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Mortality benefit of building adaptations to protect care home residents against heat risks in the context of uncertainty over loss of life expectancy from heat

Andrew Ibbetson [a,1], Ai Milojevic [a], Anna Mavrogianni [c], Eleni Oikonomou [c], Nishesh Jain [c], Ioanna Tsoulou [c], Giorgos Petrou [c], Rajat Gupta [b], Michael Davies [c], Paul Wilkinson [a,*]

[a] *London School of Hygiene & Tropical Medicine, United Kingdom*
[b] *Oxford Brookes University, United Kingdom*
[c] *University College London, United Kingdom*

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ABSTRACT

We explore methodological issues core to the cost-benefit evaluation of building adaptations designed to protect against heat risks to residents of care homes in England in the context of the uncertainties relating to the loss of life expectancy in heat death. We used building physics modelling to quantify the impact of external window shading on indoor temperatures. We calculated associated heat mortality and loss of life expectancy under three sets of assumptions of life-shortening based on: (Method 1) an England & Wales (E&W) life-table, (Method 2) E&W life-table scaled to match observed average survival of care home residents and (Method 3) assuming that those dying of heat have a life expectancy of six months. External window shading was estimated to reduce mean indoor temperatures by 0.9 °C in a 'warm' summer and 0.6 °C in an 'average' summer. In a care home of 50 residents, the heat deaths and years of life lost (YLL) averted by such shading were estimated by the three life-expectancy assumptions (Methods 1, 2, 3) to be: 0.07, 0.47 and 0.28 heat deaths and 0.29, 0.76 and 0.14 YLL for the warm year and 0.05, 0.31 and 0.19 heat deaths and 0.20, 0.51 and 0.10 YLL for the average year. Over a 20-year time horizon and assuming an annual discount rate of 3.5%, the monetized benefit of reduced YLL would be around £90,000, £230,000 and £44,000 with the three life-expectancy assumptions. Although this range represents appreciable uncertainty, it appears that modest cost adaptations to heat risk may be justified in conventional cost-benefit terms even under conservative assumptions about life expectancy.

1. Introduction

Age is one of the most important risk factors for heat-related mortality and morbidity (Arbuthnott and Hajat, 2017). There is also direct epidemiological evidence that the elderly residents of care homes are especially vulnerable during periods of high ambient

* Corresponding author at: PHES, London School of Hygiene & Tropical Medicine, 15-17 Tavistock Place, London WC1H 9SH, United Kingdom.
E-mail addresses: andrew.ibbetson@helsinki.fi (A. Ibbetson), paul.wilkinson@lshtm.ac.uk (P. Wilkinson).
[1] Current address: University of Helsinki.

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temperature, not only because of their age but also because of frailty relating to their underlying health status (Hajat et al., 2007). Measures to protect against the heat risks of care home residents include both actions by carers and adaptations to care home buildings to make them less prone to overheating during hot weather (Bolitho and Miller, 2017; Macintyre et al., 2018; Porritt et al., 2011, 2012).

Decisions over such building adaptations would conventionally be informed by calculation of cost-benefit. However, the life expectancy of elderly care home residents is comparatively short and hence the valuation of gains in life years consequent to such adaptation measures is likely to be small (Forder and Fernandez, 2769). Furthermore, those dying of heat might have shorter life expectancy than average as there is evidence that those with pre-existing illness are more vulnerable to the effects of heat (Arbuthnott and Hajat, 2017; Faunt et al., 1995; Vandentorren et al., 2003). The degree of life shortening in heat death has been an issue of epidemiological debate and remains uncertain. Although recent analyses have suggested that loss of life in heat death is likely to be at least a year in the population as a whole (Armstrong et al., 2017), the degree of life shortening may vary between populations and by age and cause of death (Hajat et al., 2005). It is probably very different in a frail care home population with underlying chronic disease than it would be in children in lower income settings, where infectious disease may be an important factor, for example (Hajat et al., 2005). For the oldest care home residents, life expectancy may often not be as long as a year.

If heat death-related loss of life expectancy is indeed short in frail care home residents, this may represent a challenge for the justification of building adaptations in cost-benefit terms when the principal monetized health benefit of heat adaptations is reduced mortality. In this paper, we examine the influence of different assumptions about the degree of such life-shortening and the implications for the assessment of the cost-benefit of building adaptations aimed at protecting care home residents against heat risk in England and Wales (E&W).

2. Methods

Our assessment is based on four components: the estimation of mortality risks and life expectancy for care home residents; the derivation of the heat attributable mortality from weather data and published temperature-mortality relationships; the assessment of the modification of these risks and life years lived by modelling the impact of building adaptation on temperature exposure during hot weather; and the valuation of the health impact of these building adaption measures in monetary terms.

2.1. *Mortality risks and life expectancy of care home residents*

Because of uncertainties about the life expectancy of care home residents and, specifically, of those at greatest risk of heat death, we use three methods for computing mortality and life expectancy.

(1) Method 1 is based on using current (2018) E&W life table for all people aged 65 + years constructed from mortality and population statistics published by the Office for National Statistics (Office for National Statistics. Deaths registered in England and Wales., 2018; Office for National Statistics. Analysis of population estimates tool. Estimated population change for England and Wales, by geography, age and sex. Mid-, 2020). These data are dominated by statistics of people living in the community, not in care homes, and using them thus represents an underestimate of mortality risk in that the residents of care homes almost certainly have a higher risk of mortality than people of similar age living in their own homes. We show calculations based on these data as a lower boundary of the mortality rate and hence of heat mortality for the care home population. But having a low mortality rate also implies a relatively long life-expectancy of those who die of heat death.

(2) Method 2 makes use of data on care home residents published by Forder and Fernandez (Forder and Fernandez, 2769) on length-of-stay in care homes. We assume most care home residents remain in care until death and thus use this length-of-stay estimate as a proxy for time to death. Their data indicate an average of 880 days (2.41 years) as the mean for a care home resident. Our calculations indicate that an age-weighted average life expectancy of 880 days (2.41 years) based on the distribution of age at death in E&W is achieved if the general population age-specific rates of death in the 65 + age-group are multiplied by a factor of 6.7. Hence, for Method 2 calculations, we used the same E&W lifetable as Method 1 but with age-specific mortality rates multiplied by 6.7 to match the higher death rates in care home residents.

(3) Method 3 is based on the assumption that all who die of heat are frail residents with an average life expectancy of 6 months, regardless of age. This is an arbitrary choice designed to represent a lower limit estimate of the length of life shortening, but we use it as a probably conservative assumption for loss of life expectancy for each heat death to calculate the likely minimum saving of life expectancy if only extremely frail residents have appreciable risk of heat death. To attain a life expectancy of just 6 months requires an underlying mortality rate of approximately 17% *per month*, which means that 85% of such at-risk residents would die within 12 months and almost all within 24 months. We partitioned the residents into those in this at-risk pool and all others into a lower mortality risk pool (not at-risk of heat death) with longer life expectancy. To be consistent with the overall mortality statistics, we specified that, for each age-group, the overall age-specific mortality rate (the average of the at-risk group and of the non-at-risk group) should match that of Method 2. The mortality rate (and hence life expectancy) in the lower risk group was adjusted accordingly. This ensured the calculations under Method 3 are consistent with observed survival in care homes. We also had to specify the proportion of care home residents in the at-risk group at each age. Calculations with the life table showed that, at age 65 years, the at-risk group with 6 months life expectancy could be no more that 2% of residents if the overall mortality rate was to match observed mortality rate for care home residents. We used this estimate of 2% for age 65 and assumed that the proportion in the at-risk group rose with age in proportion to the increase in underlying mortality. This yielded an estimate of the proportion of residents in the at-risk group by age 90 + years of 39% in men and 54% in women.

2.2. Estimating heat-related mortality and morbidity

We computed heat-related mortality for the study year by assuming a log-linear ‘hockey stick’ temperature-mortality relationship based on data published by Hajat et al. (2007) which indicates greater susceptibility to high outdoor temperatures among care home residents. Their published results do not provide a precise specification of the relationship for care home residents but is broadly consistent with a relative risk of 1.05 for each degree Celsius increase in daily mean temperature above a heat threshold of 17 °C based on a lag of 0–1 days.

For temperature distributions, we used the “Design Summer Year 1” (DSY1) and “Test Reference Year” (TRY) datasets published by the Chartered Institution of Building Services Engineers (CIBSE) for London Heathrow under the 2020 s high emissions, 50th percentile scenario (Chartered Institution of Building Services Engineers (CIBSE). CIBSE Weather Data Sets, 2016). The DSY temperature files are selected using published methods from meteorological records of the 30 year period, 1984–2013. (Chartered Institution of Building Services Engineers (CIBSE), 2016) DSY1 represents a moderately warm summer from this series, while TRY consists of the average of each month for the same period. We used DSY1 to represent the impact of a ‘warm’ summer in the mortality calculation and compared it to the effects of the ‘average’ summer captured by TRY. DSY1 was preferred for the modelling purpose of a warm summer since it has the lowest return period amongst the available DSY files and would thus likely be the most frequently occurring scenario. A weather file with a moderately cool summer was not available to indicate the smaller benefits in such a year.

For each day, i, of these temperature series, we computed the relative risk, RR_i, for heat mortality as:

$$RR_i = RR_{coef}^{(Tmean - Th,threshold)}$$

where

T_{mean} is the two-day (lag 0–1 days) mean outdoor temperature on day i
T_h is the threshold temperature for heat-related mortality
RR_{coef} is the relative risk (1.05) for a one degree Celsius increase in temperature above T_h.

From this we derived the daily number of heat attributable deaths as:

Heat deaths, day i $= \sum_{i,j} \frac{RR_i - 1}{RR_i} * D_j$ where D_j is the daily season-average age-and-sex-specific probability of death for person j. We assumed a distribution of men and women that reflects the distribution of deaths in the E&W population above 65 years. The age-and-sex-specific mortality rates were derived from the life tables for the three Methods 1–3 outlined above.

2.3. Effect of building adaptations

To assess the impact of building adaptation measures, we used a modification of an approach previously applied by Taylor et al. (2018) Its core assumption is that if a building adaptation changes the daily indoor temperature, then this will have an effect on mortality equivalent to moving an individual up or down the *outdoor* temperature-mortality function by a corresponding amount. Thus, if the building adaptation reduces the indoor temperature by 0.5 °C, we assume the effective outdoor temperature for that individual is also reduced by 0.5 °C.

To obtain an indication of the impact and cost of possible building adaptions, we simulated the effect of simple (low cost) adaptations in the form of external window louvres and side fins of 0.5 m projection to reduce solar gain and hence summer indoor temperatures using a building specification of an actual care home in London. The bespoke shading devices were adapted to the shading needs of each window according to its orientation and the level of overshadowing by neighbouring building blocks, thus minimising the shading material and associated installation costs. Following communication with UK shading suppliers a minimum all-inclusive cost of £300 per m^2 (including purchase, installation and paintwork, VAT excluded) was assumed, resulting to a weighted average cost per window of £332. This is likely to be reduced further with economies of scale and if a different material (e.g. timber) is used in the place of aluminium assumed here.

Indoor temperatures were modelled using a building physics dynamic thermal simulation model developed in DesignBuilder V6.0, a graphical user interface for EnergyPlus. We used the same temperature files DSY1 and TRY as were used for the calculation of heat-related mortality. (Oikonomou et al., 2020) EnergyPlus is an energy analysis and thermal load simulation engine tested against the International Energy Agency Building Energy Simulation Test and Diagnostic Method (IEA BESTEST) building load and ANSI/American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE) Standard 140. (U.S. Department of Energy’s (DOE) Building Technologies Office (BTO) and the National Renewable Energy Laboratory (NREL), 2020)

To derive the deaths and years of life lost (YLL) prevented by the building adaptation, we performed the daily heat deaths calculation with and without adjusting outdoor temperatures by an amount equivalent to the effect of the building adaptation on indoor temperature change. YLL were calculated as the number of heat deaths times the average life expectancy of those who died.

2.4. Monetization of health impact

Monetized health impact calculations are presented for a ‘typical’ care home of 50 residents, informed by evidence on the size and average occupancy of care homes (Competition and Markets Authority, 2017). We assumed shading adaptations would have a lifetime of 20 years, so used a 20-year time horizon for economic analysis. In line with National Institute for Health and Care Excellence

Table 1
Mortality rates, life expectancy (LE) and rate ratios for heat mortality by age-group under three assumptions of mortality risk in care home residents, England and Wales (E&W).

Gender	Age-group	Deaths distribution, E&W population		Rate of death and life expectancy using						Ratio of deaths in care homes to all E&W deaths	Relative risk for mortality per °C above heat threshold, lag 0–1 days
				(1) E&W life-table		(2) care home survival statistics		(3) 6 month life expectancy for at-risk group			
		Number	%	Rate /person-year	LE years	Rate /person-year	LE years	Rate /person-month	LE months†		
M	65–74	4,247	10%	0.0197	14.12	0.1323	5.23	0.167	6	0.081	RR = 1.05[#]
	75–84	13,280	32%	0.0568	7.44	0.3804	2.35	0.167	6	0.164	
	85+	24,360	58%	0.1782	2.04	1.1942	0.81	0.167	6	0.288	
	Total	41,887	100%								
F	65–74	3,521	5%	0.0132	15.54	0.0886	6.68	0.167	6	0.094	RR = 1.05[#]
	75–84	15,711	21%	0.0422	8.00	0.2826	2.95	0.167	6	0.221	
	85+	56,299	75%	0.1683	1.82	1.1279	0.84	0.167	6	0.426	
	Total	75,531	100%								

*Based on age distribution among all deaths of E&W.
†For at-risk group.
[#] 1.10 (men) and 1.07 (women) per °C above heat threshold in the 6-month life expectancy group.

recommendations, we used a discount rate of 3.5% per annum and each YLL was valued at £30,000 at current values (Guide to the methods of technology appraisal: National Institute for Health and Care Excellence (NICE), 2013). We did not make adjustments for the quality of life (utility value) of care home residents and nor did we attempt to quantify short-lived morbidity effects. For temperatures, we made the simplifying assumption that temperatures similar to the DSY1 year would apply one year in ten and all other years would have temperatures similar to those of the TRY file. This return period for DSY1 is greater than the CIBSE TM49 projections suggest under the high emissions scenario for 2011–2040 (Chartered Institution of Building Services Engineers. Design Summer Years for London - TM49:, 2014), but we chose ten years to be slightly conservative given that we did not have a corresponding cool summer weather file. Therefore, we calculate the total monetized value of years of life lost as:

$$\frac{Total\ benefit = \overline{b_{DSY1}} + \overline{b_{TRY}}*(rp-1)}{rp}$$

where:
$\overline{b_{DSY1}}$ and $\overline{b_{TRY}}$ are the average benefit across a 20-year time horizon in a DSY1 and TRY year, respectively.
rp is the return period (in years) of a DSY1 year.

2.5. Sensitivity analysis

We conducted a multi-way sensitivity analysis to evaluate the robustness of our results to changes of the following parameters: the return period of a ‘warm’ summer year; the monetized value of a life year; the annual discount rate; and the relative risk for heat-related mortality. Given that our choice of return period of a ‘warm’ summer year is conservative in the base case, we chose to examine the effect of a less conservative assumption of one in five years. For the monetized value of a life year, we explore the implications of using a value of £60 000 as an alternative to £30,000, in accordance with the value of a statistical life value used in the Green Book (Treasury, 2020). For the annual discount rate, we use a high value of 6% and a low value of 1%. In line with published confidence intervals for the relative risk for heat-related mortality (Hajat et al., 2007), we use an upper value of 1.06 and lower value of 1.04.

3. Results

3.1. Mortality rates and life expectancy

Table 1 summarizes the input data used for health modelling and the mortality rates and life expectancy figures by age-group for the three methods of life expectancy calculation.

Method 1, the E&W whole population life table, has an estimated life expectancy of 18.0 and 19.8 years in men and women respectively at age 65 years, 10.6 and 11.7 years in men and women at age 75, and 4.3 and 4.6 years at age 85.

The corresponding figures for Method 2 (E&W life table scaled to care home survival) are a life expectancy of 7.2 and 9.2 years in men and women at age 65 years, 3.5 and 4.6 years in men and women at age 75, and 1.35 and 1.69 years at age 85.

For Method 3, by our specification, the at-risk group vulnerable to heat death has a 6 months life expectancy at all ages.

Table 2
Summary of daily mean outdoor temperatures and intervention effect on indoor temperatures under modelling with DSY1 and TRY weather files.

		Weather file	
		DSY1 ('hot year')	TRY ('average year')
Outdoor temperature (°C)	Mean	18.4	17.3
	IQR	15.95, 20.75	15.95, 20.75
	Range	10.7, 27.9	9.6, 25.2
Intervention (shading) effect on indoor temperature (°C)	Mean	−0.90	−0.60
	IQR	−1.20, −0.61	−0.81, −0.37
	Range	−1.89, −0.17	−1.61, −0.09

Table 3
Impact of heat on deaths and life years for a care home of 50 residents: results for one year using DSY1 ('hot year') and TRY ('average year') weather files.

Weather file	Assumption for mortality and life expectancy	Average degrees Celsius per day above heat threshold, lag 0–1 days	Among 50 residents over summer months (MJJAS)			
			Expected number of heat deaths	Mean life years lost per heat death	Total life years lost due to heat	Monetized value of life years lost* (£)
DSY1 ('hot year')	E&W life table	2.20	0.24	4.18	0.99	29 800
	E&W life table scaled to care home survival		1.59	1.62	2.58	77 400
	6 months life expectancy for heat deaths		0.97	0.5	0.49	14 600
TRY ('average year')	E&W life table	1.33	0.15	4.18	0.62	18 600
	E&W life table scaled to care home survival		0.99	1.62	1.61	48 200
	6 months life expectancy for heat deaths		0.61	0.5	0.31	9 200

* – based on an assumed valuation of £30 000 per quality-adjusted life year (QALY)

3.2. Heat mortality

The temperatures of DSY1 and TRY weather files and the simulated associated change on indoor temperatures from the shading intervention are summarized in Table 2. Under DSY1, the average day in the summer period (months MJJAS) was 2.25 °C above the threshold for heat mortality, T_h, of 17 °C and 2.20 °C above T_h based on the lag 0–1 temperatures. The corresponding day average relative risk for heat death was 1.12 for Methods 1 & 2 and 1.20 for the at-risk group in Method 3.

Using the TRY temperature file, the average day was 1.38 °C above T_h (1.33 °C above T_h based on the lag 0–1 days temperatures). The corresponding average relative risk for heat was 1.07 for Methods 1 & 2 and 1.12 for the at-risk group in Method 3.

The expected number of heat deaths was highest for Method 2 assumptions on life expectancy (E&W life table scaled to care home survival) and lowest for Method 1 (E&W whole population life table) – Table 3. Although mortality risk among those at risk of heat death was highest under Method 3 assumptions (6 month survival in the at-risk group), the overall number of heat deaths was lower with these assumptions as the at-risk pool was a reduced proportion of all care home residents.

The total life years lost to heat death was highest for Method 2 calculations. The relatively long life expectancy of the E&W population meant that the life years lost to heat death were higher for Method 1 (based on the whole population E&W life table) than Method 3 (six months life expectancy) calculations using both DSY1 and TRY weather files – Table 3 and Fig. 1.

The estimated monetized value of all life years lost to heat for a care home of 50 residents ranged from just under £15,000 for Method 3, to close to around £77,000 for Method 2 using the DSY1 weather file, and close to £19,000 for Method 1 and almost £50,000 for Method 2 using the TRY weather file.

3.3. Monetization of the impact of shading

Building simulations suggest that our specified shading intervention would reduce daily mean indoor temperatures by 0.9 °C under DSY1 and 0.6 °C under TRY outdoor temperatures (Table 2). Fig. 2 shows the outdoor mean temperatures for the summer period and the outdoor temperature after subtraction of the intervention-related effect.

For a care home of 50 residents, such an intervention would reduce heat deaths by less than 0.47 during a DSY1 year and no more than 0.31 during a TRY year, with the estimates being highest for Method 2 calculations in both cases.

The monetized value of the corresponding saving of life years is relatively modest. For a care home of 50 residents, the highest estimate is around £23,000 for a DSY1 year and £15,300 for a TRY year based on Method 2 assumptions of life expectancy and

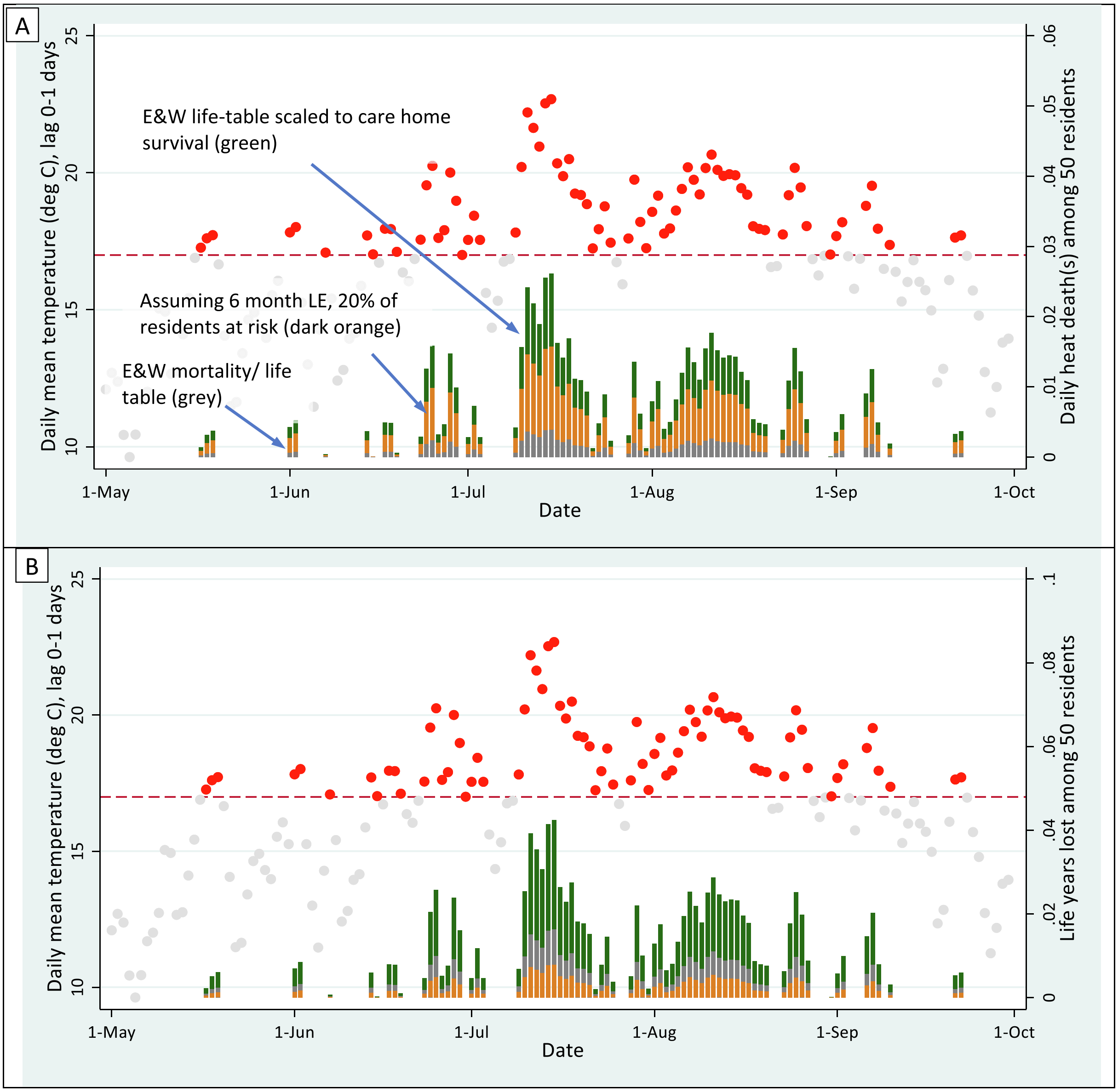

Fig. 1. Day mean temperatures (grey dots, red if above heat threshold for mortality) and [A] expected daily number of heat deaths in a care home of 50 residents and [B] expected life years lost per day among those residents. Mortality rates and life expectancy based on: E&W life-table scaled to care home survival (green bars); six month life expectancy for heat deaths (orange bars); and E&W whole population life table (grey bars).

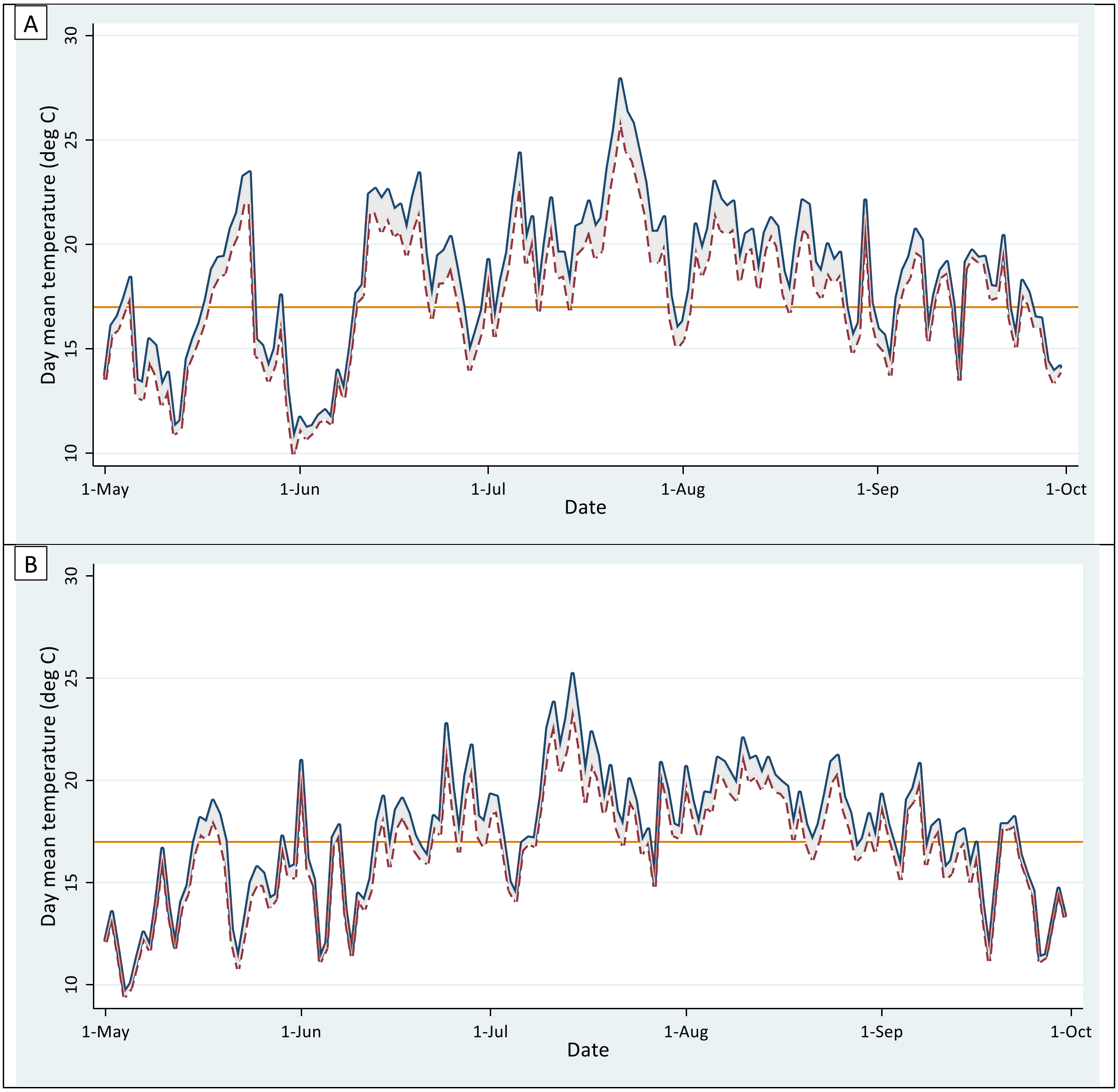

Fig. 2. Outdoor temperature (solid blue line) and outdoor temperature after subtraction of the intervention effect (red dashed line): estimates based on [A] CIBSE DSY1 weather file ('hot year') and [B] CIBSE TRY weather file ('average year'). The grey shading represents the assumed difference in effective dry bulb temperature used for risk calculations. Horizontal orange line is the epidemiological threshold for heat death (17°Celsius).

mortality (Table 4). But for Method 3 assumptions (six months life expectancy) the corresponding figures were just over £4,200 and £2,900, respectively.

If we assume that DSY1 temperatures recur every 10 years and TRY temperatures in the remaining 9 out of 10 years, the saving of life years by shading in a 50-person care home would be monetized at around £90,000 using Method 1 calculation, £230,000 using Method 2, and £44,000 using Method 3 assuming a 20-year time horizon and an annual discount rate of 3.5%. These figures make no adjustment for climate change or the quality of life (utility weighting) of care home residents who are very likely to have less than perfect health.

Our indicative estimate of the costs of a simple shading intervention were for a total cost of £15,000 to £20,000 for typical care home of 50 residents – and thus less than the lowest of the three estimates for the value of the life years saved.

3.4. Sensitivity analysis

We display results from our multi-way sensitivity analysis in Fig. 3. Within our sensitivity analysis, the minimum monetized saving

Table 4
Impact of intervention (shading) on mortality and life years lost to heat for a care home of 50 residents: results for one year using DSY1 ('hot year') and TRY ('average year') weather files.

Weather file	Assumption for mortality and life expectancy	Intervention change in indoor daily mean temp. (°C)	Heat deaths averted by intervention	Life years lost to heat			Monetized value of lost life years averted by intervention* (£)
				Before intervention	After intervention	Difference (averted life years)	
DSY1 ('hot year')	E&W life table	−0.90	0.07	0.99	0.70	0.29	8 800
	E&W life table scaled to care home survival		0.47	2.58	1.82	0.76	22 700
	6 months life expectancy for heat deaths		0.28	0.49	0.35	0.14	4 200
TRY ('average year')	E&W life table	−0.60	0.05	0.62	0.42	0.20	5 900
	E&W life table scaled to care home survival		0.31	1.61	1.10	0.51	15 300
	6 months life expectancy for heat deaths		0.19	0.31	0.21	0.10	2 900

* – based on an assumed valuation of £30 000 per quality-adjusted life year (QALY).

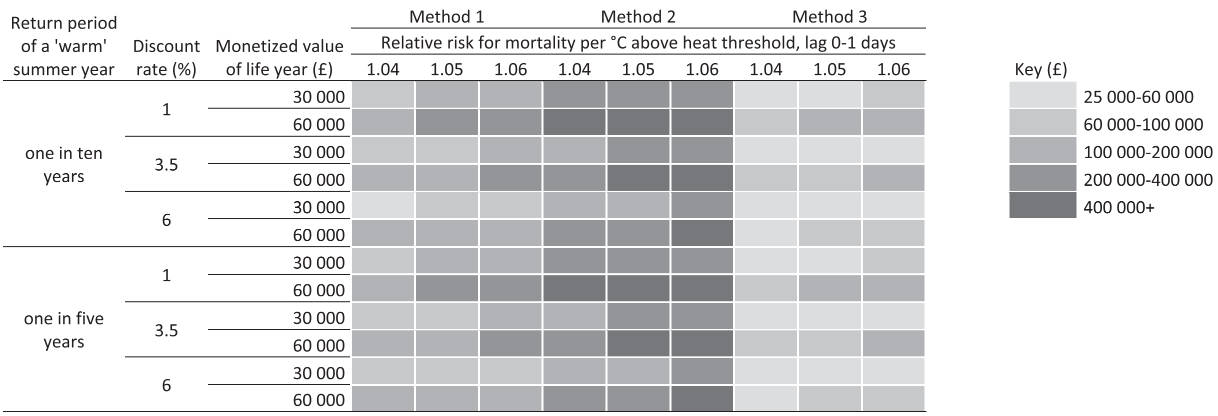

Fig. 3. Multi-way sensitivity analysis of the effect of key parameters on the monetized value of lost life years averted due to intervention (shading).

of life years is around £28,000. This occurs when using Method 3 and the following parameters: a relative risk for heat-related mortality of 1.04; a monetized value of a life year of £30,000; a discount rate of 6%; and a return period of one in ten years. The maximum monetized saving of life years is just over £730,000. This occurs when using Method 2 and the following parameters: a relative risk for heat-related mortality of 1.06; a monetized value of a life year of £60,000; a discount rate of 1%; and a return period of one in five years. Our results are most sensitive, by far, to the choice of Method, followed by: the value of a monetized life year; the annual discount rate; the relative risk for heat-related mortality; and, finally, the return period of a 'warm' summer year.

4. Discussion

This paper explores methodological issues core to the health cost-benefit assessment of adaptation to heat under climate change – specifically the quantification of the value of gains in life years of those who die of heat and in particular among the residents of care homes.

As with any modelling study, there are multiple sources of uncertainty. In this paper we focus on the assumption about loss of life expectancy. The attribution of deaths to heat is very largely based on daily time-series analyses in which daily fluctuations in mortality are related to daily temperatures (Gasparrini et al., 2015). Because of their analytical design, it is not possible from time-series studies to determine with precision the degree of life-shortening in those whose death is attributed to heat (Armstrong et al., 2017; Rehill et al., 2015). Some, perhaps even most, who die of heat may be frail and already close to the end of their lives, especially in a care home setting. For such people, it is possible that the loss of life expectancy from heat may be only a matter of months or weeks – a phenomenon often referred to as 'mortality displacement'. Evidence for mortality displacement has been found in various studies (see, for example, references (Pascal et al., 2018; Cheng et al., 2018; Saha et al., 2014; Toulemon and Barbieri, 2008), but the degree to which it occurs may be context-specific because the causes of heat death vary with age and from population to population (Hajat et al., 2005).

Although we cannot say with certainty which of the estimates is closest to reality, the estimates provide some indication of the range of values within which the true estimate is likely to lie. It is reassuring, perhaps, that even under Method 3, which assumes the shortest loss of life expectancy, it appears that adaptations costing around £40,000 could be justified in conventional cost-benefit terms for a care home of 50 residents – if such adaptations, such as shading, reduce indoor temperatures by somewhere close to 1 °C during a hot summer. The true monetized saving of life years might be several times that figure as the sensitivity analyses indicate, and probably not less than around £25,000 – which is still higher than our indicative cost estimates for very simple shading measures. The mortality rates and life expectancy that are closest to the observed survival of care home residents are those of Method 2, and the sensitivity analyses for this method suggest appreciably higher value of the life years gained, which would therefore appear to justify various forms of physical adaptation measure.

We have not assessed other sources of uncertainty, such as those that are part of building simulations, the effects of climate change, or assumptions about the quality of life of care home residents. We have also not considered various other forms of costs and benefits such as the costs associated with increased room turnover and reputational damage. These would be factors to include in any formal cost-benefit analysis of adaptation options.

The results of our analyses should encourage further consideration of physical heat adaptation measures in care homes. Public Health England provides detailed guidance for care home managers and staff on how to manage the health risks associated with severe heat but it is unclear how effective it is in preventing heat-related mortality and morbidity (England and Plan, 2015). Furthermore, the Care Quality Commission does not formally assess the preparedness of care homes for severe heat events within current regulations. Our results suggest that various physical adaptations have the potential at least to be cost-effective and should be considered as an important complement to operational responses. Our results also provide evidence that can be used to improve assumptions about the value of the gain in life years in assessing the cost-benefit of specific adaptation measures. We hope this knowledge will help to improve evidence for decision-makers and lead to an improved programme of heat adaptations in the care setting.

5. Research ethics

The project was approved by the research ethics committee of University College London.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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