

# Excess mortality in England during the 2019 summer heatwaves.

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**Abstract:** There is increasing evidence that rising temperatures and heatwaves in the United Kingdom are associated with an increase in heat-related mortality. However, the Public Health England (PHE) Heatwave mortality monitoring reports, which use provisional death registrations to estimate heat-related mortality in England during heatwaves, have not yet been evaluated. This study aims to retrospectively quantify the impact of heatwaves on mortality during the 2019 summer period using daily death occurrences. Second, using the same method, it quantifies the heat-related mortality for the 2018 and 2017 heatwave periods. Lastly, it compares the results to the estimated excess deaths for the same period in the PHE Heatwave mortality monitoring reports. The number of cumulative excess deaths during the summer 2019 heatwaves were minimal and were substantially lower than during the summer 2018 heatwaves (1,700 deaths) and summer 2017 heatwaves (1,489 deaths). All findings were at variance with the PHE Heatwave mortality monitoring reports which estimated cumulative excess deaths to be 892, 863 and 778 during the heatwave period of 2019, 2018 and 2017 respectively. Issues are identified in the use of provisional death registrations for mortality monitoring and the reduced reliability of the ONS daily death occurrences database before 2019. These findings may identify more reliable ways to monitor heat mortality during heatwaves in the future.

**Keywords:** Temperature. Mortality. Heatwave. Epidemiology.

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## 1. Introduction

Record-breaking extremes over the last century are five times higher than expected [1] driven by anthropogenic, greenhouse gas emissions [2]. The global climate has so far warmed by around 1°C since pre-industrial conditions and the Intergovernmental Panel on Climate Change's (IPCC) high-emission scenario projects an average increase in global mean surface temperature of between 2.6°C and 4.8°C by 2100 relative to 1986–2005 [3-4]. The Paris Agreement in 2015 reinforced the intention to “hold the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels” [5] (p22). However, after the impact of other greenhouse gases such as nitrous oxide and methane are taken into account, two thirds of “allowable” cumulative carbon dioxide emissions to stay below the 2°C target has already been used [6-7]. In addition, there is a high probability the planet is already committed to average warmings over land exceeding 1.5°C relative to pre-industrial times, even if present atmospheric greenhouse gas concentrations are stabilised [8]. This is confirmed by the climate models which all project that the warming rates over land will be higher than warming rates over oceans [8]. Critically, these higher warming rates over land expose human populations to higher heat stress than the average global temperature rise suggests [9].

Increasing global land and sea temperatures are leading to an intensification of extreme events such as heatwaves [10-11]. In addition, both historical records and future climate projections indicate that, as global mean surface temperatures increase, the frequency, duration and intensity of

European heatwaves will increase [12-13]. This is significant as climatic conditions of lethal heat are already exposing a third of the world's population to heat stress and exposure is expected to continue to increase [14]. The impact of this on the European population will be greater than any other weather-related hazards exacerbated by climate change [15]. On a regional scale, the impact of these changes is projected to lead to an increasing frequency of temperatures exceeding 35°C in the Southeast of England and an increased frequency of temperatures exceeding 30°C in the North of England [16]. This increasing exposure to heat is further demonstrated by the decreasing return time for summers with days above 40°C. Currently, the return time is 100-300 years, however, this could decline to a return time of 3.5 years by 2100 if greenhouse gas emissions are not reduced [17]. Anthropogenic causes are implicated in the increasing occurrence of extreme temperatures [18-19] just as anthropogenic climate change made the record-breaking summer temperatures of 2018 around 30 times more likely [20]. Therefore, whilst the UK's relatively stable maritime climate does not typically impose the same extreme continental heat as mainland Europe, hot extremes are becoming more frequent and intense in the UK [21].

The summer of 2019 was the Northern Hemisphere's warmest meteorological summer since records began in 1880, tied with 2016 [22]. During this period, there were widespread heatwaves across Europe which reached a peak over northern and central Europe [9]. For the UK, the year of 2019 was notable for a range of temperature records including a new all-time record in July (38.7°C), measured at Cambridge University Botanic Garden on 25 July 2019, which exceeded the previous record, 38.5°C measured at Faversham, Kent measured on 10 August, 2003. Surveying the summer period as a whole, there were three heatwaves, 28 to 30 June, 21 to 28 July and 23 to 29 August 2019 [23]. These heatwaves have been directly linked to climate change with the July heatwave being at least three times likely due to increasing global mean surface temperatures [24]. The UK heatwaves were brought over from the European continent as a result of stationary and high amplitude Rossby waves which form large meanders in the upper-tropospheric winds [9]. These persistent high atmospheric pressure systems, otherwise known as blocking events, are potentially due to the slowing down of mid-latitude summer circulation [9]. In 2019, these blocking events allowed low-pressure systems to develop offshore the Iberian Peninsula which induced intense advections of hot air from northern Africa to Europe [24]. These so-called 'Spanish Plumes' bring clear skies result in high, day-time heat loads due to high solar radiation inputs leading to heatwave conditions in UK [24]. There is, however, a debate as to whether the European heatwave in July 2019 was caused by subsidence rather than advection [25].

Health impacts and heat-related mortality are predicted to increase as the frequency, duration and intensity of heatwaves increase [26-27]. In recent decades, UK heatwaves have caused thousands of excess heat-related mortalities [28-29]. Once a heatwave has started, there is only a short window for action as "unlike cold weather, the rise in mortality as a result of very warm weather flows very sharply, within one or two days of the temperature rising" [30] (p6). As a result, there are relatively more impacts occurring during the first 24-48 hours of the temperature increase than during cold weather [31-32]. Heatwaves particularly impact on the health of those who are vulnerable [33] with outcomes ranging from dehydration to heatstroke and death [26]. The highest vulnerability is in the elderly, especially those with pre-existing medical conditions such as cardiovascular diseases and respiratory illnesses [34] although children [35] and other age groups can be affected particularly in hot countries [36].

Heat-related mortality occurs under environmental conditions where the human body is unable to maintain stable core body temperature. This vulnerability is a function of humans' upper physiological limit to heat which sets an upper limit to the adaptation levels of humans to future

climate-change impacts [37]. Humans maintain a core body temperature near 37 °C that varies minimally among individuals but does not adapt to local climate [38]. Critically, the human skin temperature has to be regulated at 35 °C or below as the skin must be cooler than body core for the effective conduction of metabolic heat to the skin [39]. Sustained skin temperatures above 35 °C cause hyperthermia which can be lethal if skin temperatures reach 37- 38°C even for acclimated individuals [40]. As heat-related mortality occurs predominantly because humans are unable to cool themselves, they cannot simply be attributed to the deaths of those who were going to die from illness or old age in immediate future [41]. Other claims, such as the suggestion that any increase in heat-related mortality will be offset by a decrease in cold-related deaths in temperate areas such as Europe, east Asia and Australia are also untrue [42]. Whilst mitigation strategies to limit greenhouse gas emissions are projected to reduce heat-attributable mortality [42], these strategies will have to be ambitious as stabilising current atmospheric greenhouse gases will not stabilise global mean surface temperatures [43].

In response to the 2003 European heatwaves which exceeded 70,000 deaths [44], the Department of Health in England set up the Heatwave Plan for England in 2004, which is updated yearly to integrate the learning and observations from the previous summer [30]. It predominantly aims to support the National Health Service (NHS) and local authorities by providing advice and guidance on how to prepare and respond to heatwaves [30]. An integral part of the Heatwave Plan for England is the Heat-Health Watch alert system which operates between June 1st and September 15th. During this period, the Met Office issues alerts corresponding to the level of risk of a heatwave and trigger a range of short-term protective measures [45, 30]. These alerts are based on a series of trigger temperatures (both daytime and night-time) which relate to a growing risk of impacts on health. Level 1 is the default setting which denotes that the heatwave and summer preparedness programme is in operation. Level 2 indicates a heatwave is forecast and an alert and readiness status are set. Level 3 signifies that heatwave action is activated and, finally, level 4 declares that an emergency response is implemented [30].

One key component of the Heatwave Plan for England is the PHE Heatwave mortality monitoring report which is based on the cumulative excess above the expected number of all-cause deaths registered weekly in England during a heatwave [23]. It uses data from the weekly provisional figures on deaths registered in England and Wales and is calculated using the upper 2 z-score threshold after correcting the ONS data for reporting delays using the standardised EuroMOMO algorithm [46]. The ONS data used in the PHE reports are broken down into age groups and regional areas which is only available from the deaths registered weekly database [47] and not the daily death occurrence database [48]. Excess mortality is broadly detected by subtracting the expected deaths (based on a five-year average) from the registered deaths.

As the impact of heat on mortality varies each year, it is useful to undertake an annual retrospective look at the heat-mortality relationship. Previous studies on excess mortality in the UK have used death registration data from the ONS Quarterly Mortality database [49, 29, 32, 28]. However, between 2001-2018, the median time between death occurrence and registration in England and Wales has increased from 2 to 5 days [50]. In addition, there has been a sharp rise from 8.7% to 14.5% in deaths registered one to weeks late and a rise of 1.8% in death registered two to three weeks late [50]. Studies based on daily death occurrences are lacking even though they indicate more reliably when deaths are at their highest and can be related to other factors such as climate [51].

Historically, data on daily death occurrences from the ONS Quarterly Mortality database have been problematic which may explain their lack of use in studies. The issue was that the date used to extract the death occurrences and compile the Quarterly Mortality was fixed to ensure each dataset had a similar extraction date [51]. However, this meant the datasets were effectively frozen in time despite being used to calculate the five-year average baseline for the ensuing four years for the

purposes of calculating excess deaths. There is, to our knowledge, no other database with daily death occurrences other than the Quarter Mortality. As a result, any unreliability due to the extraction date could persist and impact findings up to four years after their publication. However, from April 2019, this statistical limitation was removed to ensure the data could be more up-to-date [51]. With this, came the discovery of the impact of this practice on the mortality data as the wholesale update of daily death occurrences on the ONS Quarterly Mortality database (post April-June 2019) revealed significant discrepancies. For instance, death occurrences on 30 June 2018, was changed from 1,149 in Quarterly Mortality database of Q3 2018 to 1,250 in the Quarterly Mortality database of Q3 2019, a discrepancy of 101 deaths [48]. This has revealed a gap in existing knowledge as an analysis of the heat-temperature relationship using reliable daily death occurrence data has not yet been undertaken. In order to contribute towards filling this gap, this paper has sought to evaluate the impact of the 2019 heatwaves on mortality and compare this impact to the impact of the heatwaves of 2017 and 2018 on mortality using this hitherto unavailable data.

The need for this study is particularly pertinent as a report evaluating the Heatwave Plan for England concluded that there is no evidence of a substantial change in the general summer relationship between temperature and mortality since the introduction of the Heatwave Plan for England in 2004 [52]. This is a potentially problematic as the report did not evaluate the accuracy of the PHE Heatwave mortality monitoring report produced annually by PHE.

Equally, this study is a timely for two other reasons. Firstly, the last study into the impact of heatwaves on mortality focused on the 2013 heatwaves [28] even though 2018 and 2017 were two of the hottest ten years in the UK and collectively had six heatwave periods [17]. The reason for that is likely to be that the PHE Mortality Monitoring report was commissioned to undertake this task, however, these reports have not yet been independently evaluated. Secondly, the significance of this paper is heightened due to the impact of COVID-19 on mortality rates. Both COVID-19 and heat-related mortality impact similar groups, such as the elderly and those with cardiovascular and respiratory disease [53]. Thus, the distinction between deaths attributable to heat and COVID-19 is likely to be problematic. The figure published for the 2020 PHE Heatwave mortality monitoring report bears witness to this (Figure 1) [23]. In addition to the degree of complexity displayed, the report uses a completely different methodology making any comparative analysis of the heat-mortality relationship using this data of low utility (PHE 2020a).

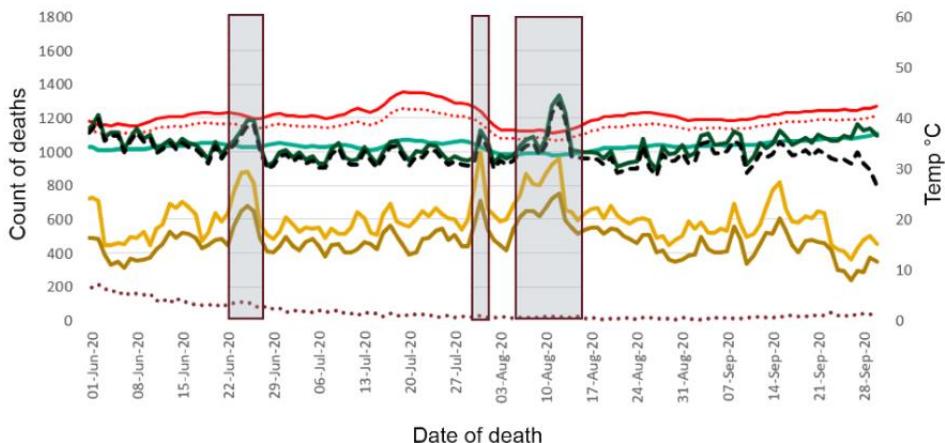


Figure 1: All-cause excess mortality in 65+ years group during the 2020 summer period. The shaded areas highlight periods which meet PHE heatwave criteria for estimating heatwave excess mortality. From top to bottom these are:

- solid and dashed red lines (3 and 2 standard deviation thresholds)
- dark green solid line (daily corrected mortality count)

- black dashed line (observed mortality counts)
- light green solid line (baseline mortality count)
- solid light gold line (maximum CET)
- solid dark gold line (average CET)
- purple dashed line (COVID-deaths) [23]

The objectives of this study are threefold. First, we aim to determine the excess death attributable to the three heatwaves in 2019 relative to the five-year average. Second, we aim to compare heat-mortality deaths during the 2019 summer period to the heat-mortality deaths during heatwaves in the 2017 and 2018 summer period. Third, we aim to compare the excess daily death occurrences found in this study to the excess registered deaths estimated in the PHE Heatwave mortality monitoring reports of 2017, 2018 and 2019.

## 2. Materials and Methods

The definition of a study period and heatwave period corresponds with the definitions used by the Heatwave Plan of England [30]. Accordingly, the study period coincides with the period of summer preparedness and long-term planning which is 1 June to 15 September and a heatwave period is defined as a period of days when:

- a) the Met Office issue a Level 3 heatwave alert in any part of the country, or
- b) the mean Central England Temperature (CET) is greater than 20°C, and

one day before or after the days identified through a) and b) above. The day before helps to include the impact linked to the initial increase in temperature and the day after helps to capture the delay from temperature to impact on mortality [28].

The daily CET from 1 June to 15 September, for the years 2014 to 2019, was extracted from the CET daily series database [54]. The latter is the weighted mean temperature derived from the mean of three observing stations (Lancashire, London and Bristol) which covers a roughly triangular area and is corrected for a small effect of urban warming [55]. It is kept up to date by the Climate Data Monitoring section of the Hadley Centre, Met Office.

The mortality data were extracted from the Quarter Mortality database of the ONS for daily occurrence deaths in England occurring from 1 June to 15 September for the period 2014 to 2018. These data straddled the Q2 and Q3 Quarterly Mortality 2019 database [48]. As found in the literature review, death occurrences are more date specific than death registrations for the purpose of relating the mortality data to other factors such as weather patterns [51]. All datasets exclude non-residents and deaths with an unknown day of death [51].

Excess mortality was calculated for the heatwave periods using a time-series regression analysis which requires the modelling of a baseline of expected levels of mortality. This baseline of expected deaths represents the variability in deaths and was determined by finding the average daily death occurrences for the same study periods in the preceding five years [56]. The difference between the expected deaths using the baseline and the observed deaths is termed the 'excess' [28]. This excess death data is used to test for a relationship between high temperature and mortality.

A time series graph was plotted showing the data for the daily number of all-cause death occurrences, the daily mean and maximum CET over the study period for the year 2019 and the average of 2014 to 2018 as well as a seven-day moving average to smooth the data. The number of death occurrences over each heatwave period was treated as a Poisson variable and 95% confidence intervals (CI) for this value were compared to the expected values to find confidence limits for excess mortality.

The results were compared to the heat-related mortality during the heatwaves of the summer periods of 2017 and 2018 using the same method and also to the estimated mortality in the PHE Heatwave mortality monitoring reports from 2017 to 2019. Graphs showing excess deaths across the summer periods for 2017 to 2019 and showing the variability in temperatures across the study period were also analysed.

### 3. Results

The summer period of 2019 saw three heatwaves with two defined by virtue of Level-3 heatwave alerts issued by the Met Office and one heatwave defined from the mean CET when the CET was greater than 20°C [28,17].

During the brief, 28 to 30 June heatwave, a peak mean CET of 30.6°C was observed on 29 June 2019 (Figure 2). The total number of deaths for the three-day period was below the five-year average for 2014 to 2018 so there were no excess deaths during this period (95%CI -508 to 134) (Table 1.1). The wide confidence interval suggests this finding has a low statistical significance. The Summer 2019 PHE Heatwave mortality monitoring report also detected there were no excess deaths for this period [23].

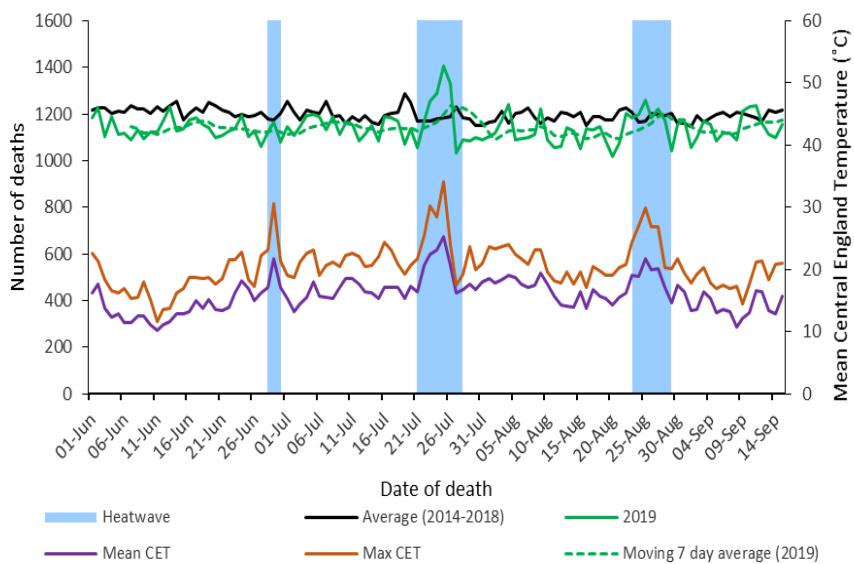


Figure 2: Comparison of observed and expected daily mortality in England in Summer 2019 relative to mean CET. Daily number of deaths (green line) and 7-day moving average are compared to expected number (black line) with daily maximum Central England Temperature (°C, brown line) and daily mean Central England Temperature (°C, purple line) during the summer period of 2019. The shaded blue area highlights periods which meet the PHE heatwave criteria as defined in Green et al. 2016.

During the longer, 21-28 July heatwave, a peak mean CET of 34.1°C was observed on 25 July 2019 which recorded 222 excess deaths, the highest number for any heatwave day in 2019 (Figure 2). However, cumulatively during that heatwave period, there was only an excess of 161 deaths (95% CI -751 to 1,053) (Table 1.2). The very large interval width again suggests the finding is not statistically significant. Nonetheless, the finding of 161 excess deaths was 3 times lower than the excess deaths (572) detected in the 2019 Heatwave mortality monitoring report [23].

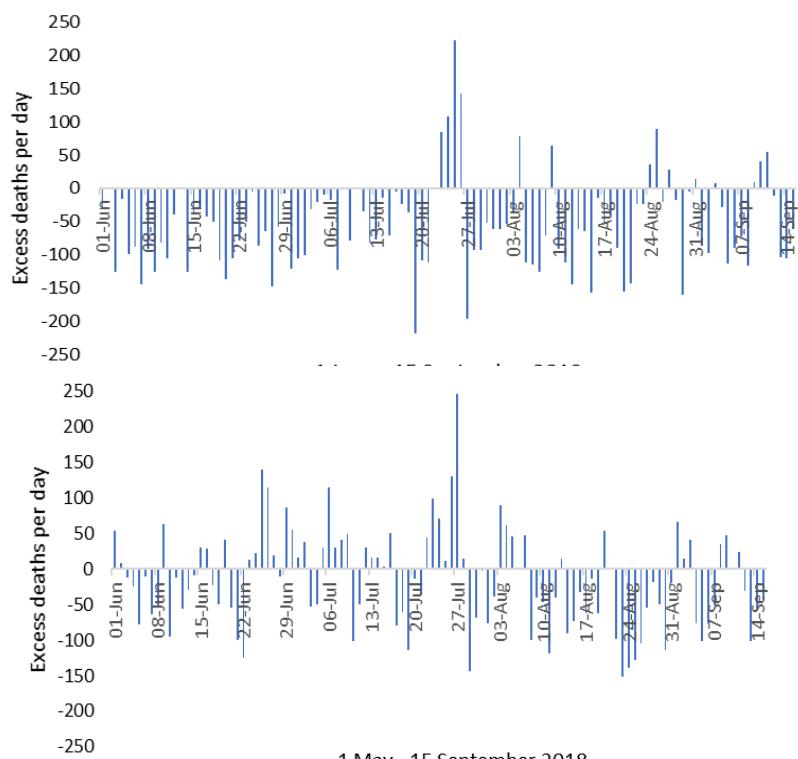
During the final, 23 to 29 August heatwave, a peak mean CET of 29.9°C was observed on 25 August which recorded 90 excess deaths, the highest for that heatwave. However, the cumulative number of deaths for the entire seven-day period was below the five-year average for 2014 to 2018 resulting in no overall excess death figure during this heatwave. In contrast, the PHE Heatwave mortality monitoring Report estimated 320 excess deaths during this heatwave.

Table 1.1. Summer 2019 heatwave periods, the corresponding five-year average of death occurrence for the same period and the excess number of deaths with 95% confidence intervals.

Heatwave period	Average deaths 2014-2018	95% Confidence limits	Total deaths	Total excess deaths	95% Confidence limits	PHE Heatwave mortality monitoring excess deaths
June 28-30	3,556	3048 to 3690	3,369	0	-508 to 134	0
July 21-28	9,471	8,720 to 10,500	9,632	161	-751 to 1,053	572
Aug 23-29	8,334	7826 to 8708	8,267	0	-508 to 374	320
Total	17,805		17,899	161		892

Accordingly, the total impact on mortality of the Summer 2019 heatwaves was estimated at 161 excess deaths which was 731 deaths less than the total 892 excess deaths estimated in the 2019 PHE Heatwave mortality monitoring report. Whilst acknowledging statistical limitations to these findings, there is a clear disparity.

The overall pattern of excess deaths across the 2019 summer period is distinctive to the patterns of excess deaths for the 2018 and 2017 summer periods (Figure 3). The main distinction is that there were relatively fewer days with detectable excess deaths. In addition, there are steep decreases in excess deaths into negative values immediately before and after the hottest day on record, 25 July. For the entire 2019 summer period, there is a cumulative total of 122,257 deaths for 1 June to 15 September 2019 which is significantly lower than the five-year average of 128,087 deaths. This is visually apparent in Figure 3. This is visually apparent in Figure 3.



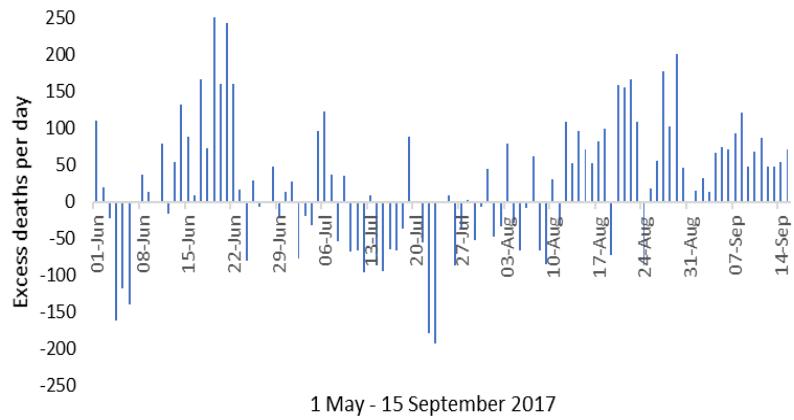


Figure 3: Daily excess deaths during the Summer period (1 June to 15 September) for 2017, 2018 and 2019 based on daily death occurrences. The negative excess deaths refer to days when death was lower than expected relative to the previous five-year period.

The excess deaths measured for the 2018 and 2017 heatwaves were equally revealing. In contrast to the finding of 161 excess deaths during the 2019 heatwaves, the analysis of the 2018 heatwaves, using the same methods, resulted in a notably, high cumulative excess death total of 1,700 (Table 1.2). This was broken down over four heatwave period, spanning 31 days in total, with the highest number of excess deaths during the third heatwave period, 21-29 July, when there were 645 excess deaths (95%CI -508 to 374). The other three heatwaves recorded 188, 266 and zero excess deaths for the heatwave periods, June 25-27, June 30-10 and August 2-9 respectively. The finding of 1,700 excess deaths for the entire summer period is 922 higher than the estimated 863 excess deaths in the summer 2018 Heatwave Mortality monitoring report. Thus, the PHE Heatwave mortality monitoring reports overestimated excess deaths by 731 in 2019 but underestimated excess deaths by 922 in 2018 (although statistical significance was again problematic) (Table 1.2).

Table 1.2. Summer 2018 heatwave periods, the corresponding five-year average of death occurrence for the same period and the excess number of deaths with 95% confidence intervals.

Heatwave period	Average deaths 2013-2017	95% Confidence limits	Total deaths	Total excess deaths	95% Confidence limits	PHE Heatwave mortality monitoring excess deaths
June 25-27	3,755	3,844 to 4,389	4,117	362	89 to 634	188
June 30- July 10	14,080	14,056 to 15,015	14,538	458	-24 to 935	266
July 21-29	11,206	11,127 to 12,575	11,851	645	-79 to 1,369	409
Aug 2-9	10,053	9,808 to 10,788	10,298	235	-255 to 725	0
Total	39,094		40,804	1,700		863

Repeating the same process for the heatwaves in 2017, the total number of excess deaths over the two heatwaves was 1,489 (Table 1.3). This was broken down over two heatwave periods, spanning only 10 days in total. The first heatwave period, 17-23 June, had 1,113 excess deaths (95%CI -508 to 374) which was the highest number for a single heatwave across the 2017-2019 summer periods (Table 1). The second heatwave period, July 5-7, recorded 180 (95% CI 196-556). Across the entire summer period, the finding of 1,489 excess deaths is 711 excess deaths higher than the estimated 778 deaths in the summer 2017 PHE Heatwave mortality monitoring report.

Table 1.3. Summer 2017 heatwave periods, the corresponding five-year average of death occurrence for the same period and the excess number of deaths with 95% confidence intervals.

Heatwave period	Average deaths 2012-2016	95% Confidence limits	Total deaths	Total excess deaths	95% Confidence limits	PHE Heatwave mortality monitoring excess deaths
June 17-23	8,216	8,730 to 9,928	9,237	1,113	514 to 1,712	598
July 5-7	3,528	3,724 to 4,084	3,904	376	196 to 556	180
Total	11,744		13,141	1,489		778

Over the entire 2017 summer period, there were relatively more days with excess deaths compared to both 2019 and 2018 (Figure 3). Equally, 2017 recorded the highest death figure (129,998) for the entire summer period compared to 2018 (124,609) and 2019 (122,257). The contrasting graphs in Figure 3 demonstrate a contrasting relationship between heat and mortality over the three heatwave period, whilst not discounting the fact that the relationship is only correlative rather than causative.

A similar broader view of the temperatures for the summer periods 2017, 2018 and 2019, demonstrate that the temperatures for 2019 were generally lower than 2018 and 2017 with short spikes for the heatwave periods and a significant spike for 25 July 2019 when the all-time highest recorded temperature of 38.7°C was measured at Cambridge University Botanic Garden (Figure 4) [17].

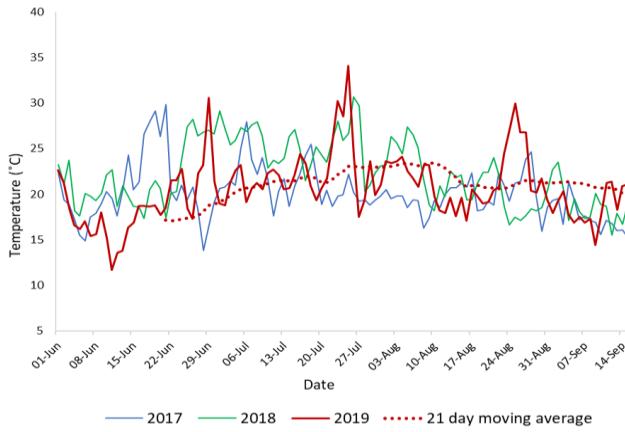


Figure 4: Maximum temperatures during the Summer period (June 1 to September 15) for 2017, 2018 and 2019

#### 4. Discussion

A retrospective analysis of the 2019 summer period was carried out to quantify excess mortality during the three heatwaves and to specifically compare these findings with excess mortality during the heatwaves in 2018 and 2017. The cumulative excess deaths for the three heatwave periods in 2019 were low (161) and was not statistically significant. The longer heatwave periods in 2018 and the more intense heatwaves in 2017 had significantly more excess deaths (1,700 and 1,489 respectively). All findings were significantly at variance to the excess deaths recorded in the PHE Heatwave mortality monitoring reports which are asserted to only include persons over 65 years old and should therefore be an underestimate of the figure for the whole population [23]. The reasons for these findings are not clear, however, several explanations are offered.

A similar linear regression model was used in this study and in the PHE study and both studies calculate excess mortality based on the cumulative excess above the expected number of deaths. The main difference between the methodologies is the use of provisional deaths registered weekly in the PHE Heatwave mortality monitoring reports which contrasts with the use of daily death occurrences in this study. As discussed in the literature review, the difference between using registered deaths and death occurrences can be significant. This is visually demonstrated in Figure 5 where death registrations and death occurrences for the 2019 summer period were compared. Daily data on death occurrences in England are only available in the Quarter Mortality database.

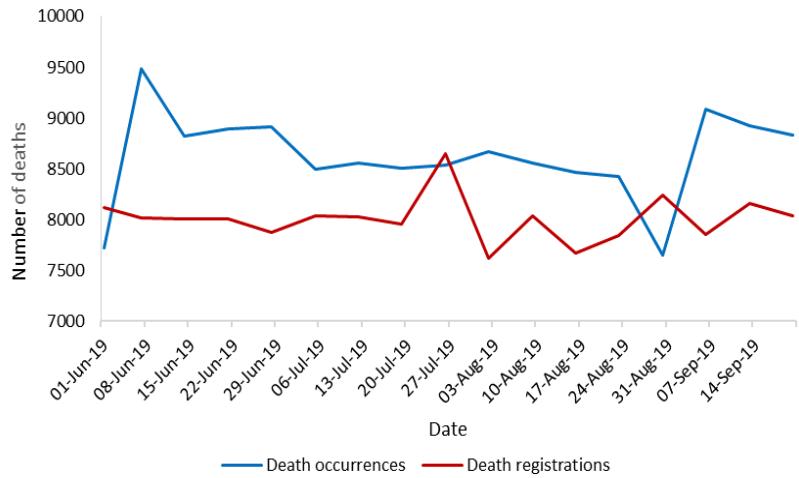


Figure 5: Daily death occurrences (red line) compared to death registrations (blue line) for the period 1 June to 15 September 2019

Further investigation is advised to confirm whether the disparity displayed is accurate as the pattern suggests that any data analysis based on provisional death registrations would be unreliable. It is acknowledged that the excess deaths in the PHE reports are estimates as they are produced within one month of the end of the summer period, however, they are not updated at any later stage [23]. In contrast, this study used data which was updated regularly and provided the most reliable evidence to test for a heat-mortality relationship.

Data before 2020 will be of inestimable value when considering heat-mortality relationship as data post-2020 will be contaminated by excess deaths from COVID-19 for, at least, 2-3 years. Indeed, the impact of COVID-19 on excess death figures may last longer as “long COVID” may become a new respiratory disease which may continue to make inferences of excess deaths due to heat problematic for many years beyond 2020.

The recently released 2020 PHE Heatwave mortality monitoring report [23] states the “Cumulative excess all-cause mortality related to heatwaves in summer 2020 was the highest observed since the introduction of the Heatwave Plan for England” [23]. It is not the remit of this study to analyse the 2020 heatwaves, however, this study does suggest that to estimate heat-related excess deaths for the 2020 summer period is problematic for several reasons. Firstly, to rely on death certificates to identify deaths attributable by COVID-19 would be unreliable due to widespread lack of testing of COVID-19 in large parts of the population during the 2020 summer period. Secondly, the 2020 report changed the methodology used to calculate heat-related excess deaths by comparing deaths on heatwave days to deaths on non-heatwave days before and after the heatwaves days to take account of COVID-19 [23]. However, this does not take account for the fact that deaths increase as temperature increases prior to actual heatwave days and people vulnerable to COVID-19 are also vulnerable to heat-related mortality. This makes using the pre-heatwave period as a baseline problematic and we suggest that it is not possible to separate the contribution of COVID-19 or heat to a particular death as the conditions would interact to some degree. This study suggests an estimate of heat-mortality during the 2020 summer period would be unreliable whichever methodology was used. The 2020 PHE Heatwave mortality monitoring report recognises this issue but nonetheless suggests that there were 2,556 excess deaths (95% CI 2,139 to 2,926) over and above COVID-19 deaths during the summer period were heat related.

In light of these observations, an evaluation of the operation of the PHE Heatwave mortality monitoring reports would be valuable to determine their reliability. This would provide stronger evidence as to whether there has been a substantial change in the general summer relationship between temperature and mortality since the introduction of the Heatwave Plan for England in 2004, as suggested in its recent evaluation [52]. This is made more pertinent by the fact that the last study on excess mortality during heatwaves in England, which analysed mortality during the 2013 heatwaves, also recorded a lower than expected mortality rate [28].

The findings that there were a low number of excess deaths during the 2019 heatwaves corresponds with the observation that 2019 heatwaves were relatively short-lived and periods of high temperatures throughout the summer were relatively short (Figure 4). In fact, the entire 2019 summer period was relatively showery, unsettled and cold as low pressure often dominated. As a result of these conditions, there was only a modest July temperature anomaly of +1.2°C [17]. Further studies could usefully consider whether unsettled, changeable weather (regardless of the temperature) affected the heat-mortality relationship.

In response to the study's objectives, the findings demonstrate that the impact of heatwaves on mortality in 2019 was low (both relative to the five-year average and relative to the excess mortality during the 2018 and 2017 heatwaves). Furthermore, the excess death findings in this study were substantially different to the majority of findings in the 2017-2019 PHE Heatwave mortality monitoring reports. Issues have been identified in the use of provisional death registrations for mortality monitoring and the potential for increased reliability through the use of daily death occurrences.

On a broader scale, the significance of heat-related mortality studies in relation to future projections is often constrained as they are often based on an assumption that the exposure-response relationship between temperature and mortality will remain the same [42]. Studies examining the exposure-response relationship consider this unlikely [57], in particular, studies in France and New York have reported improving resilience of the population to heat-related events [58-59]. Thus, simple extrapolation of data to identify relationships with higher temperatures without considering adaptation could be unreliable [60]. This has also been demonstrated by longer retrospective studies which have observed that there has been a decrease in the vulnerability of populations to heat across a number of decades [61]. This decrease exceeds anything expected from a physiological acclimatisation to a changing climate [62], which suggests that non-climate factors such as public health strategies to mitigate heat-related mortality may be a factor.

There are limitations to this study which could be addressed in future studies. For instance, there is evidence that most heat-related deaths take place outside the heatwave alert periods [52], particularly in the case of deaths from respiratory and cardiovascular failure as these deaths often take place in the days after a heatwave and they are also difficult to attribute to heat [9]. These difficulties may lead to an under-reporting of heat-related mortality. This raises questions such as whether the thresholds for the heatwave alerts should be decreased to increase the timespan of the examined heatwave period. This would correspond with studies that suggest lower or higher temperatures leading up to a heatwave have a significant impact on excess mortality [63]. Alternatively, an evaluation of heat-related mortality over the entire summer period would bring a more contextual understanding of the relationship between heat and mortality and may lead to a more nuanced understanding of the implications of higher temperatures in the future. Another difficulty of analysing specific heatwave period is that there is no universal definition for a heatwave which makes reliable comparisons between heatwave mortality studies problematic [64].

There are other recognised factors which could potentially impact heat-related mortality other than heat, for instance, the baseline used, the relative population size or the size of vulnerable groups present in the population such as those with socio-demographic markers or pre-existing conditions [65-66]. It is also recognised that heat-related mortality is higher in urban areas [67], however, this study was unable to account for this as daily death occurrences do not have this sensitivity. Likewise, the daily death occurrences data are not broken down by age or region unlike the registered deaths data.

At a statistical level, the timely recording of the date of death is essential to attribute a death to raised temperatures, however, the practice of General Practitioners who certify deaths can play a role in undermining this reliability. For instance, GPs frequently do not accurately record the date of death especially if it takes place over a weekend [68]. One retrospective study of over 100,000 deaths between 2011-2015 suggest there is a lack of concordance between national mortality records and date of deaths in primary care in 23.2% cases [68]. These practices would clearly adversely affect the reliability of a database.

Correlation between excess deaths and increased temperature do not directly attribute a death to an increase in temperature. Instead, this study indirectly identifies excess deaths by detecting unexpected death, which is problematic as factors other than temperature may be responsible for variation in mortality [28]. For instance, air pollution levels are predicated to change regionally as a result of climate change [69] and time periods with higher air pollution have been observed to have a higher heat-related mortality [70]. There are also other heat stress metrics such as humidity which impact mortality. Sweating is the main physiological coping method for heat stress as sweating helps to reduce body temperature by evaporative cooling, therefore, humidity inhibits sweating. As a result, days with higher humidity have been observed to have higher heat-related mortality [38]. Further work is advised on the relative impact of air pollution and humidity on heat-attributable mortality in England during heatwaves and over the summer period generally.

## 5. Conclusions

As climate change continues, accurate and reliable data on cumulative excess deaths during heatwaves are essential to draw up effective adaptation policies. The finding that deaths are significantly lower during relatively showery, unsettled and cold summers may be useful in future evaluations of the Heatwave Plan for England and also for other countries that have adopted heatwave plans [71-72]. This is the second time a lower than expected excess death was found during a heat-related mortality study. [28]. This study, therefore, calls for further research into reasons for lower excess mortality during heatwaves which will help to refine adaption policies and better predict the public health impact of increasing global mean temperatures as a result of climate change.

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