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Current and future burdens of heat-related dementia hospital admissions in England

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ABSTRACT

Introduction: The impacts of a changing climate on current and future dementia burdens have not been widely explored.
Methods: Time-series negative binomial regression analysis was used to assess acute associations between daily ambient temperature and counts of emergency admissions for dementia in each Government region of England, adjusting for season and day-of-week. Using the latest climate and dementia projections data, we then estimate future heat-related dementia burdens under a high emission scenario (Representative Concentration Pathway (RCP8.5), where global greenhouse gas (GHG) emissions continue to rise, and a low emissions scenario (RCP2.6), where GHG emissions are sizeably reduced under a strong global mitigation policy.
Results: A raised risk associated with high temperatures was observed in all regions. Nationally, a 4.5% (95% Confidence interval (CI) 2.9%–6.1%) increase in risk of dementia admission was observed for every 1 °C increase in temperature above 17 °C associated with current climate. Under a high emissions scenario, heat-related admissions are projected to increase by almost 300% by 2040 compared to baseline levels.
Conclusions: People living with dementia should be considered a high-risk group during hot weather. Our results support arguments for more stringent climate change mitigation policies.

1. Introduction

Climate change and population ageing are two of this century's biggest global health challenges (Watts et al., 2019; Livingston et al., 2020). The adverse impacts of climate change on human health and wellbeing are profound and wide-ranging, with ambient temperature extremes directly contributing to substantial mortality and morbidity burdens from cardiovascular and respiratory diseases, particularly among people of older age (Chen et al., 2017). Hence, sustainable and synergistic solutions for healthy ageing and climate change are urgently needed (Mavrodaris et al., 2021).

As the world continues to warm, many countries are now experiencing more frequent, intense and prolonged heat-waves (Meehl and Tebaldi, 2004). Very extreme summers, such as that in Europe in 2003 which resulted in over 70,000 excess deaths (Robine et al., 2008), are expected to become much more common in the coming decades (Barriopedro et al., 2011), raising the need to anticipate the likely impacts that such warming will bring. Providing assessments of health burdens under future climate change scenarios can therefore help with public health and adaptation planning and to support arguments for more stringent mitigation measures when climate policies are being agreed. The UK Government has committed to a net-zero greenhouse gas (GHG) emissions target by 2050 and hosted the 26th UN Climate Change Conference of the Parties (COP26); it is imperative that public health and sustainable healthy ageing are central to discussions (Climate Change Act 2008 (2050 Target Amendment), 2019; Committee on Climate Change, 2019).

Although there is an established effect of air pollution on incident dementia (Peters et al., 2019), the impacts of a changing climate on dementia burdens and other neurological diseases have not been widely

Abbreviations: CI, Confidence Interval; CMIP5, Intergovernmental Panel on Climate Change's 5th Assessment Report; COP26, 26th UN Climate Change Conference of the Parties; ELSA, English Longitudinal Study of Ageing; GHG, Greenhouse Gas; HadCET, Hadley Centre Central England Temperature; ICD, International Classification of Diseases; IPCC, Intergovernmental Panel on Climate Change; NHS, National Health Service; PLWD, People Living with Dementia; PPE, Perturbed Physics Ensemble; RCP, Representative Concentration Pathway; T_{ma}, Temperature of minimal admissions; UKCP, UK Climate Projections.

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explored (Wei et al., 2019), despite the increasing pressures associated with dementia on the public health and social care systems (Nichols et al., 2019). With rising temperatures and more extreme weather events, allied to the growing numbers of people living with dementia (PLWD) in the UK and worldwide (Livingston et al., 2020; Nichols et al., 2019), there is an urgent impetus to recognize the specific dangers posed to PLWD during periods of extreme weather.

The elderly are particularly vulnerable to heat illness, and PLWD may have heightened risk given possible impaired perception of weather conditions and limited ability to recognize and alleviate heat stress. In addition, reduced levels of thermoregulation are often reported in older people due to poorer aerobic fitness and important comorbidities (Wei et al., 2019; Culqui et al., 2017). Potential side-effects associated with certain medications commonly taken by PLWD may also heighten heat-risk (Culqui et al., 2017; Zammit et al., 2021). Furthermore, there is mounting evidence that social isolation is one of the most important risk factors for death during heat-waves (Kim et al., 2020). Social isolation is also a known risk factor for dementia (Livingston et al., 2020), with the elderly being more likely to live in isolation than other age groups in the UK (Rolls et al., 2011). Socio-economic status may also be a common risk factor for dementia and heat illness (George et al., 2020; Rey et al., 2009).

There is some epidemiologic evidence linking high temperatures with increased dementia-related hospital admissions, although with little consistency in results (Wei et al., 2019; Culqui et al., 2017; Linares et al., 2017; Ma et al., 2020; Xu et al., 2019). In the UK, PLWD have been reported to be at elevated risk of death during hot weather (Page et al., 2012); however, the impacts on emergency hospital admissions have never been assessed, even though presentation at this stage has the potential to prevent heat illness from developing into more serious outcomes. Furthermore, to the best of our knowledge, no previous study has estimated future dementia-related health burdens due to climate change, either in the UK or any other setting. This is despite the fact that the number of PLWD in the UK is projected to almost double from a current total of 850,000 people to 1.6 million by 2040 (Wittenberg et al., 2019), and increases will be even greater in low-to-middle-income countries due to a faster rate of population ageing (Prince et al., 2015). The likely impacts to the healthcare system that future warming will have within this vulnerable group can inform adaptation and public health planning. Currently, PLWD are not identified as high-risk individuals in the Public Health England national heat plan (Public Health England, 2019).

This study explores the association between ambient temperature and dementia-related emergency hospital admissions using the national hospital inpatient dataset for England, and examines potential modification of heat-risk by age and deprivation. Using the latest climate projections data, we also provide, for the first time, projections of future health burdens in PLWD under climate change scenarios.

2. Materials and methods

2.1. Data

Daily counts of emergency inpatient admissions with a primary diagnosis of dementia (ICD codes F00-F03) were obtained from NHS Digital (https://digital.nhs.uk/data) for the period 1998–2009 in England. This period includes the very hot summers of 2003 and 2006 and provides a suitable baseline for comparison with the projected periods. Series were subdivided by the nine Government regions of England and by age-group (16–74; 75–84; 85 + years) and deprivation quintiles (based on the Index of Multiple Deprivation overall rank at Super Output Area level from the 2011 UK census). Subdivision by sex was not available.

Ambient daily mean temperature data for the same time period were obtained from Met Office land surface stations from the CEDA archive (https://data.ceda.ac.uk/badc). Regionally representative series were created by averaging data from all stations recording on at least 75% of days during the study period. For national assessment, the Met Office (https://www.metoffice.gov.uk/hadobs/hadcet/) resource was used as part of the Met Office Hadley Centre Central England Temperature (HadCET) series (Parker et al., 1992).

For the climate scenarios, projected daily mean temperature data (1980–2049) for England, based on high and low future GHG emissions, were obtained from the UK Climate Projections User Interface (https://ukclimateprojections-ui.metoffice.gov.uk/) as part of the UKCP18 Global Climate Model Projections (Met Office Hadley Centre, 2018).

We considered two future emissions scenarios (Representative Concentration Pathways) – RCP2.6 reflects a low emissions scenario where GHG emissions are sizeably reduced under a strong global mitigation policy, and RCP8.5 reflects a high emissions scenario where global GHG emissions continue to rise with minimal mitigation and increasing wealth and population (Gohar et al., 2018; Lowe et al., 2019). Each RCP dataset included 15 climate projections from the Met Office Hadley Centre model (HadGEM3-GC3.05) perturbed physics ensemble (PPE-15) and 7 projections from climate models that informed the Intergovernmental Panel on Climate Change's (IPCC's) 5th Assessment Report (CMIP5) (Gohar et al., 2018; Lowe et al., 2019).

Age-specific projections of dementia prevalence in England and Wales were obtained from Ahmadi-Abhari et al. (2017) for years 2030 and 2040. Based on data from the English Longitudinal Study of Ageing (ELSA) and using a dynamic modelling approach (IMPACT-Better Ageing Model), projections accounted for increasing life expectancy and changes in mortality and cardiovascular disease incidence (Ahmadi-Abhari et al., 2017). Estimates for England alone were calculated using the Office for National Statistics age-stratified population projections (Office for National Statistics Principal projection - UK population in age groups, 2018), assuming a homogeneous population in England and Wales. Dementia projections beyond 2040 were not available.

2.2. Epidemiologic analysis to model current impacts

Negative binomial regression models were used to assess acute associations between daily mean temperature and daily emergency admissions for dementia, allowing for overdispersion. Underlying seasonal patterns (unrelated to temperature) and any trends in the admissions data were controlled for using parametric spline functions of time with 4 degrees of freedom (*df*) per year of data. Indicator terms were used to model variation by day-of-week.

Cross-basis functions were used to model the exposure–response relationship to flexibly capture any non-linear and delayed effects of temperature as part of a distributed lag framework (Armstrong, 2006). This identifies any non-linearity in the relationship, including possible heat and cold thresholds. A 7-day lag structure was used to explore potential delayed effects of temperature up to a week prior to admission date. Predictions were centred at the temperature of minimum admissions (T_{ma}). The following model was fitted:

$$\mathrm{Log}[\mathrm{E}(\mathrm{Y_i})] = \alpha + \beta_1 \mathrm{T_{i,l}} + \beta_2 \mathrm{ns}(\mathrm{time_i}, \mathrm{df} = 4/\mathrm{year}) + \beta_3(\mathrm{dow_i})$$

where $E[Y_i]$ is expected adms on day i; $T_{i,l}$ is the cross-basis matrix of temperature and lag l days; ns = natural spline functions; dow = day of week.

Separate models were developed for each age-group and deprivation quintile to examine potential modifying effects. The cumulative effect of temperature (across all lags) and lag-specific effects were obtained by fitting distributed lag linear threshold models. The heat threshold for each sub-group was defined as the value above which temperature was associated with a statistically significant ($p < 0.05$) increased risk of admission for the whole population. There was no evidence for a relationship with low temperatures.

For the regional series, simpler models were developed to accommodate the lower daily counts. Fourier terms (one sine–cosine pair per year of data) and a linear term for time were used to control for underlying seasonal patterns and long-term trends, respectively.

$$\text{Log}\left[E\left(Y_{i,j}\right)\right] = \alpha + \beta_1 T_{i,l} + \beta_2(t) + \beta_3 \sin(2\pi t/365) + \beta_4 \cos(2\pi t/365) + \beta_5(\text{dow}_i)$$

where $E[Y_{i,j}]$ is expected adms on day i in region j; $T_{i,l}$ is the crossbasis matrix of temperature and lag l days; t is time; dow = day of week.

The heat threshold for each region was defined as the 91st percentile value to correspond with the centile identified for the national-level heat threshold. Region-specific effects (coefficients and standard errors) were *meta*-analysed using the inverse variance method. Fixed-effects and random-effects were applied using restricted maximum likelihood to estimate between-region variance and Q-profile to estimate 95% confidence intervals (CIs). Sensitivity of national-level estimates involved re-specifying models with different levels of seasonal control ($df = 2$; $df = 7$), a longer lag structure (14-days), and explicitly controlling for lags with high degrees of residual autocorrelation (Bhaskaran et al., 2013).

2.3. Health impact assessment to estimate future burdens

The national-level exposure–response relationship was then applied to projections of future climate to estimate emergency hospital admissions for dementia attributable to temperature during the 2030 s and 2040 s (compared to 2000 s) under two alternative climate change scenarios (RCP2.6 and RCP8.5), following the process described in Vicedo-Cabrera et al. (Vicedo-Cabrera et al., 2019). Firstly, systematic differences between climate observations (HadCET) and UKCP18 projections were bias corrected for using a function created by Vicedo-Cabrera et al. (2019); which applies the calibration procedure developed within the first Inter-Sectoral Impact Model Intercomparison Project, as described by Hempel et al. (2013). Forty years (1980–2019) of observed temperature data were used to calibrate UKCP18 projections, which is considered more than adequate (Fung, 2018).

An annual series of total emergency hospital admissions for dementia was created by calculating mean admission counts for each day of the year from daily counts recorded between 1998 and 2009. The annual admission series was replicated along the 2000–2049 projection period, assuming no adaptation (e.g. increased prevalence of air conditioning).

The bi-dimensional model used to estimate current impacts (Section 2.2) was reduced to one-dimensional summaries defined in the temperature-admission dimension. Coefficients and covariance were extracted, defining the overall temperature-admission association (i.e. across all lags), centred at T_{ma}. Given that temperatures will increase over the coming decades to levels not previously experienced in England, a log-linear extrapolation of the estimated temperature-admission curve was performed. That is, the non-linear relationship between daily mean temperature and admission counts was extended beyond the observed boundaries.

The daily number of admissions for dementia attributable to high temperatures (i.e. greater than the identified heat threshold) were estimated for each emission scenario and UKCP18 projection (2 emissions scenarios × 22 models) and summed for each 10-year period (2010–2019; 2020–2029; 2030–2039; and 2040–2049). The difference in temperature-attributable admissions relative to the baseline period (2000–2009) was also estimated for each decade.

The uncertainty of estimates arising from variability among UKCP18 projections and estimation of the temperature-admission function was quantified through Monte Carlo simulations. One thousand samples of the coefficients were generated, assuming a multivariate normal distribution for estimated NCS coefficients. Results for each of the 22 UKCP18 projections were then generated under each emissions scenario. Results were reported as point estimates averaged across the 22 climate projections and as 95% CIs of the temperature-attributable admissions across UKCP18 projections and generated coefficient samples, thereby accounting for both sources of uncertainty (Vicedo-Cabrera et al., 2019).

The above process was repeated to estimate age-specific (16–74 years, 75–84 years and 85 + years) numbers of heat-attributable hospital admissions by 2030 and 2040. To account for future changes in the number of PLWD, as estimated by Ahmadi-Abhari et al. (2017), age-specific attributable numbers were multiplied by the age-specific growth factor in dementia cases for 2030 and 2040 (compared to 2010).

Analyses were conducted in R (version 4.04), using RStudio (RStudio Team RStudio, 2020), and were facilitated by the following packages: splines, MASS, dlnm, tsModel, ggplot2, meta; and by R scripts provided in Vicedo-Cabrera et al. (Bhaskaran et al., 2013). Microsoft Excel was used to derive the projections assuming a change in dementia prevalence.

3. Results

Fig. 1 shows the annual distribution of emergency dementia admissions for England averaged across all years in the study period. There was some suggestion of seasonality in admissions, with numbers peaking in the summer and winter months each year. Admission counts tended to be the highest on Fridays and lowest on weekends.

After adjustment for season and day-of-week effects, there was an increase in the risk of dementia-related hospital admission associated with high temperatures, with adverse effects becoming apparent once daily mean temperatures reached 17 °C (Fig. 2) at the national level. The risk of admission was lowest at 14.6 °C. We estimated a 4.5% (95% CI 2.9%–6.1%) increased risk of dementia admission for every 1 °C rise in temperature above 17 °C in England. This estimate was robust to the sensitivity analysis outlined in Section 2.2 (results available from authors on request).

Table 1 shows modification of the heat effect by age-group and deprivation. As expected, the risk was greatest in older age-groups. The risk was also highest in the most deprived groups, although with overlap in confidence intervals.

Fig. 3 shows region-specific results. An increased risk of admission was associated with high temperatures in all nine regions, with the highest risk in the Midlands regions and London.

At a national-level, emergency admission for dementia was associated with high temperatures on the day of admission (lag 0) and 3–4 days before admission (lags 3 and 4), suggesting same-day and delayed effects of heat (Fig. 4). A 1 °C increase in daily mean temperature above 17 °C was associated with a 1.8% (95% CI 0.4%–3.3%) increased risk of same-day admission.

Fig. 5 shows projected temperature changes in England until mid-century. By 2040, annual mean temperature is estimated to increase by 1.6 °C (range: 0.2 °C–2.7 °C) under RCP2.6 and by 1.8 °C (range: 0.3 °C–2.8 °C) under RCP8.5, relative to the baseline period 1981–2000.

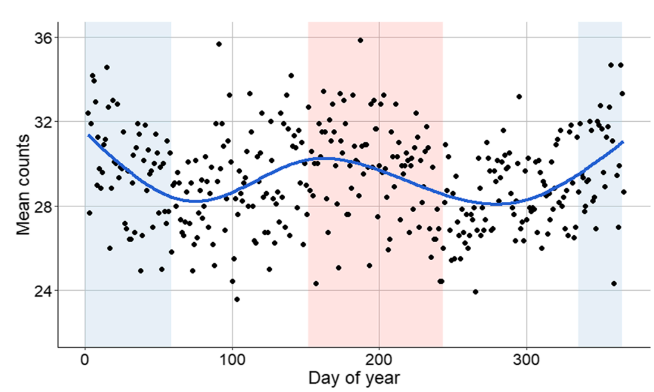

Fig. 1. Mean daily counts of emergency dementia-related admissions by day of year. Blue line summarizes the seasonal pattern using a natural cubic spline of time. Blue shading indicates months December-February; red shading indicates June-August. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

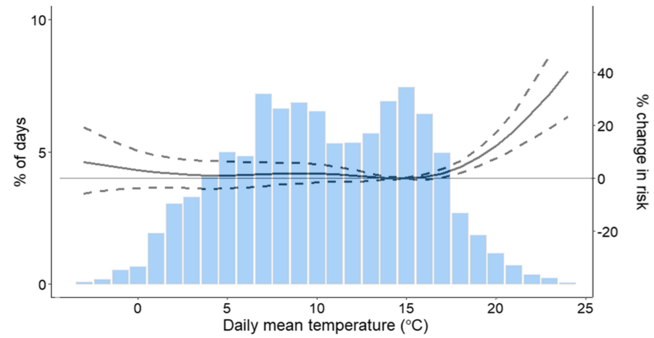

Fig. 2. Proportion (%) of days between 1998 and 2009 (blue bars) and estimated percentage change in risk of emergency hospital admission for dementia (black line) at daily mean temperature of 1 °C intervals. Dashed black lines indicate 95% confidence intervals of estimated change in risk. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 1
Overall cumulative effects of mean temperature on emergency hospital admissions for dementia, as summed over 7 days of lag (including lag 0), stratified by age group and quintile of deprivation. Effects are presented as the percentage change in risk of admission per 1 °C increase in mean temperature above 17 °C and their 95% confidence intervals (CIs).

	Estimated risks		
Age	%change	%CI lower	%CI upper
16–74 years	2.27	−0.94	5.59
75–84 years	4.84	2.75	6.97
85+ years	4.83	2.60	7.10
Deprivation quintile			
1 (least deprived)	4.36	1.28	7.53
2	4.29	1.31	7.35
3	3.23	0.36	6.19
4	5.21	2.25	8.25
5 (most deprived)	4.83	1.83	7.91

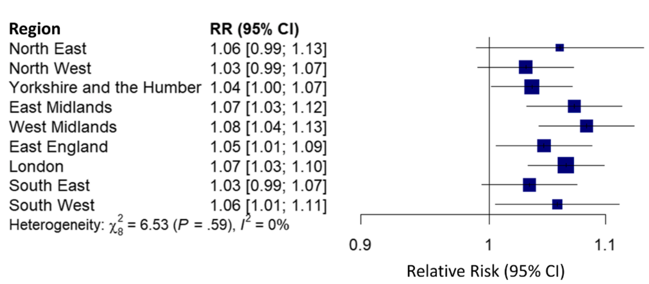

Fig. 3. Region-specific relative risk (RR) (95% CI) of emergency hospital admission for dementia per 1 °C increase in daily mean temperature above the heat threshold (91st centile): North East (15 °C), North West (16 °C), Yorkshire and the Humber (16 °C), East Midlands (17 °C), West Midlands (17 °C), East England (18 °C), London (19 °C), South East (18 °C), South West (17 °C).

Temperatures under the two emissions scenarios become more divergent by end of century (not shown).

Assuming an increase in the overall prevalence of dementia (number of cases) in England (Ahmadi-Abhari et al., 2017), we estimated the number of heat-attributable hospital admissions to increase by 214% in 2030 and by 263% in 2040 (relative to 2009) under the low emissions scenario. In absolute numbers, this equates to approximately 357 heat-related admissions in 2030 and 412 admissions in 2040 (relative to 114 admissions in 2009). Under the high emissions scenario, heat-related admissions were estimated to increase by 194% in 2030 and by 294% in 2040, which equates to approximately 360 admissions in 2030 and

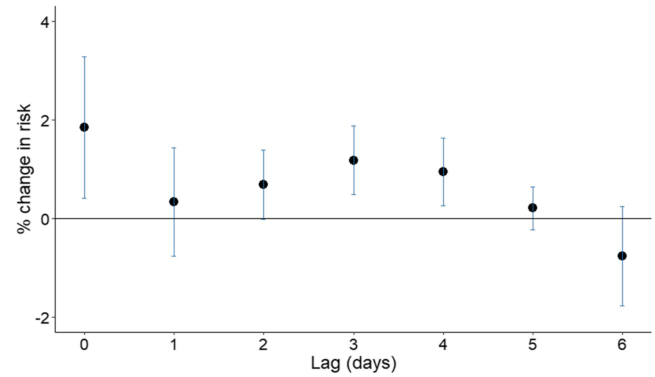

Fig. 4. Percentage change in risk of emergency dementia-related hospital admission per 1 °C increase in daily mean temperature above the heat threshold (17 °C), on the 6 days leading up to admission (lags 1–6) and on the day of admission (lag 0). Black dots represent estimated changes in risk and grey bars indicate their 95% confidence intervals.

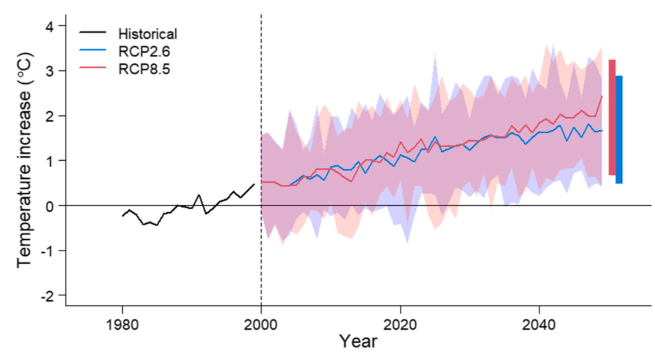

Fig. 5. Projected mean temperature in England over time (1980–2049). Solid blue and red lines represent mean annual temperature estimated across the 22 climate projections for each representative concentration pathway (RCP) scenario, expressed as the difference in annual mean temperature from the historical average temperature (black line). Shaded areas represent annual variability (range) in projected temperature across 22 UKCP18 climate projections. Blue and red horizontal bars represent mean annual maximum and minimum temperature for RCP2.6 and RCP8.5, respectively. Data source: UKCP18 Global Climate Model Projections (See: Met Office Hadley (Centre, 2018) UKCP18 Global Climate Model Projections for the entire globe. In. Centre for Environmental Data Analysis, 2021. http://catalogue.ceda.ac.uk/uuid/f1a2fc3c120f400396a92f5de84d596a). Contains public sector information licensed under the Open Government Licence v3.0. Using R code provided in Vicedo-Cabrera (See: Vicedo-Cabrera AM, Sera F, Gasparrini A (2019) Hands-on tutorial on a modeling framework for projections of climate change impacts on health. Epidemiology 30(3): 321–329). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

482 in 2040 (relative to 122 admissions in 2009). Age-specific growth rates and relative estimates are provided in Table 2.

4. Discussion

4.1. Summary of results

In our study using a comprehensive national secondary care database and the latest climate projections data, we observed adverse impacts once ambient temperatures exceeded the 91st percentile of temperature distributions. This is well below typical alert thresholds used in heat-warning systems and thus underscores that temperatures do not need to be particularly extreme before adverse impacts in high-risk groups, such as PLWD, become apparent. Therefore, prevention measures and healthy ageing will be increasingly important mitigating factors as the

Table 2
Growth factor in the number of dementia cases in England by 2030 and 2040 (compared to 2010) and estimated numbers of heat-attributable emergency hospital admissions for dementia in each age group (with percentage change in heat-attributable admissions) relative to 2009 estimates, assuming future changes in dementia prevalence.

			Relative number of hospital admissions (% change)			
	Growth factor		RCP2.6		RCP8.5	
Age	2030	2040	2030	2040	2030	2040
16–74 years	0.98	0.78	32 (74%)	21 (49%)	30 (64%)	27 (57%)
75–84 years	1.83	1.65	102 (249%)	99 (243%)	100 (227%)	119 (270%)
85+ years	2.31	3.12	110 (371%)	178 (604%)	108 (340%)	214 (674%)
Total (overall)			244 (214%)	298 (263%)	238 (194%)	360 (294%)

world continues to warm. Our projections reveal that, even as early as the year 2030 and under a low emissions scenario (i.e. regardless of any climate change), we should still expect heat-related emergency hospital admissions for dementia to increase by more than 200% from those estimated in 2009. With climate change, future increases will be substantially higher.

4.2. Comparison with previous literature

We found an estimated increase in dementia admissions of 4.5% per 1 °C rise in high temperature, which is of a similar effect size to that observed for diseases of the respiratory system in England and larger than for other common causes (Kovats and Hajat, 2004). However, absolute numbers may be lower since dementia admissions contribute a relatively small proportion of the total number of hospitalisations. The sensitivity of dementia admissions to hot weather is consistent with two previous studies, however the heat threshold in our study was much lower in comparison to the warmer settings of Madrid (Culqui et al., 2017), and Brisbane (Xu et al., 2019). Other studies have also associated high ambient temperature with a substantial increase in the risk of dementia-related hospitalization (Wei et al., 2019; Linares et al., 2017). Long-term exposure to a warmer climate, as well as greater temperature variations also greatly increased the risk of dementia-related hospitalization in New England, USA (Wei et al., 2019). Cold temperature has also been reported to increase the risk of dementia-related mortality, although we observed little effect in our admissions dataset even when considering a longer lag structure (Ma et al., 2020). This is the first study providing projections of future health burdens in PLWD under climate change scenarios.

4.3. Putative mechanisms

Advanced age is a well-established risk factor for heat illness, however, the particularly large risks observed in PLWD suggest that other factors are also involved. Prolonged heat stress can induce acute and chronic sequelae on the central nervous systems, affecting both cerebrovascular and neurodegeneration mechanisms (Zammit et al., 2021). Dysregulation in maintaining optimal body temperature often occurs in older adults (Millyard et al., 2020), and the sweating process and skin blood flow also reduce with age (Millyard et al., 2020). The involvement of neurotransmitters in emotion control and thermoregulation can be speculated (Ma et al., 2020; Xue et al., 2019), such that people with mental disorders may have reduced thermoregulation to maintain body temperature when ambient temperature fluctuates (Xue et al., 2019). The elderly may also fail to take appropriate measures such as hydrating properly and be more likely to use fans as their main cooling strategy, which can increase evaporative loss in certain climate conditions (Gupta et al).

Further, PLWD are often frail and living with multimorbidity (Banerjee, 2015), and are highly dependent on caregivers for daily functioning and activities. (Brodaty and Donkin, 2009) PLWD have reduced cognitive awareness of the environment and hence may be less likely to perceive increased threat related to heat exposure on physiological changes (Millyard et al., 2020; Gasparrini et al., 2012). PLWD may have reduced capacity to adapt to extreme heat, for example, being less likely to seek out cooler ambient environments, increasing fluid intake and removing layers of clothing to dissipate heat (Millyard et al., 2020). Compromised language capacity in PLWD (Cornali et al., 2004) mean that some heat-related manifestations and symptoms of distress and agitation may be overlooked by their caregivers (Tartarini et al., 2017).

Putative biological mechanisms for the link between heat stroke and neurodegeneration have been proposed, such that oxidative stress induced by heat stress can accelerate neurodegeneration via hyperphosphorylation and aggregation of the tau proteins forming neurofibrillary tangles (Zammit et al., 2021; Alavi Naini and Soussi-Yanicostas, 2015). Heat strokes can induce neurodegeneration via cell excitotoxicity, necrosis and apoptotic death of neuronal cells (Zammit et al., 2021; Kourtis et al., 2012). Whether these mechanisms also play a role in exacerbating cognitive and non-cognitive symptoms related to dementia, resulting in higher hospital admission rates, needs to be further investigated.

Lastly, the thermoregulatory side-effects of antipsychotic or psychotropic medications have been well documented (Stöllberger et al., 2009). Insufficient water intake, compromised thermoregulation and perspiration may be directly linked to the use of these drugs (Culqui et al., 2017; Zammit et al., 2021).

4.4. Public health and policy implications

The number of PLWD is projected to increase in the UK over the coming decades (Ahmadi-Abhari et al., 2017). Our study was able to establish a link between high temperatures and exacerbation of symptoms among PLWD, and the projections results showed that heat-related emergency hospital admissions for dementia will increase substantially over the coming decades. From a public health perspective, these findings are particularly informative given that heat exposure and impacts can be minimized by taking simple health protection measures whenever hot weather is forecast. Such information can ensure that public health and hospital systems, as well as caregivers for PLWD, can be better prepared in the face of more frequent and extreme weather events. The Heatplan in England should now consider PLWD as a 'high risk' group (Public Health England, 2019). Prediction of future risk and disease burden can be useful tools in public health priority settings and can inform planning and capacity in hospital facilities dedicated to individuals with dementia to help with ensuring that their future needs are met.

With the US rejoining the 2015 Paris Agreement, this year is seen as pivotal for climate action and the strengthening of GHG mitigation policies formulated at COP26 and elsewhere. Many policies to reduce emissions also have health co-benefits and so can contribute to lowering the dementia burden via multiple pathways. For example, policies that encourage a switch to more active transport promote more physical activity, improve air quality, and reduce noise pollution. As well as poor aerobic fitness being linked to the development of dementia, air pollution is also an established risk factor for early dementia development (Livingston et al., 2020). Other environmental risk factors, such as traffic-related noise, have also been identified (Yu et al., 2020). Therefore, as well as reducing the burden of heat-related exacerbation of symptoms amongst PLWD, strategies to reduce CO_2 emissions can, in the nearer term, also contribute to lowering dementia incidence by promoting physical activity and reducing air pollution concentrations and other environmental factors linked to the development of dementia. Furthermore, policies that improve air quality, reduce congestion, and decrease the impact of extreme weather events, can have a plethora of profound effects to improving public health in general and in driving socio-economic progress. We advocate for the strengthening of sustainable strategies that address the dual challenges of population ageing and climate change in synergy (Mavrodaris et al., 2021).

4.5. Strengths/limitations

To the best of our knowledge, this is the first study to examine associations between ambient temperature and hospital admissions related to dementia in England. Furthermore, using the latest climate projections data, this is also the first study to provide projections of future health burdens in PLWD under climate change scenarios.

Several study limitations should be mentioned here: first, due to limited patient information, we could only consider admissions with a primary diagnosis of dementia and not admissions from other causes in PLWD. An assessment of hospital admissions by PLWD in a high-income setting found that dementia was the main cause of admission in only 6.5% of cases, with other common causes being pneumonia, urinary tract infection and acute cerebrovascular disease (Bernardes et al., 2018). Since these outcomes may also be sensitive to heat stress, our results should be regarded as lower-bound estimates of the total health burden of climate change for dementia sufferers and for the health care system. Second, there is a risk of exposure misclassification since we are using aggregate temperature measures to represent personal exposure. Previous work demonstrated a very high degree of correlation between monitoring stations within each English region. (Armstrong et al., 2011) The English population spends most of its time indoors, however previous work has also reported high correlation between indoor and outdoor temperatures (Anderson et al., 2013). Third, due to power limitations with the analysis undertaken for individual regions, age- and deprivation-specific results were only possible for the national model which used a single temperature series considered to be representative of the country (Parker et al., 1992). We did not control for humidity or air pollution in our model since they are more localized than temperature, however previous work suggests that this would have had little impact on our estimates (Arbuthnott et al., 2020). In modelling future burdens, there is likely to be some degree of population adaptation to living in a warmer world – this may occur from physiological acclimatization but also due to changes in behaviour, technological improvements and other measures. We did not aim to model possible adaptation as we wished to isolate the contribution of climate change to future burdens of dementia admissions. Also, the dementia projections used in our assessment were created before the COVID-19 pandemic which may have long-term consequences for underlying mortality rates. Lastly, there are inevitably other uncertainties that exist when considering future climate change scenarios, however our projections are based on an ensemble of 22 climate models and two RCP scenarios to address the uncertainties associated with modelling the climate system.

5. Conclusions

The findings are likely to have important public health implications for priority settings, such as for hospital emergency department planning during the hot season. The dangers of heat-exacerbated symptoms among PLWD can be anticipated by caregivers whenever hot weather is forecast. The projections data provides some clues as to how future dementia burdens may increase under climate change scenarios given the growing ageing population.

CRediT authorship contribution statement

Jessica Gong: Investigation, Writing – original draft. **Cherie Part:** Formal analysis, Investigation, Methodology, Software, Visualization, Writing – review & editing. **Shakoor Hajat:** Conceptualization, Data curation, Investigation, Methodology, Supervision, Writing – review & editing.

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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