Quantifying the health-care burden of temperature in the National Health Service in England: an economic analysis of resource use and costs

Patrick Fahr, Francois Cohen, Jessica Schiff, Anant Jani, Mateo Petel, Malcolm McCulloch, Radhika Khosla, Rafael Perera-Salazar

Summary

Background Climate change poses a severe and escalating threat to human health, yet its broader implications for health-care systems remain poorly understood. Although previous studies have examined mortality and hospital admissions, crucial domains such as medical prescriptions and system-wide costs have been overlooked. This study aims to provide the first comprehensive analysis of the impact of daily average temperature variability on a national health-care system.

Methods In this economic analysis of resource use and costs, we analysed 4 366 981 patient records from the National Health Service (NHS) in England from the Clinical Practice Research Datalink GOLD, from April 1, 2007, to June 1, 2019. We sourced weather data from the Met Office HadUK-Gridded climate observations. We used a fixed-effects regression model, aligned with methodologies used in other climate-health studies, to estimate the temperature–health-care relationship while controlling for seasonality and practice-specific characteristics. Outcomes included daily counts of health-care events and associated costs per 1000 general-practice-registered individuals, stratified by age, sex, and care domains. We conducted additional robustness checks using alternative lag structures and model specifications.

Findings Colder days (average temperature 0°C to 9°C) were associated with cumulative increases in consultations with general practitioners, inpatient admissions, and deaths, with disproportionately larger effects among older adults (age >65 years). In contrast, attendance to the Accident and Emergency (A&E) department declined on cold days. Very hot days (>23°C) produced sharp same-day surges in A&E attendances and prescriptions, but cumulative effects were attenuated once the dips in the following days were included. Overall, suboptimal temperature exposure accounted for 3·0% (95% CI 1·2–4·7) of total health-care expenditure, with cold driving 64·4% of this burden. Robustness checks confirmed that these results were stable across alternative model specifications and lag structures.

Interpretation Temperature variability disrupts health-care delivery, straining service capacity during busy periods. These findings provide the first system-wide benchmark for understanding the health burden of temperature, highlighting potential discrepancies between mortality and access to care. Globally, health-care systems must anticipate these disruptions, and adaptation policies outside of health-care systems are essential to reduce health and financial pressures. Investments in climate-resilient infrastructure and strategies to protect vulnerable populations, especially older adults, are urgently needed.

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Nuffield Department of Primary Care Health Sciences, University of Oxford, Oxford, UK (P Fahr DPhil, J Schiff SM, Prof R Perera-Salazar DPhil); **Future of Cooling Programme, Oxford Martin School, University of Oxford, Oxford, UK** (P Fahr, Prof M McCulloch PhD, R Khosla PhD, Prof R Perera-Salazar); **Smith School of Enterprise and the Environment, School of Geography and the Environment, University of Oxford, Oxford, UK** (F Cohen PhD, R Khosla); **Chair of Energy Sustainability, Institute of Economics of Barcelona, Department of Economics, University of Barcelona, Barcelona, Spain** (F Cohen); **Heidelberg Institute of Global Health, Heidelberg University, Heidelberg, Germany** (A Jani PhD); **Ecole Normale Supérieure Paris-Saclay, Université Paris-Saclay, Gif-sur-Yvette, France** (M Petel MSc); **Department of Management Science and Engineering, Stanford University, Stanford, CA, USA** (M Petel); **Energy and Power Group, Department of Engineering Science, University of Oxford, Oxford, UK** (Prof M McCulloch)

Correspondence to: Prof Rafael Perera-Salazar, Nuffield Department of Primary Care Health Sciences, University of Oxford, Oxford OX2 6GG, UK
rafael.perera@phc.ox.ac.uk

Introduction

Climate change represents an urgent and intensifying challenge to human health, yet its broader impacts on health-care systems have received little attention. Research has predominantly focused on mortality and hospital admissions, leaving substantial gaps in understanding the implications for health-care resource use (HRU) and costs.[1–7] A global projection published in 2022, estimates that climate change could result in an additional 73 deaths per 100 000 individuals annually by the end of the century.[8] This projected mortality burden is comparable in scale to the current global mortality rates associated with all cancers or infectious diseases.

However, other domains of care, including primary care, have been largely overlooked, which has resulted in a crucial gap in the comprehensive assessment of how temperature exposure affects health-care systems. Additionally, the financial implications of temperature exposure remain unexplored, with no existing cost estimates quantifying the impact of daily temperature variations on system-wide health-care delivery.

This study addresses these gaps by presenting the first comprehensive analysis of the effect of temperature on a national health-care system, the National Health Service (NHS), in England. The analysis covers all major care

Research in context

Evidence before this study

We conducted a systematic review by searching Embase, MEDLINE, and Scopus from database inception to Feb 9, 2024, using terms such as “extreme heat”, “hospitalisation”, and “economics”, to synthesise the available evidence on health-care resource use (HRU) and direct health-care costs associated with temperature extremes. Full search terms are listed in the appendix (p 45). We found a marked increase in interest on this topic in recent years, with a rise in publications between 2019 and 2024. The latest research underscores the importance of analysing the full temperature spectrum, capturing delayed and harvesting effects, and accounting for seasonality in understanding the relationship between temperature exposure and HRU. Although most studies address these factors, several fall short, limiting the comparability and generalisability of findings. Overall, the review revealed substantial impacts of temperature exposure on HRU, particularly in secondary care settings. Notably, no studies investigated the effects on primary care or considered the entire health-care chain, from primary to secondary and specialist care. This gap highlights a crucial limitation in the research, hindering efforts to inform resource allocation and ensure health-care systems can adapt to the growing pressures of climate change.

Added value of this study

Our study is the first to quantify the impact of temperature exposure on HRU and costs across the full spectrum of care within a single national health-care system. Unlike previous research, which focused on isolated settings or specific care domains, this analysis encompasses both primary and secondary care, providing a system-wide perspective on the financial and clinical burden of suboptimal temperatures. By leveraging comprehensive national-level health-care data and employing advanced econometric methods, this study estimates that approximately 3% of total health-care costs are attributable to temperature exposure. This finding establishes a benchmark for understanding the impact of climate change on health-care systems. Our results also highlight the potential for cold exposure to drive costs, even in temperate climates, and raise awareness of the likely role of heat, which could become more prominent with rising global temperatures.

Implications of all the available evidence

The evidence, including findings from this study, underscores the urgent need for targeted interventions to mitigate the health and economic impacts of suboptimal temperatures on health-care systems. Cold exposure, a dominant driver of health-care costs due to its frequency and cumulative effects, highlights the importance of investing in protective measures, particularly for older populations who are disproportionately affected. Additionally, the projected rise in the frequency and severity of heatwaves due to climate change poses emerging risks, even in temperate regions such as the UK. This is confirmed by our study, which further highlights that all HRUs are weather-sensitive, leading to system-wide pressures. Policy makers must prioritise adaptive strategies, including climate-resilient infrastructure, cross-sectoral investments in preventive measures, and enhancements in health-care capacity to manage temperature-related surges in demand. Additionally, the study highlights the need for continued research, particularly into the long-term effects of temperature extremes on health-care systems and the potential for disparities in access to care. A coordinated global effort to address these challenges will be crucial to safeguarding health-care systems and protecting vulnerable populations as global temperatures rise.

See Online for appendix

domains within both primary and secondary care, including previously underexplored areas such as prescription drug utilisation. By linking health-care events to costs, we provide the first economic assessment of temperature’s impact on system-wide health-care delivery. This study highlights the substantial burden that temperature variability places on health-care systems and the populations they serve, offering actionable insights for clinical practice and policy development globally.

This study uses millions of patient records from the NHS, an institution particularly vulnerable to temperature extremes. Between 2000 and 2019, cold temperatures were associated with an estimated 60 573 excess annual deaths and hot temperatures with 791 excess annual deaths across England and Wales.[3] The UK Health Security Agency reported 2295 heat-associated deaths during the summer of 2023 and 1311 during the summer of 2024, based on defined heatwave periods in England.[9] Although cold temperatures have historically accounted for the majority of health burdens in northern Europe, projections indicate that the health impacts of heat might surpass those of cold by the end of the century.[10]

UK-specific projections suggest cold-related mortality will peak in the 2030s before declining midcentury, and heat-related mortality will rise steadily. Population growth and ageing amplify this burden, with mortality nearly threefold higher when demographic change is included (277·3 per 100 000 people *vs* 75·5 per 100 000 people).[11] Recent events, such as record-breaking high temperatures in Europe in the summer of 2022, which resulted in an estimated 72 000 heat-related deaths, highlight the pressing need to address the health consequences of temperature variability.[1]

By encompassing all major care domains and associated costs, this study aims to provide a crucial benchmark for assessing the broader implications of temperature on health-care systems. This study underscores the urgency of investing in climate-resilient infrastructure and adaptive policies, which are essential not only for England or the UK but also globally, because rising temperatures pose increasing risks to health-care provision worldwide.

Methods

Study design and data

In this economic analysis of resource use and costs, we used high-quality patient-level data from England from the Clinical Practice Research Datalink (CPRD) GOLD, from April 1, 2007, to June 1, 2019.[12] CPRD GOLD is a well established resource for epidemiological research, providing anonymised electronic primary care records from a representative sample of UK general practices, historically covering approximately 4–7% of the British population. The dataset comprises 4 366 981 patients registered with participating general practices.

To ensure comprehensive coverage of health-care events across the care continuum, the dataset was linked to Hospital Episode Statistics for secondary care and mortality data from the Office for National Statistics.[12–14] CPRD GOLD captures a broad range of health-care activities, enabling a detailed analysis of the effects of temperature exposure on health and the health-care system.

Daily counts of health-care events were aggregated at the general practice level. For primary care, these events included consultations, laboratory tests, and prescriptions, and for secondary care, they encompassed emergency care attendances, outpatient appointments, and inpatient admissions. Daily mortality counts were also calculated for patients registered in each practice. To standardise comparisons across practices, all counts were expressed as events per 1000 registered individuals.

Expenditures for each event type were calculated in 2020 GBP, following established national costing methodologies (appendix p 3), enabling us to estimate the financial impact of ambient temperature on the English NHS. To further examine population subgroups and better understand the health burden of suboptimal temperatures, the final dataset was stratified by sex (male and female), age groups (0–64, 65–74, 75–84, and >85 years), and disease categories (five distinct groups: respiratory, cardiovascular, endocrine, renal, and mental health).

Weather data were sourced from the Met Office HadUK-Gridded climate observations, which provide robust daily data for temperature and rainfall at a 5 km grid resolution across the UK.[15] The criterion for data use was whether it could be merged with the health data. Average daily temperatures were calculated using the minimum and maximum values, adhering to international standards. Weather data were matched to health-care events by date and location (details on the matching process are in the appendix p 4).

To maintain patient anonymity, CPRD GOLD restricts location data to ten Strategic Health Authority regions (eg, East Midlands, London, and North West), each covering an average area of approximately 13 000 km^2. Although Strategic Health Authority regions are relatively large, temperature patterns within these regions are geographically stable. To improve exposure measurement, we used population-weighted averages so that weather data better reflected the spatial distribution of health-care events within each region.

The CPRD Independent Scientific Advisory Committee approved the prespecified protocol (20_044).

Statistical analysis

The statistical model estimates the association between adverse health events and temperature, building on established methodologies commonly used to assess climate change impacts.[16] The full model specifications are in the appendix (pp 5–9), allowing for easy replication and adaptation to other datasets and countries.

We used a linear model; therefore, the coefficients represent the change in the number of cases per 1000 registered patients associated with a day in each temperature bin. We employed a fixed-effects framework to control for unobserved heterogeneity across regions and time periods.[17]

The model accounts for the non-linear nature of the temperature–health relationship, which typically follows a U-shaped curve, with more pronounced effects observed at temperature extremes. Delayed effects are also incorporated, because the impact of temperature on health might take time to manifest, with individuals potentially delaying the seeking of health care by several days or receiving an appointment a few days later. The baseline analysis estimates the cumulative impact of temperature over a 15-day period, reflecting a midpoint choice within the range of lag structures used in the literature, where studies have variously applied 10-day, 15-day, and 21-day horizons.[1,3,18,19]

The model also incorporates controls for location and seasonality. Practice-by-year fixed effects account for practice-specific characteristics, including the patient population, organisational culture, and annual variations in overall patient health within each practice. Practice-by-calendar-day fixed effects adjust for seasonal patterns and holidays that might influence health-care outcomes within each practice. This design effectively compares outcomes occurring on the same calendar days (eg, March 4 across different years) within the same practice, while accounting for variations between years (eg, 2011 *vs* 2012).

The approach assumes that temperature differences on the same calendar day across years, such as March 4, 2011, and March 4, 2012, are effectively random once adjustments are made for climate change trends. This quasi-random variation enables a causal interpretation of temperature effects, a methodology widely employed in the literature.[5,16] Because these data include all health-care resource uses, including those planned in advance, the fixed effects absorb variations in baseline health-care use that are uncorrelated with weather conditions.

We applied this model to seven primary outcome variables, representing daily counts per 1000 registered patients for (1) general practitioner consultations, (2) laboratory tests in primary care, (3) prescriptions in primary care, (4) emergency care attendances, (5) inpatient admissions,

	Count per day per practice per 1000 registered individuals (SE)	Cost per day per practice per 1000 registered individuals (SE)*	Average (SE)	15-day lagged average (SE)
Primary care				
General practitioner consultations	14·46 (11·14)	£421 (325)	..	..
Laboratory tests	10·44 (8·93)	£155 (134)	..	..
Prescriptions	44·82 (35·80)	£388 (310)	..	..
Secondary care				
Outpatient appointments	3·18 (3·02)	£499 (486)	..	..
Inpatient admissions	0·68 (0·54)	£1238 (1000)	..	..
Emergency attendances	0·76 (0·44)	£134 (79)	..	..
Deaths	0·02 (0·05)	..	..	..
Temperature bins, °C				
≤0	..	..	2·1% (14·3)	2·1% (8·9)
0–3	..	..	6·5% (24·6)	6·5% (14·4)
3–6	..	..	12·7% (33·3)	12·8% (18·7)
6–9	..	..	18·1% (38·5)	18·2% (21·6)
9–12	..	..	17·8% (38·2)	17·8% (20·1)
12–15	..	..	19·1% (39·3)	19·0% (22·2)
15–18	..	..	17·4% (37·9)	17·3% (24·2)
18–21	..	..	5·6% (23·0)	5·6% (13·1)
21–23	..	..	0·7% (8·1)	0·7% (3·6)
>23°C	..	..	0·1% (3·7)	0·1% (1·4)
Precipitation, mm	..	..	2·19 (3·92)	..
Mean practice size, number of registered patients	..	..	8779 (4497)	..
Number of observations†	656 502	656 502	656 502	656 502

The table summarises the key statistics for all observations and variables used in the baseline estimations. The counts of events per practice per day and associated costs have been weighted based on the number of registered patients in each practice. *All costs are in 2020 GBP. †Total number of daily practice-level observations during the study period. Temperature bins include all observations above the lower bound, up to and including the upper bound (eg, above 0°C and up to and including 3°C for the 0–3°C bin).

Table 1: **Summary statistics**

(6) outpatient appointments, and (7) mortality. Secondary outcomes were HRU-associated costs, calculated as daily health-care costs per 1000 registered patients. These costs were categorised by the primary outcome groups (1–6) and aggregated to compute total daily health-care costs (ie, the sum of categories 1–6).

The primary exposure variable was mean daily temperature, defined as the mean of the daily minimum and maximum temperatures. Evidence from a large multi-country study shows that although the optimal heat metric varies across locations, attributable risk fractions for mortality are nearly identical when using mean air temperature versus apparent temperature in the UK.[20]

Temperatures were grouped into ten bins (<0°C, 0–3°C, 3–6°C, 6–9°C, 9–12°C, 12–15°C, 15–18°C, 18–21°C, 21–23°C, and >23°C; temperature bins include all observations above the lower bound and up to and including the upper bound). The reference bin, 18–21°C, was chosen because it represents the temperature range typically associated with the minimum on the temperature mortality curve.[21,22] Temperature-associated excess events were estimated relative to this reference range. Each temperature bin was coded as 1 if the average temperature on day t in practice p fell within its range and was coded as 0 if it did not.

Notably, excessively hot days, defined as those with an average daily temperature exceeding 23°C were rare in the dataset. Such days typically corresponded to maximum daytime temperatures exceeding 30°C in 75% of cases or at least 27°C in 99% of cases. On average, approximately 1·4 days per 1000 days in the dataset had an average daily temperature above 23°C.

We also tested model robustness (appendix pp 10–44). We first examined on-the-day effects and short-term dynamics by re-estimating equation 1 (appendix p 6) with lag structures ranging from 1 day to 21 days, reporting cumulative effects for each health-care outcome and mortality (appendix pp 10–18). We then estimated separate models for minimum and maximum daily temperatures (appendix pp 19–20), explored seasonal patterns (appendix pp 21–22), impacts by deprivation index (appendix p 23), and respecified fixed effects (appendix pp 24–30). Additional analyses included re-estimation with wet bulb globe temperature as an alternative heat index (appendix pp 31–32), stratification by disease type (appendix pp 33–34), use of Poisson pseudo-maximum likelihood models instead of linear specification (appendix p 35), an assessment of precipitation effects (same-day and 15-day averages; appendix pp 36–37), and estimations with a distributed lag non-linear framework (appendix pp 38–44).[23]

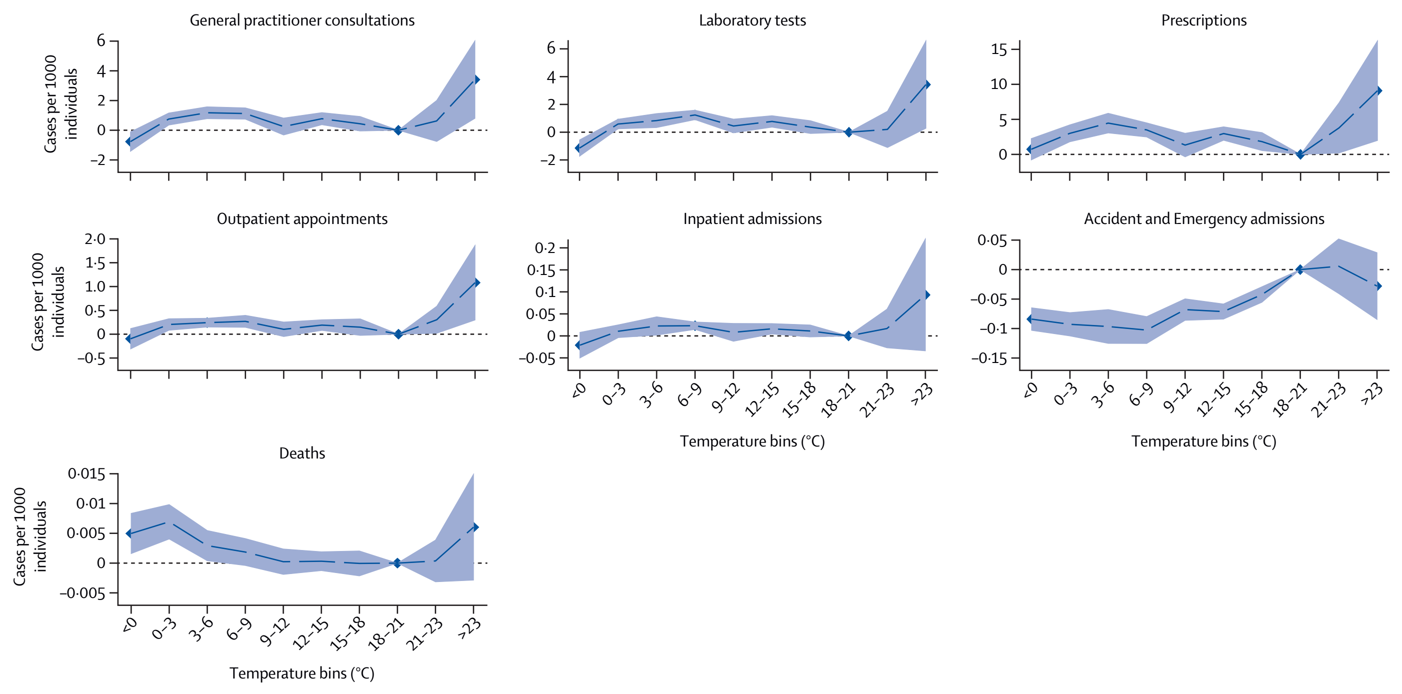

Figure: **The effect of temperature on health-care resource use and mortality**
The temperature bins are displayed on the x-axis, with 18–21°C being the reference bin. The effect of the temperature bins (y-axis) is the total effect after 15 days. Note that the y-axes scales are different for each plot. The light blue area corresponds to the 95% CI. Temperature bins include all observations above the lower bound and up to and including the upper bound. Model details are in the appendix (pp 4–9).

The data management was conducted in R (version 2024.04.1+748 and earlier), and the statistical analyses were performed using Stata version 18.

Role of the funding source

The funders of the study had no role in the data collection, data analysis, data interpretation, or writing of the report.

Results

The dataset included 244 general practices from across England, with an average practice size of 8779 registered individuals (table 1). On average, a general practice recorded 14·46 (SE 11·14) consultations per 1000 registered individuals per day. These consultations were associated with an average cost of £421 (SE 325) per 1000 registered individuals per day per practice.

The total average health-care costs, encompassing general practitioner consultations, laboratory tests, prescriptions, outpatient appointments, inpatient admissions, and emergency attendances, amounted to £2835 per 1000 registered individuals per day per practice.

The cumulative 15-day effects of temperature on health-care resource use and mortality per 1000 individuals registered at each practice is in the figure. Estimates reflect the immediate effect of temperature and the sum of the lagged effects over the subsequent 15 days. General practitioner consultations, prescriptions, laboratory tests, outpatient appointments, and inpatient admissions showed similar patterns. This finding is natural because these resources were used jointly to treat the same pathologies, and early diagnosis and intervention might avoid complications and secondary care intervention. For cold exposure, temperatures between 0°C and 9°C were associated with higher HRU compared with the reference temperature bin (18–21°C). However, HRU decreased at temperatures below 0°C. For example, subzero temperatures were associated with 0·76 (SE 0·33) fewer consultations per 1000 registered individuals relative to the sample average. A plausible explanation is that adverse weather conditions below 0°C, such as snow or black ice, might deter individuals from seeking health care. Combining the frequency of cold days reported in table 1 with the point estimates from the figure, we estimate that temperatures below 9°C are associated with an increase in mortality of approximately 46 cases (95% CI 7–85) per 100 000 person-years.

For heat exposure, the results should be interpreted with caution. Immediate effects of warm days on the outcome variables were seen (appendix p 10); however, uncertainty in the econometric results suggests that these effects might be offset by reductions in HRU on subsequent days due to harvesting effects. Harvesting refers to a phenomenon whereby temperature exposure accelerates health-care use or mortality among frail individuals, causing them to seek care or die a few days earlier than they would have in the absence of such exposure. This phenomenon typically results in a temporary spike in events, followed by a decline.

	Temperature			
	≤0°C	0–3°C	21–23°C	>23°C
General practitioner consultations				
Women	−1·08 (0·37)	0·89 (0·24)	0·83 (0·79)	3·92 (1·65)
Men	−0·44 (0·30)	0·65 (0·18)	0·44 (0·63)	2·91 (1·03)
Age, years				
0–64	−0·22 (0·24)	0·78 (0·15)	0·63 (0·61)	2·63 (1·08)
65–74	−1·98 (0·57)	0·47 (0·41)	0·22 (0·90)	6·68 (2·09)
75–84	−4·51 (1·02)	0·30 (0·68)	0·11 (1·58)	7·67 (2·44)
≥85	−3·99 (1·17)	2·12 (0·86)	−0·24 (2·18)	9·90 (3·40)
Prescriptions				
Women	0·48 (0·89)	3·15 (0·75)	4·45 (2·03)	9·85 (4·26)
Men	0·88 (0·67)	2·88 (0·50)	3·03 (1·63)	8·22 (3·01)
Age, years				
0–64	0·48 (0·45)	1·63 (0·35)	2·24 (1·14)	4·95 (2·01)
65–74	1·67 (1·51)	7·36 (1·88)	8·66 (4·63)	23·71 (7·50)
75–84	2·68 (3·00)	12·18 (2·52)	11·59 (6·35)	28·41 (13·35)
≥85	1·36 (3·38)	12·61 (3·51)	10·53 (7·26)	46·98 (15·75)
Laboratory tests				
Women	−1·55 (0·34)	0·56 (0·18)	0·08 (0·67)	3·88 (1·81)
Men	−0·75 (0·28)	0·64 (0·19)	0·32 (0·69)	2·96 (1·41)
Age, years				
0–64	−0·33 (0·19)	0·48 (0·12)	−0·06 (0·38)	1·66 (0·98)
65–74	−2·79 (0·80)	1·13 (0·59)	0·66 (1·6)	11·87 (3·65)
75–84	−6·38 (1·10)	1·30 (0·80)	−0·49 (2·44)	15·42 (4·13)
≥85	−7·06 (1·27)	0·51 (0·86)	3·64 (2·66)	16·82 (6·77)
Outpatient appointments				
Women	−0·08 (0·13)	0·26 (0·07)	0·35 (0·16)	1·25 (0·43)
Men	−0·11 (0·10)	0·14 (0·05)	0·26 (0·14)	0·91 (0·37)
Age, years				
0–64	−0·08 (0·10)	0·19 (0·07)	0·3 (0·16)	0·82 (0·31)
65–74	−0·02 (0·23)	0·51 (0·17)	0·69 (0·37)	2·97 (0·55)
75–84	−0·35 (0·33)	0·62 (0·19)	0·99 (0·36)	2·97 (0·94)
≥85	−0·54 (0·51)	0·32 (0·26)	0·28 (0·60)	5·81 (1·03)
Inpatient admissions				
Women	−0·013 (0·011)	0·024 (0·01)	0·065 (0·014)	0·121 (0·103)
Men	−0·03 (0·021)	−0·003 (0·01)	−0·032 (0·035)	0·064 (0·035)
Age, years				
0–64	−0·017 (0·007)	−0·009 (0·006)	0·013 (0·017)	0·06 (0·047)
65–74	−0·187 (0·059)	−0·023 (0·043)	−0·041 (0·067)	0·456 (0·286)
75–84	−0·103 (0·087)	0·107 (0·056)	0·14 (0·096)	−0·299 (0·47)
≥85	0·141 (0·142)	0·417 (0·075)	−0·016 (0·372)	0·500 (0·261)
Accident and Emergency admissions				
Women	−0·05 (0·01)	−0·08 (0·01)	−0·02 (0·05)	−0·06 (0·05)
Men	−0·12 (0·02)	−0·10 (0·01)	0·03 (0·03)	0·01 (0·06)
Age, years				
0–64	−0·11 (0·01)	−0·12 (0·01)	0·01 (0·03)	−0·02 (0·02)
65–74	−0·03 (0·03)	−0·07 (0·04)	−0·05 (0·07)	−0·03 (0·09)
75–84	0·04 (0·05)	0·02 (0·04)	0·12 (0·05)	0·02 (0·14)
≥85	0·15 (0·12)	0·20 (0·07)	−0·21 (0·17)	−0·25 (0·35)
Mortality				
Women	0·006 (0·003)	0·008 (0·002)	0·004 (0·003)	0·000 (0·004)
Men	0·003 (0·002)	0·006 (0·002)	−0·003 (0·003)	0·012 (0·006)
Age, years				
0–64	0·002 (0·001)	0·001 (0·001)	0·000 (0·001)	0·000 (0·003)
65–74	0·007 (0·006)	0·001 (0·009)	−0·012 (0·012)	0·036 (0·011)

(Table 2 continues on next page)

In most specifications, unusually hot days (>23°C) are not offset and would lead to the highest levels of health-care resource use, even after 15 days. Especially, point estimates in the figure, corresponding to our baseline specification, suggest that 3·41 (SE 1·33) additional general practitioner consultations per 1000 registered individuals occur on a day hotter than 23°C, compared with a sample average of 14·4 consultations per 1000 registered individuals, and 9·10 (SE 3·63) additional prescriptions per 1000 registered individuals, compared with a sample average of 44·8 prescriptions per 1000 registered individuals. These values represent increases of 23·7% for general practitioner consultations and 20·3% for prescriptions.

Excessive temperatures were associated with 0·09 (SE 0·06) additional admissions or appointments per 1000 registered individuals for inpatient care and 1·08 (SE 0·40) additional admissions or appointments per 1000 registered individuals for outpatient care compared with the sample averages of 0·68 for inpatient care and 3·18 for outpatient care. These values correspond to increases of 13·2% for inpatient care and 34·0% for outpatient care.

Interestingly, Accident and Emergency (A&E) admissions follow a distinct pattern, with the lowest rates on colder days (<0–9°C) and the highest on warmer days (>18°C). For the hottest temperature bin (>23°C), the point estimate in the figure appears slightly below zero, but this finding reflects the 15-day cumulative specification, netting a sharp same-day surge against subsequent short-term dips, combined with the rarity of such days (0·14% of observations), which results in wide confidence intervals. Same-day surges in A&E attendances were seen on very hot days (appendix p 10).

The results for mortality largely mirror those for general practitioner consultations, prescriptions, laboratory tests, outpatient appointments, and inpatient admissions. However, a key difference was observed at temperatures below 0°C: when HRU decreases, mortality remains elevated, highlighting the persistent health risks associated with extreme cold.

The breakdown of the results by age and sex for the most extreme temperature bins on both ends of the temperature distribution is in table 2. Coefficients are expressed as changes in cases per 1000 registered patients relative to the 18–21°C reference bin. Our findings suggest that older adults might have a greater vulnerability to temperature changes. For instance, prescription rates on days hotter than 23°C increase by 4·95 (SE 2·01) per 1000 patients for individuals aged 0 years to 65 years, and by 46·98 (15·75) for individuals aged 85 years or older. For each temperature bin, the magnitude of the coefficients is consistently larger for individuals aged 85 years and older compared with individuals aged 0 years to 65 years, highlighting the heightened vulnerability of older adults to temperature extremes.

Robustness checks were conducted to assess the consistency of the results presented in the figure and table 2 across different model specifications. Full details of these checks are in the appendix (appendix pp 9–37). Most notably, the figure highlights the effects of temperature exposure after 15 days, and additional results in the appendix explore short-term dynamics. For cold temperatures, the immediate impacts on the day (appendix p 10) were smaller than those observed after 15 days (figure), because the effects of cold tend to accumulate over time. This cumulative effect is evident across various lag periods and is consistently observed for all HRU groups and mortality (appendix pp 12–18).

Conversely, for high temperatures, there was a pronounced increase in HRU and mortality on the same day the heat occurs (appendix p 10), indicating an immediate effect of warm temperatures. When examining different lag periods (appendix pp 12–18), results for days hotter than 23°C were not consistently significant and point estimates sometimes showed negative but non-significant values. This variability suggests that the models struggled to precisely quantify the additional effect of hot days, possibly due to harvesting effects. Despite this variability, most specifications, including those reported in the figure, suggest that the health burden of heat could remain substantial even after accounting for harvesting effects. The variability in heat-related results was likely driven by the limited number of days hotter than 23°C in the dataset, leading to wide confidence intervals and increased uncertainty across model specifications.

For computational efficiency we relied on a linear specification, but we also estimated alternative models: (1) Poisson pseudo-maximum likelihood, (2) a distributed lag non-linear model (DLNM), and (3) models including precipitation effects. Across all these robustness checks, results were very similar to the baseline (appendix p 2). Notably, the DLNM results indicated that hot days were associated with substantial increases in A&E admissions, even after accounting for potential harvesting effects.

Summing up all HRU-associated costs into a single cost category allowed us to capture cross-correlations, for instance, the joint use of general practitioner consultations and prescriptions, or, conversely, that some entries might substitute for others (eg, that some health-care services might substitute for others, such as a hospital admission reducing the need for multiple outpatient visits or prescriptions). Aligning with previous analyses, we found significant cost impacts of cold temperatures (0–9°C; table 3). Total health-care costs increase at colder temperatures, such as £114 (SE 42) per 1000 individuals at 0–3°C, before turning negative below 0°C, with cost savings of £97 (64) per 1000 individuals. This finding reflects the lower HRU observed in the subzero temperature bin, as shown in the figure.

Additionally, based on the baseline model, excessive heat might result in very high costs on days exceeding 23°C, with an estimated increase of £486 (SE 257) per 1000 individuals. However, this effect is more uncertain, because some specifications with a different number of lagged temperature bins (appendix pp 12–18) suggest that the health impacts of heat might be offset by harvesting effects.

	Temperature			
	≤0°C	0–3°C	21–23°C	>23°C
(Continued from previous page)				
75–84	–0·003 (0·01)	0·026 (0·011)	0·009 (0·039)	0·05 (0·044)
≥85	0·067 (0·04)	0·157 (0·023)	0·004 (0·052)	0·046 (0·116)

Data are changes in cases per 1000 registered patients (SE). This table breaks down the results from the figure by sex and age. We only report the effect for four of the temperature bins, focusing on the total effect for low and high temperatures. All effects are after 15 days to account for delayed impacts and harvesting effects. Model details are in the appendix (pp 4–9). Temperature bins include all observations above the lower bound, up to and including the upper bound (eg, above 0°C and up to and including 3°C for the 0–3°C bin).

Table 2: **Effect of unusual temperature (most extreme temperature bins) by sex and age group; reference is 18–21°C**

The temperature bin-specific cost estimates from table 3, combined with the distribution of hot and cold days in the sample (table 1), allowed us to calculate the total cost of temperature exposure for the NHS in England. Overall, suboptimal temperature exposure outside the reference bin (18–21°C) led to an average increase in daily costs of £84 (SE 26) per 1000 individuals. Given that the total health-care costs in the sample amount to £2835 per 1000 patients per day, temperature exposure accounts for approximately 3·0% (95% CI 1·2–4·7) of all recorded costs.

This health-care burden was largely driven by the impact of cold temperatures on HRU and mortality. Although the data in the figure indicate that the cumulative effect of a single cold day might be smaller in magnitude than that of heat, colder days were far more frequent than excessively hot days. For example, days at 3–6°C represented 12·7% of the sample. Days between 0°C and 9°C alone accounted for 64% of all weather-induced costs (£54 [SE 13] per 1000 patients per day), followed by mild days between 9°C and 18°C (£31 [SE 13] per 1000 patients per day). In contrast, days warmer than 21°C contributed negligibly to the average daily costs per patient (£1·5 [0·63] per 1000 individuals), although this negligibility could change if warm days became more frequent. Very cold days (<0°C), by comparison, resulted in minor cost savings in the model, reducing average daily costs by £2 (SE 1·3) per 1000 patients annually compared with days at 18–21°C. However, this minor and infrequent cost-reducing effect was far outweighed by the larger and more common increases in costs associated with moderately cold days (0°C to 9°C). Taken together, cold days remained the dominant driver of temperature-related health-care costs.

Costs were also substantially higher for individuals aged 65 years and older (table 3) For the group aged 85 years and older, the baseline model estimates that a single day above 23°C could result in additional costs of £2485 (SE 499) per 1000 individuals. This finding stands in stark contrast to the £335 (183) per 1000 individuals estimated for the 0–65 years age group, highlighting the heightened vulnerability of older populations to temperature extremes.

	Temperature									
	<0°C	0–3°C	3–6°C	6–9°C	9–12°C	12–15°C	15–18°C	18–21°C	21–23°C	>23°C
Total	–£97 (64)	£114 (42)	£141 (45)	£158 (31)	£55 (50)	£108 (34)	£68 (44)	··	£119 (93)	£486 (257)
By resource use										
General practitioner consultation	–£19 (11)	£29 (8)	£37 (8)	£43 (8)	£15 (10)	£25 (7)	£11 (9)	··	£18 (23)	£72 (38)
Prescriptions	£6 (7)	£26 (5)	£39 (6)	£30 (4)	£12 (7)	£26 (4)	£16 (6)	··	£33 (16)	£79 (31)
Laboratory tests	–£17 (4)	£9 (3)	£13 (4)	£18 (3)	£7 (4)	£11 (3)	£6 (4)	··	£3 (10)	£55 (25)
Outpatient appointment	–£9 (18)	£35 (13)	£40 (9)	£47 (14)	£20 (14)	£32 (10)	£25 (14)	··	£47 (28)	£161 (58)
Inpatient admission	–£45 (28)	£31 (22)	£26 (21)	£36 (8)	£11 (18)	£28 (12)	£18 (14)	··	£18 (40)	£124 (114)
Accident and Emergency admission	–£13 (2)	–£16 (2)	–£13 (3)	–£17 (2)	–£9 (2)	–£13 (1)	–£8 (1)	··	£1 (4)	–£5 (6)
By sex and age										
Women	–£92 (58)	£153 (45)	£184 (44)	£208 (26)	£99 (53)	£142 (36)	£94 (48)	··	£200 (85)	£599 (352)
Men	–£107 (71)	£73 (40)	£98 (49)	£106 (37)	£10 (49)	£74 (34)	£39 (40)	··	£37 (105)	£368 (164)
Age, years										
0–64	–£69 (42)	£49 (39)	£96 (32)	£122 (31)	£46 (39)	£84 (33)	£64 (39)	··	£101 (78)	£335 (183)
65–74	–£427 (175)	£178 (129)	£219 (114)	£276 (99)	–£43 (135)	£109 (76)	–£1 (135)	··	£90 (260)	£1606 (683)
75–84	–£455 (253)	£507 (167)	£458 (219)	£476 (166)	£95 (136)	£366 (110)	£184 (146)	··	£579 (265)	£220 (1179)
≥85	£90 (468)	£1152 (282)	£908 (290)	£785 (217)	£276 (239)	£542 (199)	£241 (168)	··	–£77 (768)	£2485 (499)

Data are 2020 GBP per 1000 registered patients (SE). Results are for the total cost of temperature exposure on a given day, after 15 days have passed to account for delayed or harvesting effects. 18–21°C is the reference temperature bin. Methodological details are in the appendix (pp 4–9). Temperature bins include all observations above the lower bound, up to and including the upper bound (eg, above 0°C and up to and including 3°C for the 0–3°C bin).

Table 3: **Effect of temperature on health-care costs**

Discussion

This study provides the first systematic analysis of the effect of temperature on HRU and associated costs across both primary and secondary care within a single health-care system. Using granular data, we find that suboptimal temperatures account for approximately 3·0% (95% CI 1·2–4·7) of total health-care costs, with cold days (0–9°C) contributing to 64·3% of this burden. Reductions in health-care resource use during milder winters could be offset by new risks during summer months. Our findings underscore the substantial economic and clinical strain suboptimal temperatures place on health-care systems and highlight the potential for even health systems in temperate climate regions to face substantial challenges as climate change intensifies. Importantly, the disproportionate burden on older populations emphasises the urgent need for targeted interventions and policies to protect vulnerable groups globally.

The results align with existing literature demonstrating U-shaped relationships between temperature and mortality,[3] and our mortality and inpatient findings are consistent in both direction and magnitude with previous UK and international studies.[3,6,7] However, we also observed deviations from this pattern, such as reduced HRU at subzero temperatures, which might reflect individuals being deterred from seeking health care during adverse weather, likely exacerbating health risks given the elevated mortality observed in extreme cold. To our knowledge, no previous study has provided national-level estimates of temperature impacts on general practitioner consultations, prescriptions, or diagnostic testing, nor translated these into comprehensive cost estimates. This lack limits direct comparability but underscores the novelty and added value of our analysis.

The strength of this study lies in its comprehensive scope, capturing HRU across the continuum of care and extending the analysis beyond mortality to resource use patterns. This approach reveals that temperature sensitivity varies across health outcomes, reinforcing the need for broader analyses that include access to care, rather than solely focusing on mortality.

Nonetheless, our study had limitations. The translatability of these results requires caution. In the English NHS, primary care acts as a gatekeeper, so some excess demand during temperature extremes is absorbed outside emergency departments. In systems where A&E is the main entry point, surges might be more pronounced, and capacity constraints might concentrate demand differently across services. Climate context and adaptation capacity (eg, housing, urban design, and acclimatisation) will also shape both health risks and care-seeking behaviour. Thus, although our findings are relevant internationally, local context is crucial when extrapolating.

The analysis was also constrained by the relatively small number of very hot days in the dataset, which limits our ability to fully quantify the health burden of extreme heat. As climate change accelerates, the frequency and intensity of heatwaves will increase, likely introducing new risks that extend beyond the scope of historical data. Projections for the UK show that cold-related mortality is expected to peak in the 2030s before declining, and heat-related mortality will continue to rise, particularly under scenarios of population ageing.[11] Additionally, because the study focuses on individuals registered with general practices, it does not account for the costs associated with non-residents or unregistered individuals seeking emergency care.[24]

The results presented also offer a conservative estimate of the causal effect of temperature on HRU. By focusing on a 15-day window and controlling for seasonality, the broader role of temperature in driving seasonal patterns remains unexplored. Seasonal trends evident in mortality and emergency care attendances highlight fluctuations that might be shaped by both temperature and health-care system dynamics. For other forms of care, the absence of detectable seasonal patterns could reflect the NHS's capacity constraints and backlog, as providers adjust appointments to manage surges in demand. These adaptations, which are not captured by our model, suggest that the true impact of temperature on health care might be underestimated.

While each approach has strengths, our fixed effect framework was chosen for its ability to control finely for spatial and seasonal confounding in a high-dimensional panel dataset. Nonetheless, alternative parameterisations such as constrained DLNMs might provide complementary insights, particularly for characterising lagged responses. Our DLNM results suggest that heat could lead to a sharp increase in A&E admissions.

Given current capacity challenges in health-care systems globally, including the NHS, policy makers must prioritise investments in infrastructure and interventions that address temperature-related health risks. Efforts should focus on protective measures beyond hospital settings, such as community-based initiatives and primary care enhancements. Investments in cross-sectoral policies that mitigate the health and financial burdens of suboptimal temperature exposure are essential. Strengthening temperature-related action plans across levels of care, general practices, hospitals, and local authorities, will be crucial to safeguarding health-care systems and vulnerable populations as climate change accelerates.[25,26]

Contributors

PF and FC contributed equally to this paper and take joint first authorship. PF was involved in the project administration, conceptualisation of the research and study design, data collection and analysis, manuscript writing, reviewing, and editing. FC was involved in the funding acquisition, project administration, conceptualisation of the research and study design, data collection and analysis, manuscript writing, reviewing, and editing. JS, initially acknowledged for her work on the systematic review that supported this analysis, later became substantially involved in carrying out reviewer-requested additional analyses and revising the manuscript. AJ was involved in the funding acquisition, conceptualisation of the research and study design, and manuscript reviewing and editing. MP was involved in the data analysis and manuscript reviewing. MM was involved in the funding acquisition and manuscript reviewing. RK was involved in the funding acquisition, project administration, and manuscript reviewing and editing. RP-S was involved in the funding acquisition, project administration, data collection and analysis, and manuscript reviewing and editing. PF, FC, and RP-S act as guarantors and accept full responsibility for the finished work, the conduct of the study, had access to the data, and controlled the decision to publish. PF and FC conducted data management and, as such, accessed and verified the data. All authors had full access to the data in the study.

Declaration of interests

FC declares consulting fees from WHO for being a coauthor of a policy brief on investing in health, support for attending WHO-sponsored meetings on health equity, and other financial or non-financial interests through being a member of the WHO Europe New Economics Expert Group. All other authors declare no competing interests.

Data sharing

Access to the raw data is restricted due to its proprietary nature, because it was obtained through a purchased licence. The study protocol is available at CPRD Approved Studies (Study reference: 20_044). The programming code used in the analysis can be made available upon request from the corresponding author.

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