 events) and some coincided with negative peaks of temperature residuals (three out of 12).

Figure 14 depicts the comparison between excess mortality events of the funeral book with actual daily temperatures. We observe that all excess mortality events in 2021 coincided with peaks in actual daily temperature and all but one of the excess mortality events in 2022 coincided with either peaks or negative peaks in actual daily temperature levels.

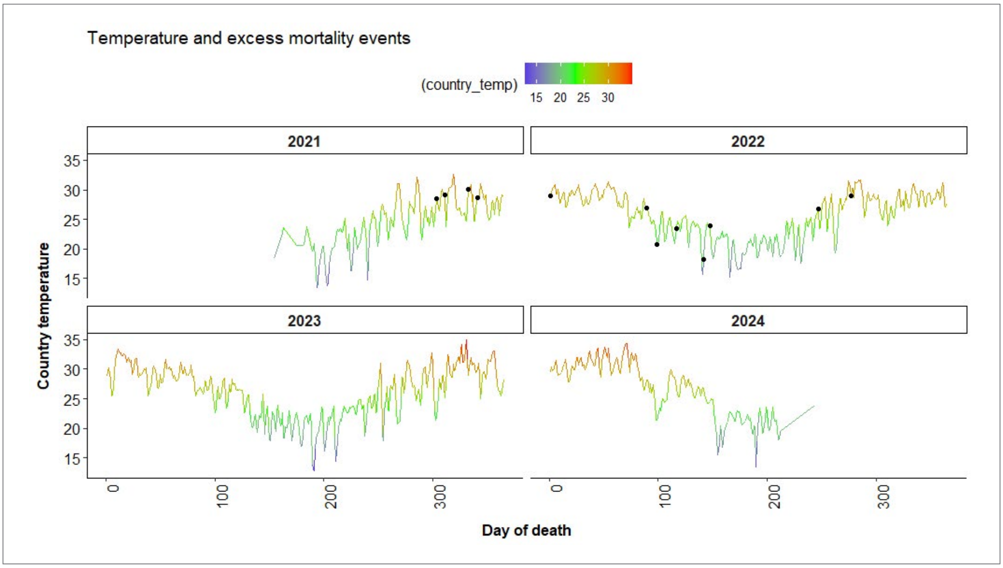

Figure 14. Line graph of daily temperature overlaid with excess mortality events (dots) for funeral data. Colour of the line is determined by the value of the temperature observed on the day.

Quantile regression

To further investigate this relationship, a scatter plot (Figure 15) of the residual daily deaths against residual temperatures was generated. Thereafter different hypotheses were tested focusing on this association at the 95th and 99th percentiles, i.e., at the upper tail of the mortality distribution. First, a linear quantile regression was fitted to the data. The results of the 99th percentile quantile regression model are shown in Table 4.

Table 4. Quantile regression (99th percentile, linear specification) model summary for funeral data

	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	2.43217	0.11232	21.65432	0.00000
Residual temperatures	−0.01358	0.05575	−0.24357	0.80761

From this fitted model we can infer that there is no linear relationship between temperature residuals and mortality rate residuals, particularly at the 99th quantile (shown by the red line in Figure 15). This high p-value and the scarcity of dots we see above the red line in the figure, could suggest that there are insufficient data points to perform quantile regression at a 99th percentile.

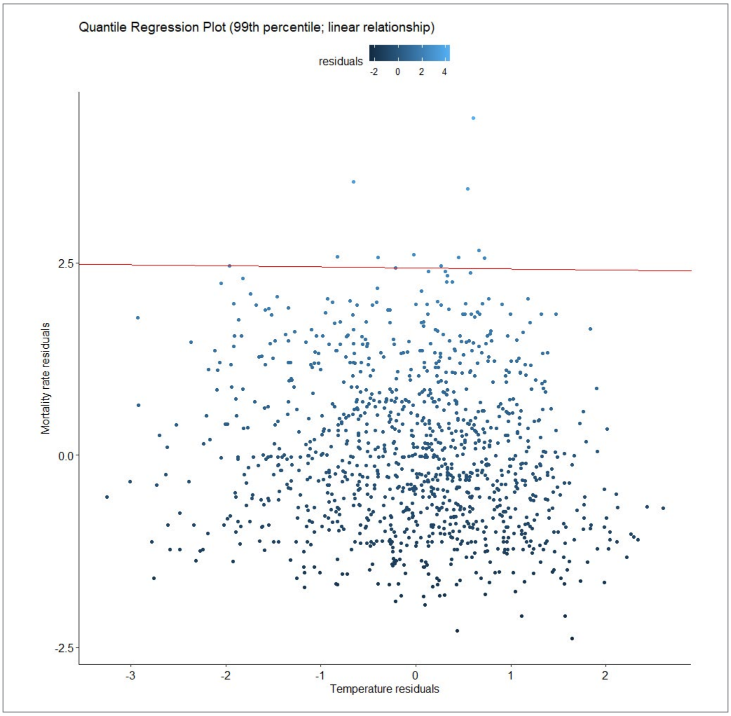

FIGURE 15. Scatter plot of daily standardised temperatures and death rates overlaid with a 99th percentile linear quantile regression model

This seems to suggest that there is also no linear relationship between temperature residuals and mortality rate residuals, shown for the 99th percentile (see red line in Figure 15). However, although not statistically significant, it should be noted that the relationship is a weakly negative one, hinting to the possibility that deviations below the mean monthly temperature have greater impacts on excess mortality than deviations above the mean monthly temperature. Repeating this at a 95th percentile produces a weakly significant result of the same direction (p=0.09) (model output not shown).

A further test assessed whether a quadratic function would better fit the data and whether the data are symmetrical around a temperature residual of 0. This was done by fitting a quadratic equation at the 99th percentile. The fitted quantile regression model is summarised in Table 5 and Figure 16. While the linear component is significant in this model (p=0.03), the quadratic component is not significant (p=0.19).

TABLE 5. Quantile regression (99th percentile, quadratic specification) model summary for funeral data

	Value	Std. Error	t value	Pr(>|t|)
(Intercept)	1.84222	0.06338	29.06768	0.00000
Residual temperatures	–0.16999	0.07827	–2.17193	0.03007
(Residuals Temperatures)^2	–0.06423	0.04904	–1.30980	0.19053

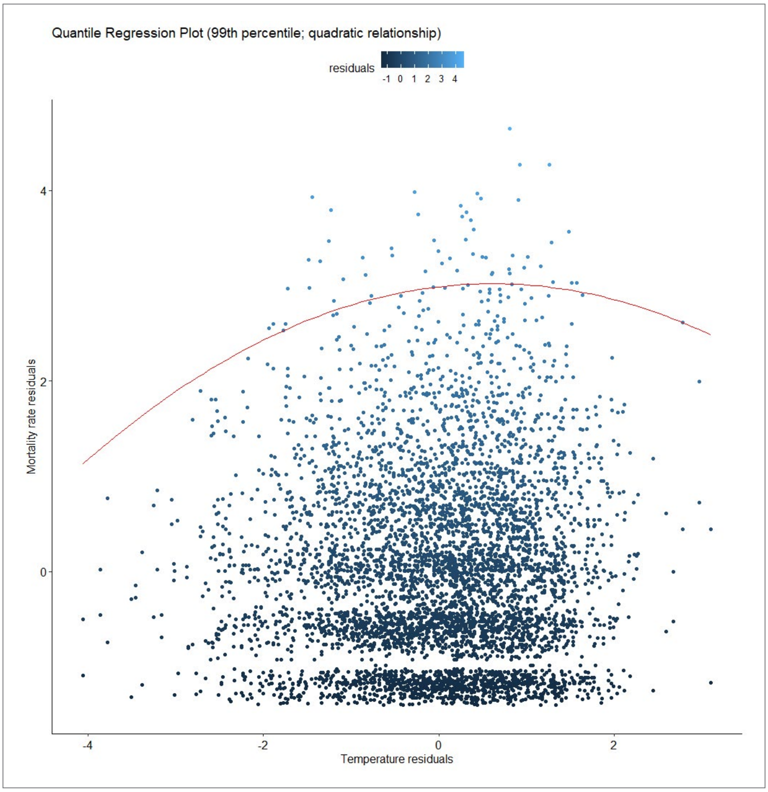

FIGURE 16. Scatter plot of daily standardised temperatures and death rates overlaid with a 95th percentile parabolic quantile regression model

In summary, the funeral dataset shows no linear or quadratic relationship between temperature residuals and mortality residuals rates at 99th percentiles, and this holds for the 95th percentile too. It is worth noting that the potential skewing of baseline mortality rates due the impact of COVID-19 in this dataset could be impacting the ability to identify any potential relationships. A next step should be to obtain additional comparable data over a longer time horizon such that a new baseline mortality level can be identified and utilised.

Copula fitting

Figure 17 depicts a 2D-kernel density plot of the bivariate distribution of temperature residuals (x-axis) and mortality residuals (y-axis) for the funeral data. The high-density region in the top left is of interest. This region indicates an overlap between extreme low temperature residuals (cold temperatures only) and extreme mortality events. The high-density region on the bottom right is unexpected and warrants further investigation.

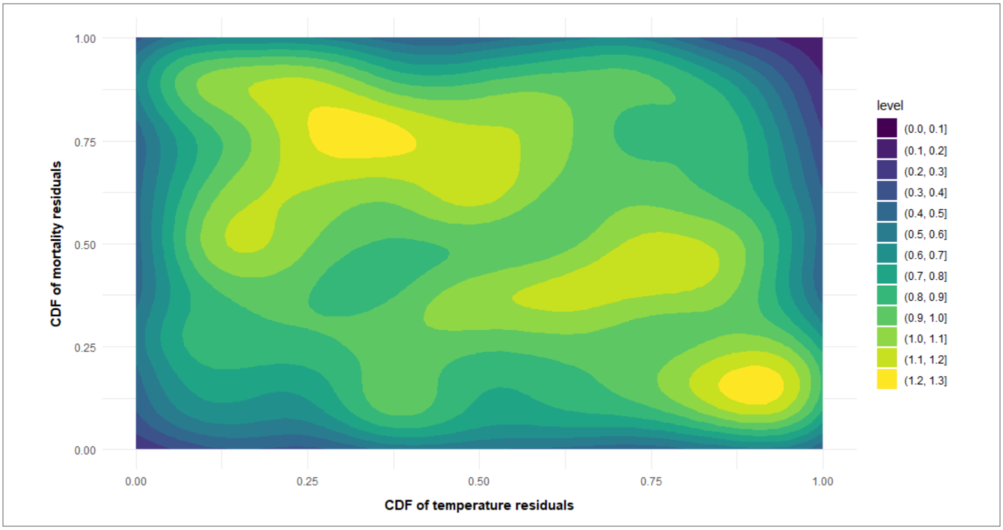

FIGURE 17. Bivariate distribution of residual mortality and temperature for funeral data

Examining the same plot for each year (Figure 18) reveals that deaths in 2022 are responsible for the correlation between low temperature residuals and high mortality residuals and that deaths in 2024 are responsible for the unexpected correlation between high temperature residuals and low mortality residuals (i.e. bottom right quadrant).

As was done for the pensioner data, a non-parametric copula was fitted to 1,123 paired observations of mortality and temperature residuals, providing a large dataset to estimate the copula (although not as large as the pensioner sample due to the smaller period of investigation). The results are summarised in Table 6 and Figure 19.

TABLE 6. Non-parametric copula model summary for funeral data

Summary of Kernel copula density estimate	Value
Kendall tau	–0.093
Spearman rho	–0.139
Observations	1123
Bandwidth (alpha)	0.5273698
Bandwidth (B)	matrix(c(0.71, –0.71, 0.71, 0.71), 2, 2)
Other model information: logLik: 24.68 AIC: -20.06 cAIC: -19.65 BIC: 53.52. Effective number of parameters: 14.65	

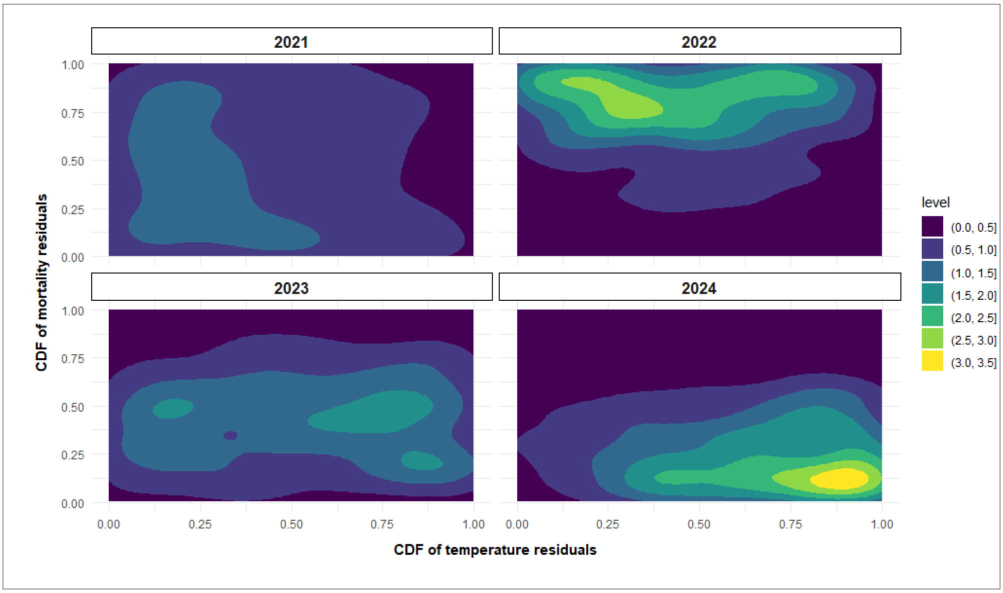

FIGURE 18. Bivariate distribution of residual mortality and temperature for funeral data by calendar year

The value of Kendall's tau (–0.093) and Spearman's rho (–0.139) indicates a very weak negative correlation between temperature residuals and mortality residuals. This can also be observed by the shape of the copula density (Figure 19), which affirms that extremely low temperature residuals are associated with high mortality residuals, but the strength of this association is weak. This however does not mean that the correlation is weak at all points.

DISCUSSION

For the pensioner dataset, a significant linear relationship was found between the crude daily temperature residuals and the upper tail of the mortality residuals (99th percentile, $p=0.02$; 95th percentile, $p=0.05$). Overall concordance between excess deaths and excess temperature as measured by the respective residuals was weak (Kendall's tau = 0.014), and this was confirmed by the fitted copula. There was, however, some weak association in the upper tail of the joint distribution, as observed in the bivariate density plot.

The observed impact of high temperature residuals on excess mortality in the pensioner dataset is consistent with the finding that higher apparent temperatures were associated with an increased risk of mortality, particularly among the elderly (Wichmann, 2017), discussed in the literature review. So this finding may be reflective of the susceptibility of elderly lives to heat-related deaths.

For lives in the funeral book, no significant linear relationship was found between the crude daily temperature residuals and the upper tail of the mortality residuals (99th

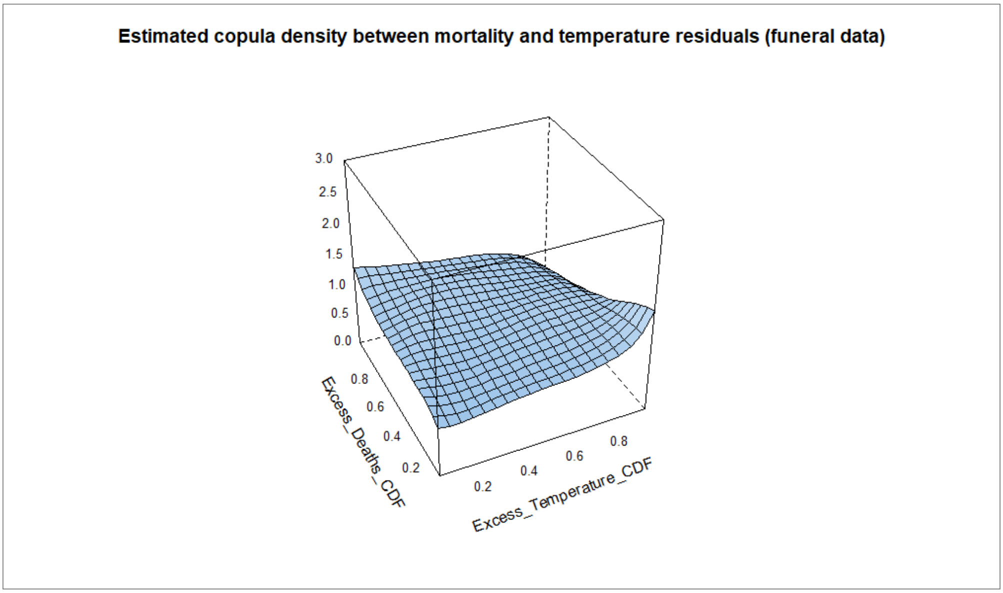

FIGURE 19. Non-parametric copula density of temperature residuals and mortality residuals (funeral data)

percentile, p=0.81; 95th percentile, p=0.09). Since data were available for a study period of less than four years, the credibility of these results for the funeral dataset is questionable and so this finding should be interpreted with caution. Another factor affecting the credibility of the findings from the funeral dataset is the likelihood that COVID-19 influenced the observed death data. The relatively high number of excess mortality events in 2021 and 2022, for example, compared to no excess mortality events observed in 2023 and 2024, is possible evidence of this.

Moreover, if the deaths in years 2021 and 2022 are unusually high relative to historical experience of this group of policyholders, then this elevated death count would have unduly biased the average mortality rate used in the calculation of the mortality residuals. This would have had the effect of attenuating the peaks of the morality residuals, thereby possibly diminishing the clarity of the results from the analysis.

An interesting finding with respect to the lives in the funeral book was the relationship between temperature residuals in the first quartile and mortality residuals in the fourth quartile. This could be evidence of the relatively lower socio-economic status of these lives leaving them vulnerable to cold-related deaths. This argument, however, is countered by the fact that less than half of the excess mortality events observed in the funeral book occur during winter months (five out of 12) and only two of the excess mortality events appear to occur on days that experienced relative negative peaks in actual temperature.

CONCLUSIONS AND AREAS FOR FURTHER RESEARCH

The analysis presented in this paper found that extreme high temperature is a significant predictor of excess mortality for pensioners while extreme low temperature was found to have a weakly significant effect on excess mortality for the lives covered by funeral insurance. This suggests that insurers need to pay close attention to the impact that extreme temperatures have on mortality. The initial findings, and especially the differences found between the pensioner and the funeral insurance datasets, warrant further analysis which could also contribute to calibration of temperature shocks to be incorporated into the Own Risk and Solvency Assessment (ORSA) and other applications of scenario analysis.

The use of the calculations described in this paper for capital modelling of insurers deserves further investigation. To this end, one can investigate whether a compound distribution, where incidence and severity of excess mortality claims induced by extreme temperatures, can be derived from these findings. In particular, further analysis of the potential for extreme climatic events to result in significant losses for the insurance sector is a promising avenue for future research.

Natural model improvements and extensions will include extending the analysis to other datasets. The copula fitting methodology could also benefit from refinement and establishment of concrete guidance of when the non-parametric fitting is preferred to well-known families of copulas. The quantile regression analysis deserves a closer look and other (non-linear) relationships between temperature and mortality residuals could be explored. Finally, there is room for increased granularity by considering the data at province level (or other smaller administrative boundaries where data permits), by age, by sex (which was not yet done for the funeral data).

Other definitions of extreme value need to be considered. For example, the analysis could be repeated using absolute levels of temperature instead of temperature residuals. Block maxima and block minima could be used to determine extreme temperature values. Finally, considering high temperatures over a certain threshold and low temperatures below a certain threshold could yield a more informative view of extreme temperature behaviour that impacts mortality.

Future research could entail studying the effects of temperature on morbidity of insured lives as well as considering the multitude of environmental factors that are known to cause excess mortality and morbidity for other populations, such as air pollution, precipitation and other climate factors.

Finally, a host of other statistical techniques could be employed for the current datasets, including more sophisticated Poisson models of mortality and time series analysis, including models that allow for lagged effects of climate factors on mortality and morbidity. As more data become available on other subsets of the insured population (i.e. not funeral and not pensioners), more can be done in this regard.

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REFERENCES

Ahima, RS (2020). Global warming threatens human thermoregulation and survival. *The Journal of Clinical Investigation* **130**(2), 559–561. https://doi.org/10.1172/JCI135006

Barnett, AG, Tong, S & Clements, ACA (2010). What measure of temperature is the best predictor of mortality? *Environmental Research* **110**(6), 604–611. https://doi.org/10.1016/j.envres.2010.05.006

Calleja-Agius, J, England, K & Calleja, N (2021). The effect of global warming on mortality. *Early Human Development* 155. https://doi.org/10.1016/j.earlhumdev.2020.105222

Chen, K, De Schrijver, E, Sidharth, S et al. (2024). Impact of population aging on future temperature-related mortality at different global warming levels. *Nature Communications* 15, 1796. https://doi.org/10.1038/s41467-024-45901-z

De Schrijver, E, Bundo, M, Ragettli, MS et al. (2022). Nationwide Analysis of the heat- and cold-related mortality trends in Switzerland between 1969 and 2017: The role of population aging. *Environmental Health Perspectives.* **130**(3). https://doi.org/10.1289/EHP9835

Dorrington, RE, Moultrie, TA & Timæus, I (2004). Estimation of mortality using the South African Census 2001 data. Centre for Actuarial Research, University of Cape Town.

Gasparrini, A, Armstrong, B & Kenward, MG (2010). Distributed lag non-linear models. *Statistics in medicine*. 29, 2224–34. https://doi.org/10.1002/sim.3940

Gasparrini, A, Guo, Y, Sera, F et al. (2017). Projections of temperature-related excess mortality under climate change scenarios. *The Lancet Planetary Health* 1(9), e360–e367 https://www.thelancet.com/journals/lanplh/article/PIIS2542-5196(17)30156-0/fulltext

Guo, C, Lanza, K, Li, D et al. (2023). Impact of heat on all-cause and cause-specific mortality: A multi-city study in Texas. *Environmental Research* 224. https://doi.org/10.1016/j.envres.2023.115453

Islam, SN & Winkel, J (2017). Climate change and social inequality. United Nations DESA Working Paper No. 152. https://desapublications.un.org/file/183/download

Joe, H (2014). *Dependence modeling with copulas*. Chapman & Hall/CRC

Johnston, P, Egbebiyi, TS, Zvobgo, L, Omar, SA, Cartwright, A & Hewitson, B (2024). Climate change impacts in South Africa: What climate change means for a country and its people. University of Cape Town. https://web.csag.uct.ac.za/~cjack/South%20Africa_FINAL_22%20Jan_ONLINE.pdf, 23/09/2024

Joubert, S (Unpublished). Higher excess death rate among fully underwritten policyholders. *Moonstone*, 15/12/2021. https://www.moonstone.co.za/higher-excess-death-rate-among-fully-underwritten-policyholders/, 24/09/2024

Mazdiyasni, O, AghaKouchak, A, Davis, S et al. (2017). Increasing probability of mortality during Indian heat waves. *Science Advances* 3

Murray, CJL, Aravkin, AY, Zheng, P, Abbafati, C, Abbas, KM, Abbasi-Kangevari, M, et al. (2020). Global burden of 87 risk factors in 204 countries and territories, 1990–2019: a systematic analysis for the global burden of disease study 2019. *Lancet* **396**(10258), 1223–1249. https://doi.org/10.1016/S0140-6736(20)30752-2

Nagler, T (2017). kdecopula: An R package for the kernel estimation of bivariate copula densities. arXiv:1603.04229. https://arxiv.org/abs/1603.04229

Pinto, I, et al. (2022). Climate change exacerbated rainfall causing devastating flooding in Eastern South Africa, World Weather Attribution

Prudential Authority (2024). Financial Sector Regulation Act, 2017 Guidance Notice 1 of 2024: Guidance on climate-related governance and risk practices for insurers. [Online] Available at: https://www.resbank.co.za/content/dam/sarb/what-we-do/prudential-regulation/climate-related-risk/2024/G1%20Insurers%20Climate%20Guidance_Risk.pdf

Richman, R (2017). Old age mortality in South Africa. Cape Town: University of Cape Town.

Robben J, Antonio K & Kleinow T (2024). The association between environmental variables and short-term mortality: evidence from Europe. arXiv preprint arXiv:2405.18020v2. 20 August 2024. https://doi.org/10.48550/arXiv.2405.18020

Schwartz, J (2001). Is there harvesting in the association of airborne particles with daily deaths and hospital admissions? *Epidemiology.* **12**(1), 55–61. https://doi.org/10.1097/00001648-200101000-00010

Scovronick, N, Sera, F & Acquaotta, F (2018). The association between ambient temperature and mortality in South Africa: A time-series analysis. *Environmental Research.* 161, 229–235. https://doi.org/10.1016/j.envres.2017.11.001

Warren, R, Arnell, N, Nicholls R et al. (2006). Understanding the regional impacts of climate change. Research Report prepared for the Stern Review on the Economics of Climate Change. Tyndall Centre for Climate Change Research. https://citeseerx.ist.psu.edu/document?repid=rep1&type=pdf&doi=3f04e1965e04906a9f6f5f78ab74c1b41614e19e

Wichmann, J (2017). Heat effects of ambient apparent temperature on all-cause mortality in Cape Town, Durban and Johannesburg, South Africa: 2006–2010. *The Science of the Total Environment* **1**(587–588), 266–272. https://doi.org/10.1016/j.scitotenv.2017.02.135

Zhao, Q, Guo, Y, Ye, T et al. (2021). Global, regional, and national burden of mortality associated with non-optimal ambient temperatures from 2000 to 2019: a three-stage modelling study. *The Lancet Planetary Health.* **5**(7), e415–e425. https://doi.org/10.1016/S2542-5196(21)00081-4