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To cite this article: Emily Ball *et al* 2025 *Environ. Res. Lett.* **20** 044042

View the article online for updates and enhancements.

IOP Publishing Environ. Res. Lett. 20 (2025) 044042 https://doi.org/10.1088/1748-9326/adc1e6

ENVIRONMENTAL RESEARCH
LETTERS

OPEN ACCESS

RECEIVED
16 October 2024

REVISED
12 March 2025

ACCEPTED FOR PUBLICATION
18 March 2025

PUBLISHED
28 March 2025

LETTER

No detectable decrease in extreme cold-related mortality in Canada from Arctic sea ice loss

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Keywords: cold-related mortality, Canada, Arctic amplification, sea ice loss

Supplementary material for this article is available online

Abstract
Arctic amplification (AA), the phenomenon by which Arctic surface temperatures are warming faster than the global average, may have significant unexplored impacts on temperature-related mortality in human populations across Canada. We explore the role of Arctic sea ice loss, a key driver of AA, in changing cold temperature extremes across Canada and their impact on human mortality. We use a multi-model ensemble of climate simulations from the Polar Amplification Model Intercomparison Project and a distributed lag nonlinear mortality model in 27 regions covering Canada to quantify the role of Arctic sea ice loss in changing human mortality in the cold season. We find that despite a robust increase in 5th percentile temperatures across eastern Canada, there is no detectable decrease in mortality associated with the most extreme cold, due to mortality in many regions having low sensitivity to warming of cold extremes. The study attributes the temperature-related mortality impact of a physical process, namely Arctic sea ice loss, and highlights Canada's robust adaptation to extreme cold.

1. Introduction

Extremely warm or cold temperatures are associated with a substantial mortality burden globally (Zhao *et al* 2021), and exposure to cold temperatures has been shown to be responsible for a large proportion of the temperature-related mortality burden in many regions (Vardoulakis *et al* 2014, Gasparrini *et al* 2015, de Schrijver *et al* 2022, Mitchell *et al* 2024, Shrestha *et al* 2024). Between 2000–2019, over 200 000 excess deaths per year globally have been attributed to cold spells, and of these, over 11 000 in Northern America (Gao *et al* 2024). Despite a decreasing number of cold spells globally per year over this time period, the excess death rate from cold temperatures was not shown to decrease (Gao *et al* 2024), which invites the question of whether cold weather will remain a significant burden of mortality as global temperatures rise (Kinney *et al* 2015). The majority of deaths attributable to cold are cardiovascular or respiratory deaths (Arbuthnott *et al* 2018). In Canada, Gasparrini *et al* (2015) found a relatively low minimum mortality temperature (MMT) of 6.5 °C, and estimated 4.46% of deaths are attributable to cold.

Several studies have explored temperature-related mortality in Canada, including future projections of mortality. Using an intermediate-level climate scenario, Martin *et al* (2012) found that in many cities a projected reduction in cold-related mortality would be balanced by an increase in heat-related mortality. Under a high-emission future scenario with an ageing population, net temperature-related mortality is predicted to increase across Canada, with this largely being driven by a projected increase in heat-related mortality and a smaller increase in cold-related mortality (Hebbern et al 2023). Many studies have investigated on heat-related mortality, including Boudreault et al (2024), who quantified total and extreme (above 95th percentile) heat-related burden on mortality and other health outcomes in Québec. Similarly, in a study focused on summer heat-related mortality in Montreal and found a projected increase in estimated numbers of deaths attributable to daily mean ambient temperatures during 2020–2037, with a large variability ranging from 34 to 174 deaths per summer, compared with 62 deaths attributable to daily observed mean temperatures in 1990–2007 (Benmarhnia et al 2014).

Populations are differently susceptible to temperature in different cities and regions. For example, one study found no strong association of cold temperatures with elevated mortality in Montreal, and hypothesised that prevalent indoor heating may alleviate the worst impacts of cold temperatures (Goldberg et al 2011). This is in contrast to Martin et al (2012), who showed an elevated risk of mortality at cold temperatures in Montreal, but less so in other cities including Québec city. These differences between studies may be linked to modelling choices and data availability, such as the choice to control for air pollution or the length of the mortality time series. Other studies have shown an elevated risk of death with exposure to ambient cold temperatures in Ontario (Chen et al 2016) and that mortality in Nunavut and the Northwest Territories is associated with extreme frequency of very low temperatures (Zhang et al 2024). In British Columbia, Shrestha et al (2024) found that the majority of temperature-related mortality between 2001–2021 was attributable to cold, and estimated that 0.38% of all deaths were attributable to extreme cold. Factors that affect susceptibility in different regions can include deprivation, education, age, racism, and percentage of indigenous population: these community-level indicators can affect a population's health status, access to health care and green space, and housing insulation quality (Zanobetti et al 2013, Son et al 2019, Jurgilevich et al 2023). Understanding the impact of the changing climate on mortality across cities, countries and globally is vital in planning effective public health strategies, such as cold weather warning systems. These can be based on temperature thresholds such as those proposed in Yan et al (2020), wherein excess hospitalisations and mortality in four regions in Québec are used to identify absolute thresholds below which a cold-weather warning system may be effective.

One aspect of climate change is Arctic amplification (AA), the phenomenon in which surface warming in the Arctic is greater than the global average. Recent work has estimated this amplification to be between three to four times the global warming rate since 1979 (Rantanen et al 2022, Zhou et al 2024). Arctic sea ice loss plays a central role in AA, and there is a strong positive ice-temperature feedback that increases the chances of further warming and sea ice loss (Screen and Simmonds 2010, Dai et al 2019, Jenkins and Dai 2021). Current Arctic sea ice cover is at its lowest level since 1850 (Intergovernmental Panel on Climate Change (IPCC) 2023), and consistently ice-free September conditions are anticipated by mid-21st century independent of emission scenario (Jahn et al 2024). Sea ice loss itself is associated with a reduced risk of cold air outbreaks over North America (Screen et al 2015b), which may thus impact population exposure to cold. However, there are substantial uncertainties in understanding the impact of Arctic sea ice loss on population exposure to cold. Observational evidence of trends in the frequency and magnitude of cold extremes is mixed, with some studies finding a strong decrease across the midlatitudes (Blackport et al 2024), and others indicating regionally varying trends (Cohen et al 2023). Future projections of Arctic sea ice loss are also uncertain due to contributions from internal variability, emissions scenario, and model uncertainty (Bonan et al 2021). Additionally, dynamic and thermodynamic effects complicate the surface air temperature response to sea ice loss (Ye et al 2024a).

To investigate the phenomenon of AA, its pathways and impacts, the Polar Amplification Model Intercomparison Project (PAMIP) simulations were designed as part of the Coupled Model Intercomparison Project 6 (CMIP6) (Smith et al 2019). The PAMIP simulations investigate the individual effects of sea ice concentration (SIC) and sea surface temperature (SST) changes in atmosphere-only climate models. Using the PAMIP simulations, previous research has identified a strong warming signal in winter temperature extremes (1-in-20 year events) from future Arctic sea ice loss at 2 °C global warming above pre-industrial, particularly in eastern Canada (Lo et al 2023). A similar spatial pattern in the lower 5th percentile temperature difference was found in a very large initial-condition single model ensemble following the same protocol (Ye et al 2024b). In this study, we investigate the role of Arctic sea ice loss on temperature-related mortality, focusing on these cold extremes in Canada, as understanding how Arctic sea ice loss contributes to temperature-related mortality is an important question to ask in order to plan effective public health strategies.

We aim to quantify the change in cold temperatures across Canada associated with Arctic sea ice loss, explore how the changing tail of the temperature distribution impacts mortality, and quantify this change. The rest of the paper is organised as follows. Section 2 describes the data and methods used, section 3 presents the results of the study, and sections 4 and 5 are the discussion and our concluding remarks.

2. Material and method

2.1. PAMIP+ simulations

To explore the impact of changing Arctic SIC, we use experiments from PAMIP. Specifically, we use atmosphere-only time-slice experiments with pre-industrial (piArcSIC), present-day (pdSIC), and future (futArcSIC) Arctic SIC, corresponding to experiments 1.1, 1.5, 1.6 described in Smith *et al* (2019). All three experiments are forced by present-day (year 2000–2001) SSTs. Present-day SST and SIC fields are obtained from observations using a 1979–2008 climatology (Smith *et al* 2019). Pre-industrial and future Arctic SICs are taken from CMIP5 simulations (pre-industrial or at 2 °C global warming from pre-industrial). Pre-industrial/future SSTs are imposed in grid-points where pre-industrial/future SIC deviates by more than 10% of its present-day value. Differencing these experiments provides an estimate of the contribution of Arctic SIC changes to AA and of the climate response to SIC loss. All simulations are run for at least 12 months with the first two months to be discarded, at a daily temporal resolution. Each model has a different number of ensemble members and spatial resolution, which are given in table 1. Further details of all PAMIP experiments, including spatial patterns of sea ice forcings, may be found in Smith *et al* (2019).

In addition to simulations from the PAMIP multi-model ensemble, we also make use of a large initial condition ensemble of N144-resolution (∼90 km) simulations from the Met Office Hadley Centre global atmospheric model Version 4 (HadAM4; Ye *et al* 2024b). These experiments follow the same protocol as PAMIP experiments pdSIC and futArcSIC, and have been used to show that large ensembles are required to robustly estimate extremes (Ye *et al* 2024b). For all simulations we restrict our analysis to cold temperatures within the months of December–January–February–March (DJFM). Circulation changes within the large HadAM4 ensemble are largely consistent with PAMIP results, and the large ensemble was used to show that ⩾1000 ensemble members are needed to simulate regional climate and extremes via sub-sampling (Ye *et al* 2024b).

We call the combined multi-model ensemble and HadAM4 simulations the PAMIP+ ensemble. All models used within this study are shown in table 1.

2.2. Berkeley earth surface temperature (BEST)

We use a gridded climate dataset (GCD) to associate observed temperature and mortality, rather than local station data, as our regions of study are spatially inhomogeneous and can be large. Using a GCD allows to assign an exposure to remote areas regardless of the presence or not of a weather station (de Schrijver *et al* 2023). Previous studies have shown that certain GCDs provide reliable daily estimates of ambient temperature (e.g. Spangler *et al* 2019, de Schrijver *et al* 2021). In Canada specifically, GCD data has been used previously to investigate temperature-mortality relations in British Columbia (Shrestha *et al* 2024), and GCD and weather station data were shown to produce similar temperature-mortality associations in Southwestern Ontario (Clemens *et al* 2021).

We use the BEST temperature product, which is a 1° × 1° GCD based on station observations (Rohde and Hausfather 2020). We use daily mean temperature in our analysis (rather than daily minimum) as more PAMIP models are available. It has been shown previously that these measures are highly correlated with similar predictive ability for mortality (Barnett *et al* 2010), including in Canada (Martin *et al* 2012).

2.3. Mortality data and health regions (HRs)

Daily recorded all-cause mortality was obtained via Statistics Canada. Coverage is across 111 HRs over the period 1 January 1981 to 31 December 2015, with HRs recorded according to their 2018 boundaries[8]. HRs are defined by provincial ministries of health and represent entities such as hospital boards or regional health authorities; individual HRs may be strictly urban or rural, or some combination of the two. For this study, we have combined the 111 HRs to provide a total of 27 aggregated HRs (AHRs). Individual HRs are aggregated within provinces and territories based on their location, climate, and population. AHRs are chosen such that they have a population over 200 000 where possible, and daily mortality count within an AHR is simply the total mortality from all sub-HRs. The AHRs, along with their total population according to the 2011 Census, are shown in figure 1. The date range over which data is available for different AHRs is shown in the supplementary information (SI; supplementary figure 1).

2.4. Population exposure to temperature

We use BEST to calculate observed temperature, using a population-weighting method, as in de Schrijver *et al* (2021). We use 10 km population polygons based on the 2011 Canadian Census (Government of Canada Agriculture and Agrifood Science and Technology Branch 2019) within each AHR. 2011 population data was chosen for this study as being the closest available to 2000–2001 present-day PAMIP+ simulations. We use a bilinear interpolation of temperature from BEST to the centroid of each population polygon. Temperature is then multiplied by the

[8] A map of all 111 HRs in 2018 can be found at Statistics Canada (2018).

Table 1. Models, resolutions, and number of ensemble members available for each experiment. Models for which all experiments are available are in bold. Horizontal resolutions are reported as number of longitude points (nlon) times number of latitude points (nlat). HadAM4 is separated from the PAMIP models by a dashed line.

Model Name	Resolution (nlon × nlat)	Ensemble size		
		piArcSIC	pdSIC	futArcSIC
AWI-CM-1-1-MR	384×192	100	100	100
CanESM5	128×64	—	300	300
CESM2	288×192	200	200	—
CNRM-CM6-1	256×128	—	275	275
FGOALS-f3-L	288×180	100	100	—
HadGEM3-GC31-MM	432×324	250	250	250
IPSL-CM6A-LR	144×143	200	200	200
MIROC6	256×128	100	100	100
NorESM2-LM	144×96	100	100	100
TaiESM1	288×192	—	69	69
HadAM4	288×109	—	1572	1572

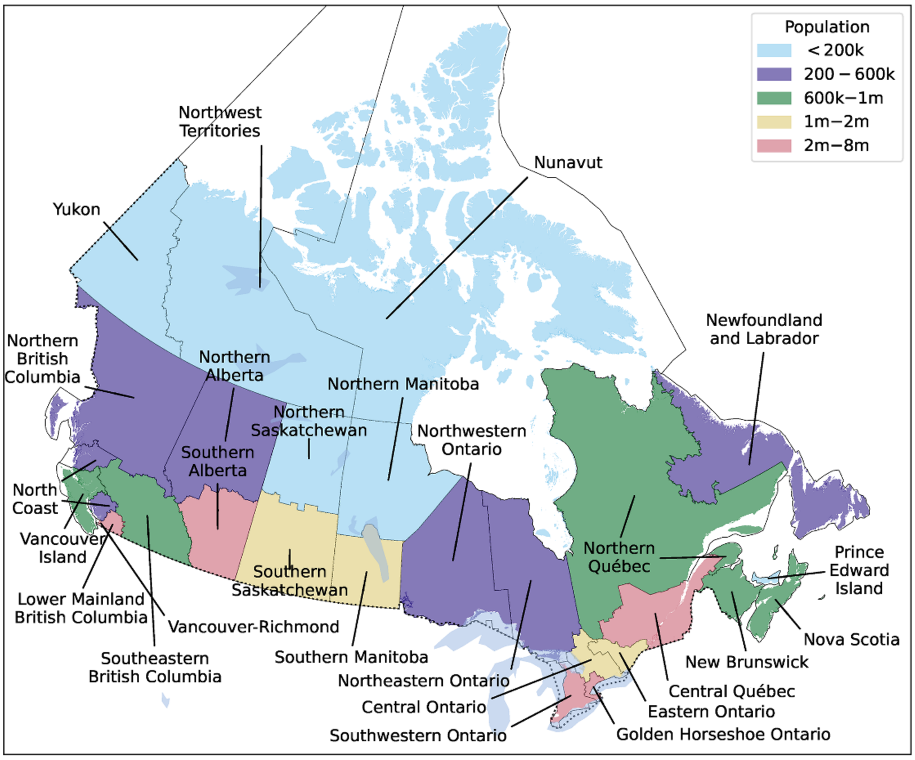

Figure 1. Map of regions studied, coloured by total population. Regions are aggregated from 111 individual health regions into 27 larger regions.

polygon's population and divided by the total population of the whole AHR. These weighted temperatures are then summed across the AHR to give a population-weighted average across the region.

2.5. Model temperature bias-correction

We perform a variance bias correction of PAMIP+ model temperatures to observed temperature from BEST. To bias-correct each model, we remove from each ensemble member the bias between the ensemble-mean DJFM population-weighted surface air temperature and the corresponding 1990–2010 mean BEST value, and variance is scaled to match the observed variance.

2.6. Distributed lag nonlinear model (DLNM)

We use a time-series regression model to associate temperature exposure and mortality over the coldest months, November to April. DLNMs have been used in many previous studies to investigate the relationship between temperature and mortality (e.g. Gasparrini *et al* 2015, Vicedo-Cabrera *et al* 2018 and others). A time-series quasi-Poisson regression with overdispersion is applied for each AHR separately to obtain temperature-mortality associations for each, following Gasparrini *et al* (2015). It is a spline regression model with knots fixed at the 10th and 50th percentiles, a reflection of the warm-season modelling in Vicedo-Cabrera *et al* (2021), with the knots fixed at lower percentiles to ensure flexibility at cold temperatures (e.g. Wang *et al* 2017, Zhan *et al* 2017). Five degrees of freedom per year are included to control for seasonal and long-term trends, and an indicator for day of week, as in Gasparrini *et al* (2015, 2016). The choice of natural splines allows the log-linear extrapolation of the function beyond the boundaries of the observed temperature time-series (Vicedo-Cabrera *et al* 2019). We include a lag period of 21 days to fully capture the long delay in the physiological effects of cold temperatures and to exclude deaths that were advanced by only a few days (harvesting) (Gasparrini *et al* 2015, Arbuthnott *et al* 2018), and cumulate the risk over this period to obtain an overall temperature-mortality relationship. For each location, the time series regression model is

$$\log\left[E\left(Y_t\right)\right] = \alpha + f(x_t;\vartheta) + s\left(t;\beta\right) + \sum_{p=1}^{P} h_p\left(z_{pt};\gamma_p\right) \tag{1}$$

where Y_t corresponds to the daily mortality count, $f(x_t;\vartheta)$ specifies the association with temperature x at time t, $s(t;\beta)$ represents the baseline trend which captures the effects of seasonal and long-term trends, and $h_p(z_{pt};\gamma_p)$ models the contributions of other confounders varying on a daily basis (Vicedo-Cabrera *et al* 2019).

The MMT at each location is obtained via the best linear unbiased prediction of this association, and corresponds to the temperature percentile in which mortality risk is minimum. We impose this to be between the 10th and 99th percentile of temperatures, to avoid the choice of extreme cold temperatures as MMT (e.g. Huber *et al* 2022, Boudreault *et al* 2024). The MMT varies across regions due to differences in healthcare settings, mean climate, and adaptation to cold or heat; in a global study of 420 locations, Yin *et al* (2019) found that on average, the MMT lay at the 78th percentile of the temperature distribution of each location. We use the DLNM to estimate the relationship between temperature and mortality based on their observed values (as described in section 2.4), then apply the model to PAMIP+ simulations to quantify the impact of changing SIC on mortality.

The overall cumulative exposure-response associations between temperature and mortality over 21 days of lag for all AHRs is shown in supplementary figure 1. The association is presented in terms of relative risk (RR), with a RR of 1 at the MMT. Note that the mortality data for the different HRs can vary throughout the time series. This is due to changes in the definitions of boundaries for certain regions, or systematic changes in reporting of mortality. The yearly mortality count for each AHR, and the years of data available are shown in supplementary figure 2. However, there is a degree of freedom within the DLNM that accounts for year, meaning that systematic changes in mortality are incorporated into our projections.

2.7. Calculation of attributable mortality

For each AHR, we apply the coefficients from the DLNM for each individual bias-corrected PAMIP+ model.

We calculate the sum of temperature-attributable deaths below the 5th percentile temperature for each model, obtaining both an estimate and the 5%–95% empirical confidence interval (eCI) via 500 Monte Carlo simulations of the DLNM coefficients. For the Monte Carlo simulations, for each climate model and each ensemble member, we assume a multivariate normal distribution of the best linear unbiased predictions of the reduced coefficients, as in Gasparrini *et al* (2015). These same possible exposure-response associations are applied across piArcSIC, pdSIC, and futArcSIC simulations—so that the exposure-response curve does not change between experiments (equivalent to suggesting no adaptation, and ensuring that the possible responses to temperature in each ensemble member is consistent across all three experiments). Climate model uncertainty, inter-model spread, and mortality model uncertainty are combined by calculating temperatures below the 5th percentile for each individual model, and the 500 Monte Carlo simulations for each. We take the average of the best estimates, weighting each model equally, to obtain the predicted change, and obtain the 5%–95% eCI from the Monte Carlo simulations across all models.

3. Results

3.1. Change in cold extremes

All models show a warming pattern in 5th percentile temperatures from pdSIC to futArcSIC simulations (figures 2(a) and (b)), and all agree that the strongest warming signal across the northern hemisphere lies in east Canada. The temperature difference in HadAM4 simulations agrees with that of the PAMIP ensemble, although the signal is generally weaker. Models disagree on the sign of change on the west coast of Canada. The strength of the signal in past change (pdSIC—piArcSIC) is generally more spatially equal across the northern hemisphere, although all models agree on a warming in east Canada (figures 2(c) and (d)).

Certain models predict a cooling of the 5th percentile temperature in some regions of Canada. For example, MIROC6 and TaiESM1 suggest a decrease in 5th percentile temperature around Vancouver in future change (figure 2(b)), and NorESM2-LM suggests a decrease across much of western and central Canada in past change (figure 2(d)). We

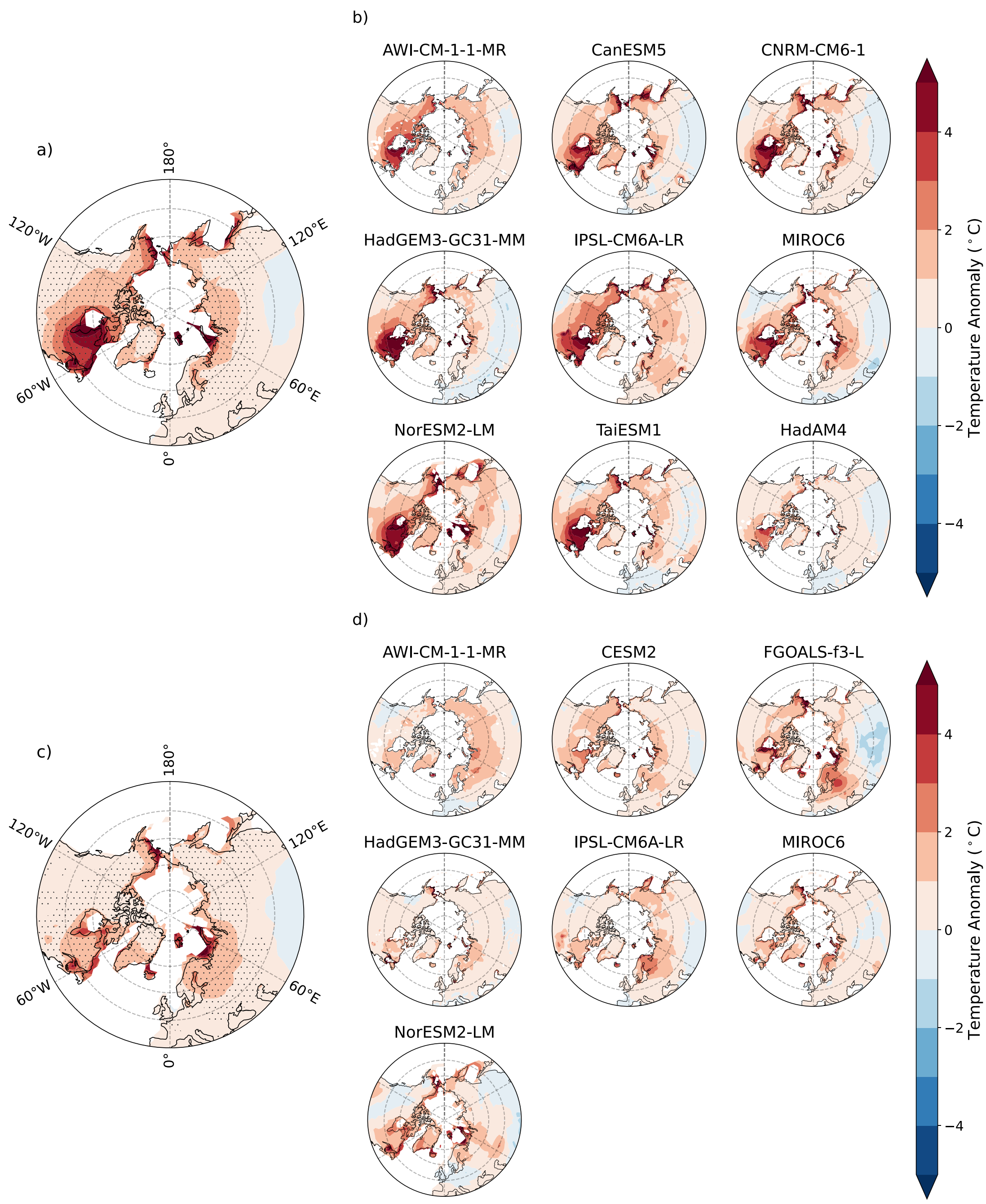

Figure 2. Responses in extreme cold temperatures to prescribed Arctic sea ice loss, defined as the 5th-percentile of the temperature distribution. (a) Multi-model mean future minus present (futArcSIC—pdSIC) 5th percentile difference; (b) individual model future minus present 5th percentile difference; (c) multi-model mean present minus pre-industrial (pdSIC—piArcSIC) 5th percentile difference; (d) individual model present minus pre-industrial 5th percentile difference. In panels (a) and (c), differences are stippled where 3/4 of models agree on the sign of change.

show where these changes are statistically significant in figure 3. Overall, the models are fairly consistent, and in the case of HadAM4, differences are in line with the multi-model mean difference.

Figure 3 shows the 5th percentile temperature difference for the 27 AHRs. There is an increase in 5th percentile temperatures for all AHRs in east Canada and all models (figures figure 3(a) and (b)) due to the direct warming from Arctic SIC loss in this region, in agreement with previous studies (Screen *et al* 2015a, Smith *et al* 2022, Lo *et al* 2023). All models agree on a positive warming signal in both past and future change in AHRs east of Saskatchewan (see figure 1), and in Nunavut (figure 3(b)). In Prince Edward Island and Northern Québec, both of which are located in east Canada, the multi-model mean difference indicates cold extremes could warm by over 3 °C from future Arctic SIC loss. In the present-day (pdsic) simulations, the 5th percentile of DJFM daily mean temperatures ranges from −37 °C in Yukon to −2.8 °C in Vancouver Island.

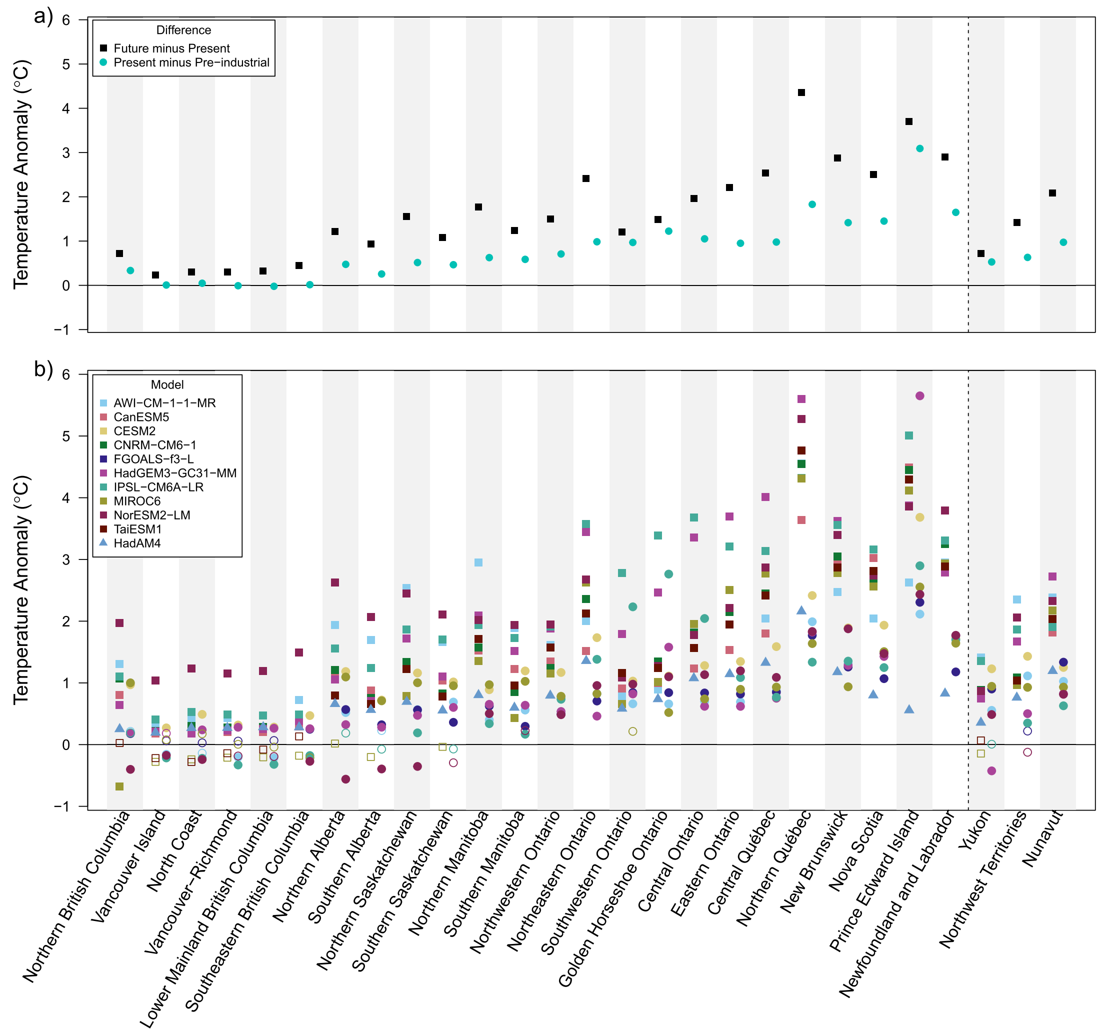

Figure 3. Difference in 5th percentile temperatures for all AHRs. AHRs are ordered approximately west-east, with the three territories shown last. (a) Multi-model mean and (b) all individual models. Square markers indicate future minus present (futArcSIC—pdSIC) 5th percentile difference. Circular markers indicate present minus pre-industrial (pdSIC—piArcSIC) 5th percentile difference. In (b), markers are open where the difference is not statistically significant.

In western AHRs, models disagree on the sign of change, and the magnitude of the change is generally weaker. In British Columbia (regions Southeastern BC to Northern BC), the multi-model mean difference is less than 1 °C in both past and future change. Some models predict a negative temperature change in these regions (figure 3). However, across all AHRs, the sign of change in the multi-model mean is positive, indicating warming cold extremes as a result of Arctic SIC loss. In all AHRs, the warming signal in cold extremes is stronger in future change compared to past (square markers compared to circular) in the multi-model mean.

3.2. Change in mortality burden

We investigate the change in the mortality burden associated with the change in extreme cold temperatures (5th percentile) by calculating the sum of the mortality associated with temperatures below the 5th percentile in each scenario. We present both relative future change (futArcSIC-pdSIC) and relative past change (pdSIC-piArcSIC). Note that the climate models used to calculate these two changes are different due to the availability of simulations for each model and scenario (see figures 3(b), 4(b) and table 1).

Figure 4(a) shows that that there is no detectable change in extreme cold-related mortality in any region, despite multi-model mean temperature differences of up to 4.5 °C. The multi-model means of certain regions (e.g. Northern Saskatchewan, Northwestern Ontario, Northeastern Ontario) suggest a predicted decrease in mortality, but the uncertainty in these regions is large. Conversely, the multi-model mean suggests a small increase in mortality in other regions (e.g. Prince Edward Island, and Newfoundland and Labrador), although again this is not a detectable increase and uncertainty is large. The estimated mortality change in general reflects the difference in futArcSIC-pdSIC

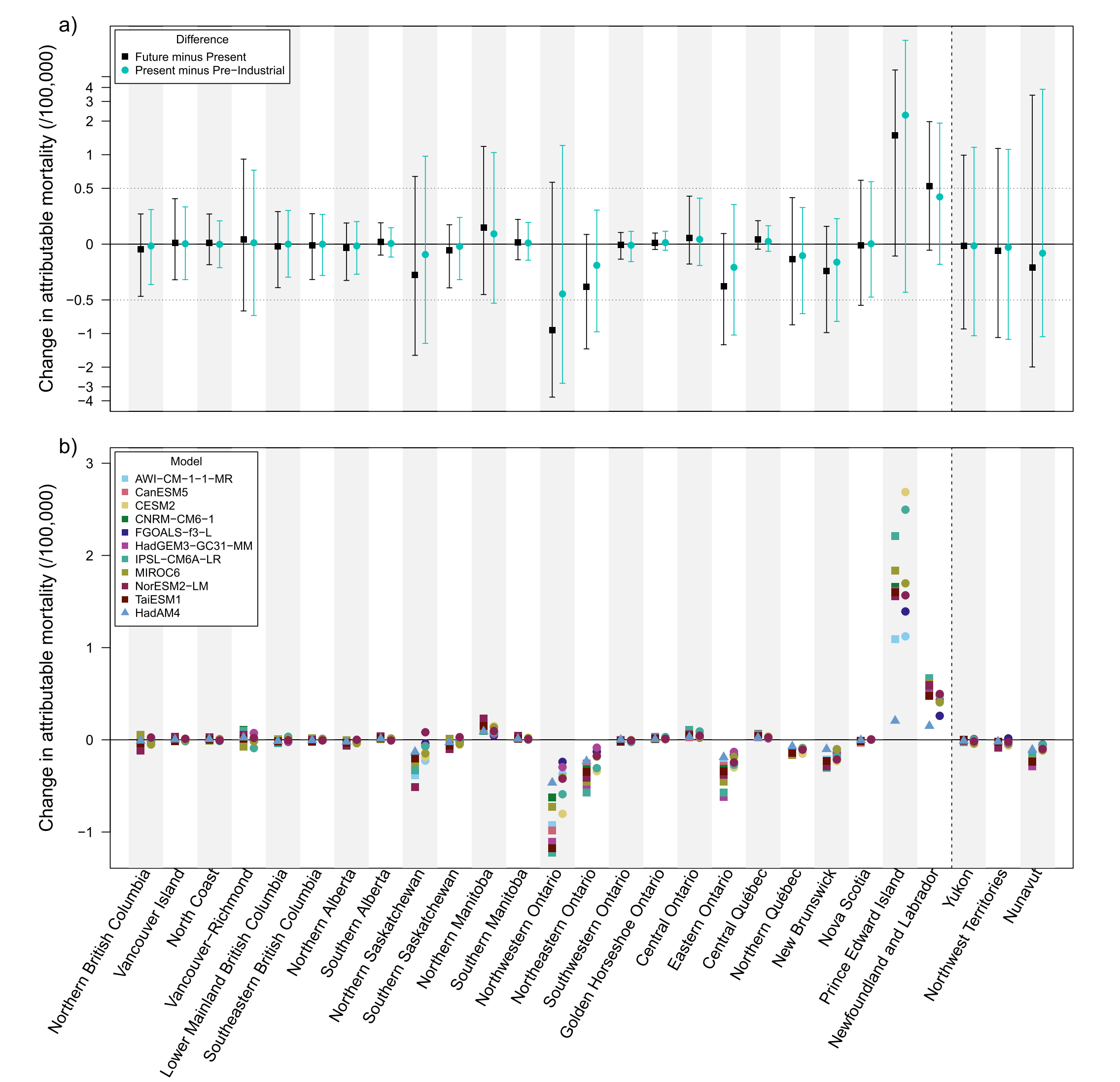

Figure 4. Change in attributable mortality per 100 000 associated with temperatures below the 5th percentile for all AHRs. AHRs are ordered approximately west-east, with the three territories shown last. (a) Multi-model mean and (b) all individual models. Square markers indicate future minus present (futArcSIC—pdSIC) difference in mortality from temperatures below the 5th percentile. Circular markers indicate present minus pre-industrial (pdSIC—piArcSIC) difference in mortality from temperatures below the 5th percentile. In (a), contributions from all models are weighted equally and the 90% confidence interval is shown. Note that panels (a) and (b) have different scales on the *y* axis. Panel (a) is scaled linearly between −0.5 and 0.5 and logarithmically beyond this.

and pdSIC-piArcSIC temperature changes: that is, the estimated mortality change is weaker in past change versus future change in most regions (circular markers compared square, figure 4). In many regions (e.g. Northwestern Ontario, Northeastern Ontario, Eastern Ontario, Northern Québec, and New Brunswick), estimates from all individual models agree on a decrease in mortality. In three regions (Northern Manitoba, Prince Edward Island, and Newfoundland and Labrador), estimates from all individual models agree on an increase in mortality (figure 4(b)). While these changes are all undetectable, that results from all climate models agree on the sign of change gives us some confidence in the anticipated sign of change in mortality burden.

Figure 5 illustrates how the shape of temperature-mortality curve controls the change in mortality for two AHRs. The first, Northern Québec (figure 5, left), has an approximately flat exposure-response curve at low temperatures, and the second, Newfoundland and Labrador (figure 5, right), has a positive gradient at low temperatures, i.e. RR peaks at around −10 °C and decreases at colder temperatures. As the 5th percentile warms in both regions, there is a differing response in the excess mortality. The mortality burden associated with temperatures below the 5th percentile may be understood as the area below the curve to the left of the vertical line for each scenario (figure 5, bottom row). In Northern Québec there is no change in this area despite a large increase in 5th percentile temperature, whereas in Newfoundland

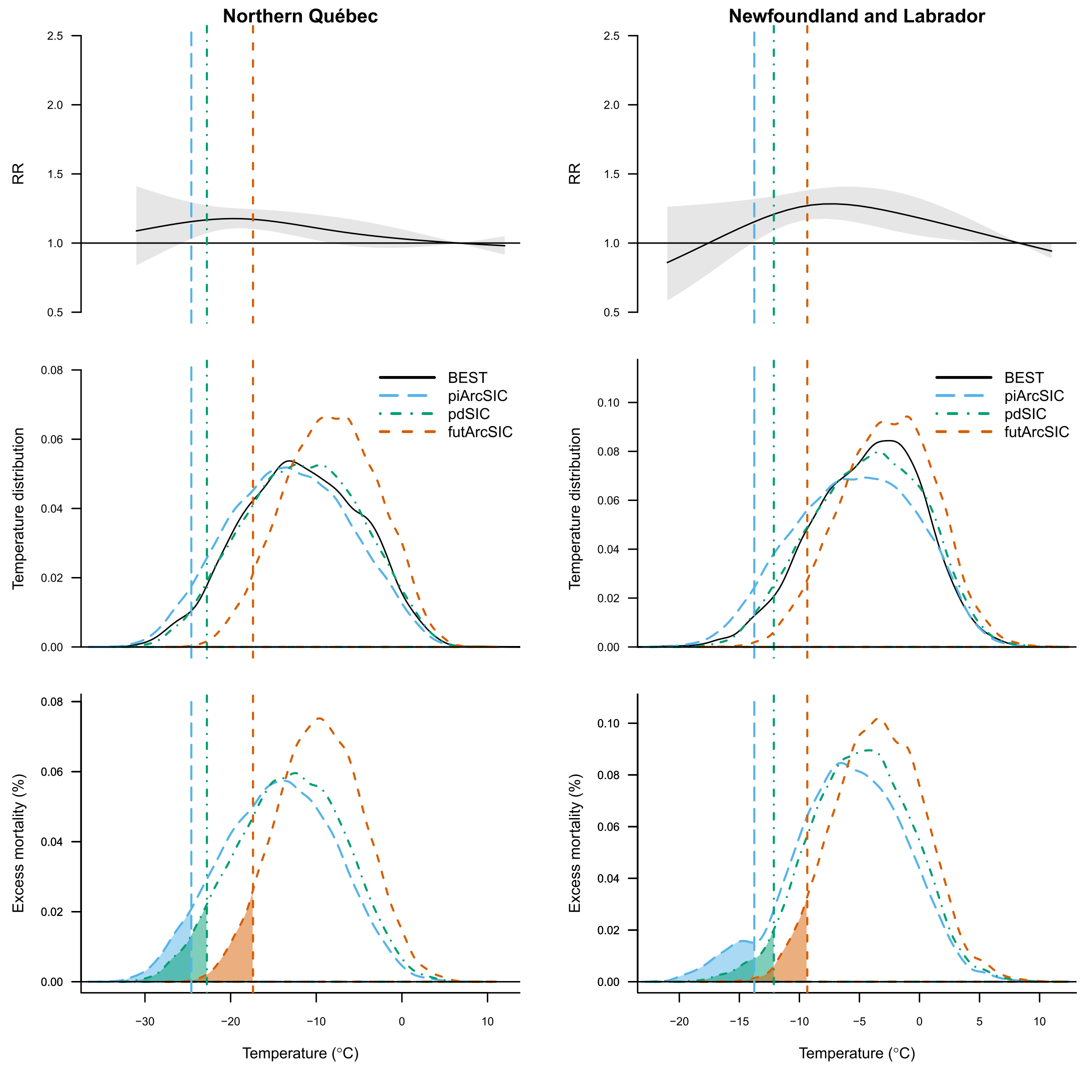

Figure 5. The exposure-response curve, temperature distribution, and temperature-related excess mortality in two illustrative AHRS. Top row; the temperature-mortality association. Middle row; the DJFM temperature distribution for all three SIC scenarios. Bottom row; the excess mortality from non-optimal temperatures for all three SIC scenarios. The 5th percentile temperature is shown as a vertical line for all scenarios. In the bottom row, the shaded areas correspond to the mortality associated with temperatures below the 5th percentile temperature.

and Labrador it is possible to see an increase, although this change is uncertain.

Given the large uncertainties in some AHRs, we performed sensitivity analyses of our results to the choice of cold threshold, to the knot placement within the DLNM, and to choice of AHR definition. We explore the impact of Arctic SIC changes on mortality associated with temperatures below the 1st and 10th percentile, and on total DJFM cold-related mortality (all temperatures below each region's MMT). We do not find any qualitative difference in terms of the sign of change or uncertainty in our results, indicating our results are valid across various cold thresholds (supplementary figures 4–6). For example, the mean change in mortality across all AHRs from temperatures below the 1st, 5th and 10th percentiles in the future—pre-industrial scenarios is always positive (respectively +0.017/100 000, +0.048/100 000, +0.044/100 000). The lack of detectable signal is also persistent under alternative knot placements within the DLNM (supplementary figures 7 and 8). Our results are also insensitive to choice of AHR scale, as investigating individual HRs yields no detectable change (supplementary figure 9). Even by aggregating across all HRs east of Manitoba, where the temperature signal is largest, yields no detectable change in mortality (not shown).

4. Discussion

Despite Arctic SIC loss leading to a clear warming signal in extreme cold temperatures experienced across Canada, particularly in the east, we have identified no detectable decrease in the mortality associated with these extreme temperatures. This is primarily linked to the relatively flat shape and large uncertainties in the exposure-response curve in many AHRs of Canada (figure 5 and supplementary figure 1). This is consistent with results from Martin *et al* (2012), who found a flat tail in several Canadian cities, and from Shrestha *et al* (2024), who found flat or decreasing RR at the cold tail of the exposure-response curves for regional health authorities of British Columbia. Across many regions in our study, RR is largely independent of temperature below a moderate cold threshold (supplementary figure 1). This flat curve explains why we do not see a strong signal in mortality, in contrast to previous studies of Canadian temperature-related mortality under future projected warming, which have primarily focused on heat-related deaths (e.g. Vicedo-Cabrera *et al* 2021). In studies that have also considered cold-related mortality, such as Gasparrini *et al* (2017), Hebbern *et al* (2023), the response to warming temperatures is somewhat weaker. Indeed, for the AHR Golden Horseshoe Ontario (which contains Toronto), the exposure-response curve is very similar to that in Gasparrini *et al* (2015).

The shape of the temperature-mortality association for Prince Edward Island, and equally for Newfoundland and Labrador, explains the anticipated increase in mortality (supplementary figure 1). As cold extremes warm in these regions, the estimated mortality increases as the temperature distribution shifts towards this higher risk peak. The shape of this association is consistent with previous studies (e.g. Martin *et al* 2012), and the protective effect of extreme cold may be linked to changes in population behaviour at such temperatures, for example as people reduce their time spent outdoors. Although this protective effect has been previously observed by Martin *et al* (2012), it is not clear the extent to which this shape may be an artefact of the modelling, given the relatively milder cold temperature exposures in these regions compared to other locations in Canada, which may result in a lack of statistical power at the lowest temperatures.

In regions with smaller populations spread over greater land area, or in regions with a shorter record of daily mortality, the uncertainty in the mortality modelling is large due to the lack of statistical power. In particular, we identify North Coast BC, Northern Saskatchewan, Northern Manitoba, Yukon, Northwest Territories, and Nunavut as regions with largest uncertainty from the DLNM. In North Coast BC, the RR is less than one at low temperatures, increasing to 1 at the MMT = 10.6 °C. In Yukon, the MMT = -8.6 °C but could have been at any temperature between −20 and 0 °C because the RR in this whole temperature range is minimum (Tobías 2017), suggesting that mortality results for these regions may not be robust. Nonetheless, in 21 of 27 regions, the exposure-response curve is well-constrained and we are confident in our results in these regions. The uncertainty in the modelling in parts of Canada highlights the need for continuous, reliable healthcare records.

Within uncertainty, our results suggest that Arctic SIC loss may reduce extreme cold-related mortality in certain regions (e.g. Nunavut). However, we have quantified only the temperature-related mortality burden from Arctic SIC changes, but have not considered how changes in SIC may lead to changes in morbidity, population behaviour, and direct mortality from SIC loss. Changing SIC increases risk of accidental impacts and injuries, related to unpredictability in sea ice travel (Durkalec *et al* 2014), as well as the mental health impact of sea ice becoming less known and less accessible in Inuit communities (Durkalec *et al* 2015). Furthermore, while our results are robust to the choice of cold temperature threshold, we have not considered the impact of the duration of cold spells, that is to say the persistence of surface temperature which may change with Arctic sea-ice loss (Lewis *et al* 2024), on mortality.

5. Conclusion

Arctic sea ice loss impacts surface air temperatures in the Arctic and sub-Arctic, and in particular has a warming effect on cold extremes. We have shown here that this warming is not associated with a detectable decrease in mortality across Canada, despite cold extremes warming by up to 4.5 °C in some regions. This lack of detectable signal is primarily linked to the relatively flat shape of the exposure-response curve at the coldest temperatures calculated for many regions of Canada, which indicates that these regions are equally well adapted to extreme cold as they are to milder cold weather. Our research suggests that Arctic SIC changes have not contributed to a detectable reduction in extreme cold-related mortality from the pre-industrial period, and are not anticipated to do so under a global warming of 2 °C.

Data availability statement

The HadAM4 dataset analysed is not publicly available due to ongoing work to create a permanent data deposition at Centre for Environmental Data Analysis (www.ceda.ac.uk/). Mortality data used in our study was obtained under a data-sharing agreement between Health Canada and Statistics Canada, and cannot be made publicly available. The data that support the findings of this study are available upon reasonable request from the authors.

Acknowledgments

The authors would like to thank two anonymous reviewers, whose comments and suggestions greatly improved the quality of this paper. E B and J A S are supported by the Natural Environment Research Council (NERC) under Grant Agreement

ArctiCONNECT (NE/V005855/1). P A G W was supported by a NERC Independent Research Fellowship (Grant No. NE/S014713/1). Y T E L is supported by the University of Bristol Climate Change and Health Fellowship, which is jointly supported by the Cabot Institute for the Environment and the Elizabeth Blackwell Institute for Health Research. K Y is supported by the UK NERC Grant NE/V005855/1 and the UKRI Horizon Europe Guarantee MSCA Postdoctoral Fellowship EP/Y029119/1. The authors declare no conflicts of interest. HadAM4 data are not publicly available.

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