Estimating the effects of temperature on mortality and hospitalisations under RCP2.6 and RCP8.5 scenarios in the short- and long-term by region in Chile: a population-based, modelling study

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Summary

Background In a warming world, it is generally accepted that increasing temperatures affect human health. In many regions of the world, however, these effects are poorly understood. To address this issue in Chile, we estimated the potential change in all-cause and cardiovascular and temperature-related (CVT) mortality and hospitalisations associated with four different climate scenarios by region.

Methods Using Chilean health data and ERA5 reanalysis data, we modelled the relationship between historical health outcomes and monthly temperature indices using Generalised Additive Models. After evaluating the models' predictive performance, we used them to estimate changes in health outcomes associated with bias-adjusted climate projections representing four scenarios: short-term (2031–2060) and long-term (2061–2090) periods under both Representative Concentration Pathways (RCPs) 2.6 and 8.5.

Findings Scenario-based health outcomes show clear north-south variations. Compared to historical levels, all-cause mortality increases by ~1.5% in northern regions but decreases by ~1% in southern regions across scenarios. CVT mortality decreases (0.2–3.6%), especially in the south; however, Arica and Tarapacá in the north show sharp increases (up to 30%) under warmer scenarios. Conversely, all-cause and CVT hospitalisations increase in northern/central regions (higher in summer, lower in winter), while southern/austral regions show slight decreases (~1%).

Interpretation These findings highlight the need for region-specific analyses and public health strategies in Chile. Northern regions might require plans that reduce the risk of heat-related mortality and morbidity, while southern regions might adjust healthcare services because of potential shifts in healthcare needs.

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Keywords: Public health; Climate change; Health planning; Climate models; Mortality; Morbidity

Introduction

Climate change poses several challenges to public health by changing the expected weather patterns that have historically influenced the development of human societies. Therefore, understanding the potential health effects of new weather patterns from a local perspective is critical for informing local public health preparedness and adaptation actions, and for reducing climate change-related health risks.

In particular, ambient temperature and extreme temperatures (e.g., cold or warm spells) are rapidly changing, with some parts of the world experiencing

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Translation: For the Spanish translation of the abstract see Supplementary Materials section.

Research in context

Evidence before this study

The spatial and temporal distribution of population exposure to extreme temperatures and the resulting health impacts (e.g., frostbite, heatstroke, and heat exhaustion) is changing due to climate change, challenging public health response. The health impacts associated with a change in the climate are usually assessed via setting-specific exposure-response functions. Currently however, most of the evidence comes from high-income countries: the resulting functions are not fully applicable to other settings, limiting a comprehensive global understanding of the problem. We searched PubMed in April 2025 using the search strategy ("extreme temperature" OR "hot" OR "heat" OR "cold") AND ("human health" OR "mortality" OR "morbidity") AND ("climate change") AND ("scenario" OR "projection") without restrictions on language or publication year. We identified five international studies using Chilean data (none from Chile). These studies used only four land-based monitors, limiting the ability to assess important regional variations in climate change-related health outcomes across Chile's diverse north-south geography. To date, no study has analysed the regional variation in health impacts of changing temperatures under different climate scenarios in Chile.

Added value of this study

This is the first study to estimate the potential impacts of climate change on temperature-related mortality and hospitalisations at a regional level in Chile, highlighting a diverse range of potential health impacts across age categories and geographical areas. The geographical diversity arises mainly due to the north-south extent of the country, with climates ranging from arid deserts to polar. This diversity is reflected in a clear north-south regional variation in scenario-based health outcomes compared to the historical climate, where northern regions (considered arid and dry) show the highest relative increases in mortality and hospitalisations and southern regions (considered temperate and polar) show relative decreases. This emphasises that previous national-scale studies, based on limited data, may not capture the full picture due to regional differences. Additionally, the analysis of hospitalisations broadens the focus to capture less severe but widespread health effects and is needed in the development of medium- and long-term resourcing strategies.

Implications of all the available evidence

The evidence shows that climate change is changing population exposure to potentially harmful temperatures, with resulting health outcomes varying depending on the frequency and intensity of these changes, as well as sub-national social characteristics. To effectively protect people's health, the results from this study demonstrate that a one-size-fits-all approach is insufficient. Local analyses are needed for tailoring public health approaches that reduce the exposure and/or vulnerabilities to climate hazards, for example, through the implementation of heat-health plans or mental health hotlines during specific weather events. Also, understanding the potential changes in healthcare demands under different climate scenarios helps public health preparedness and planning of services, which potentially enables better targeting of resources and improved health outcomes.

more frequent and intense hot temperature events than pre-industrial times.[1] These events, although not all linked to climate change, have been associated with severe impacts on human health, including higher prevalence of heatstroke, heat exhaustion, cardiovascular and respiratory diseases, and mortality.[2,3] Whilst the health impacts of changing temperatures are increasingly studied globally, global and region-specific exposure-response functions may not be directly applicable elsewhere due to differing vulnerabilities, environmental contexts, and healthcare systems.

In this sense, relevant local scientific evidence is critical to inform effective local public health adaptation strategies in the face of climate change. This is particularly true for Chile (and other similar countries), a country characterised by remarkable climatic diversity along its extensive north-south axis, where health impacts observed in one region may not be representative of others. Despite this heterogeneity, evidence concerning climate change-related health impacts remains limited. One study, which informed the first Health National Adaptation Plan, is now outdated as it was based on previous climate projections (i.e., CMIP3)[4] that have since been superceded.[5] Several international collaborative studies, whilst including Chilean data, typically utilised information from only a few land-based weather stations, predominantly located in central Chile.[6–10] This sparse spatial coverage has precluded a detailed examination of potential regional disparities in health outcomes across the country. Consequently, a significant knowledge gap exists regarding how different regions within Chile might be heterogeneously affected under various climate scenarios.

This study addresses these critical gaps by providing the first regional assessment of potential temperature-related mortality and hospitalisation changes across Chile under climate scenarios. Such a territorially focused analysis is essential to inform precise evidence for regional decision-makers, enabling the development of targeted public health interventions tailored to the specific risks and vulnerabilities of each diverse region. In particular, we estimated the potential change in all-cause and cardiovascular and temperature-related (CVT) deaths and hospitalisations associated with two climate scenarios across two future periods and all 16 administrative regions of Chile.

Methods

In this observational study, we analysed health outcomes (i.e., mortality and hospitalisations) at a monthly temporal resolution across all 16 administrative regions of Chile ("region" hereafter. Appendix Figure 1A). This monthly scale was chosen as it allowed us to focus on the health impacts pertinent to long-term climate change: understanding responses to projected climate scenarios necessitates focussing on long-term shifts in seasonal exposure patterns and the resulting cumulative health burdens, rather than solely on acute and short-duration physiological responses. The monthly resolution facilitated i) the detection of climate change signals (long-term trends, changed seasonality) whilst potentially reducing noise associated with daily variability, and ii) substantial optimisation of computational resources required for fitting complex spatio-temporal models across all regions and decades. To ensure our monthly analysis remained sensitive to climate-relevant variability, we employed diverse monthly temperature indices reflecting within-month extremes and spell durations (e.g., TXx, WSDI, SU).

Using these monthly indices and regional health data, we first estimated exposure-response functions defining the historical relationship between temperature and health outcomes. We then used these empirically derived functions to estimate the potential change in health outcomes with the latest set of high spatial resolution climate projections currently available for South America, under Representative Concentration Pathways (RCPs) 2.6 and 8.5 in the short- (2031–2060) and long-term (2061–2090). These two RCPs were chosen as they represent respectively the lowest and highest scenarios in terms of radiative forcing (i.e., the net amount of energy entering the Earth's atmosphere),[11] giving the opportunity to analyse potential health impacts across the whole range of scenarios for which projections are available.

We have checked the information in this manuscript against the suggestions from "The REporting of studies Conducted using Observational Routinely-collected health Data (RECORD) statement".[12]

Temperature indices

Monthly climate change-related temperature indices were calculated from historical (1990–2019) and projected (2031–2090) data. Several potential temperature indices were considered based on their relevance to climate change and human health.[13–15] Ten high temperature indices were included: monthly maximum value of daily maximum temperature (TXx), monthly maximum value of daily minimum temperature (TNx), monthly number of summer days (SU25 and SU30), monthly number of tropical nights (TR20), monthly number of warm days (TX90p), monthly number of warm nights (TN90p), warm spell duration index (WSDI), monthly number of heatwaves (HWn and HWx). Seven low temperature indices were included: monthly minimum value of daily maximum temperature (TXn), monthly minimum value of daily minimum temperature (TNn), monthly number of frost days (FD), monthly number of ice days (ID), monthly number of cold days (TX10p), monthly number of cold nights (TN10p), cold spell duration index (CSDI). One index focused on the monthly mean of the daily temperature range (DTR), and three on relative humidity (RHmin, RHmean, Rhmax) were included.

Collinearity among the monthly temperature indices was assessed. Pairwise correlations revealed varying degrees of association between indices (Appendix Section 6.2). Multicollinearity can hinder the interpretation of regression coefficients and reduce the precision with which each one is estimated, essentially because different linear combinations of collinear indices produce similar predictions so that it is hard to isolate their individual effects. In the current context however, the focus is on prediction (i.e., evaluating the effects of alternative climate scenarios) and the individual coefficients are of limited interest: they are considered in combination rather than individually and hence multicollinearity is not a problem, precisely because different sets of plausible coefficients yield similar predictions. Empirical confirmation of this is provided by, for example, in Morris and Lieberman, 2018.[16]

Temperature indices were aggregated spatially by region using population-weighting derived from the Global Human Settlement Layer (GHSL) dataset (see below) to ensure that the aggregated indices reflected the regional population exposure.

Historical climate data from 1990 to 2019

Temperature data (2 m temperature and 2 m dew point temperature) from 1990 to 2019 were obtained from the ERA5 reanalysis dataset[17] in October 2020. The datasets provide hourly estimates on a 0.25° × 0.25° latitude-longitude grid (approximately 28 km × 28 km at the Equator), offering better temporal and spatial coverage than land-based monitors.

Projected climate data from 2031 to 2090

This study used regional-scale climate projections at the same spatial resolution as the ERA5 dataset. At the time of writing, for South America the most recent set of such projections is from the Coordinated Regional Climate Downscaling Experiment (CORDEX), which employed CMIP5 (i.e., Climate model Intercomparison Project version 5) Global Climate Model (GCM) simulations to drive a set of higher-resolution Regional Climate Models (RCMs)[18] under various RCPs.[11] We used simulations from the GCM MPI-M-MPI-ESM-MR[19,20] coupled with the RCM ICTP-RegCM4-7,[21] which have shown a good reproduction of the observed surface air temperature over South America.[22–24] Daily maximum 2 m temperature, minimum 2 m temperature, and mean 2 m relative humidity data from 2031 to 2090 were downloaded from the C3S-CDS platform[25] in February 2022.

Bias adjustment was performed to correct for potential systematic errors in the climate model simulations (Appendix Section 3).

Health outcomes data

Datasets of deaths and hospitalisations (based on hospital discharges) were obtained from the Ministry of Health of Chile.[26] These official registries are considered reliable, benefiting from national coverage and routine quality assurance processes conducted by the relevant authorities.

The deaths dataset covered from 1990 to 2019 (total of 2,658,985 deaths) and hospitalisations from 2002 to 2019 (total of 29,402,229 hospitalisations), both containing anonymised individual-level information. The following variables were considered: date of the event, sex (i.e., female/male), age categories (5-year groups), region of residence, region of hospitalisation (as healthcare centre's region), length of stay (days), cause of the event (coded using the International Classification of Diseases (ICD) versions 9 and 10).

Besides mortality and hospitalisations due to all causes, we included cardiovascular diseases (e.g., ICD-10 I00–I99) as a major climate-sensitive health outcome and commonly associated with temperature extremes, complementing the specific but often underreported direct temperature causes (e.g., ICD-10 T67-68).[27] Mortality and hospitalisations due to CVT causes were identified according to ICD (Appendix Section 4). Deaths and hospitalisations were aggregated to provide counts for each combination of year, month, region, sex, and age categories.

Population data

Two population datasets were used: i) population size by year, region, sex, and age categories based on the 1992 and 2017 Chilean censuses,[28] and ii) the Global Human Settlement Layer (GHSL) that contained an estimated number of people living per grid cell at a spatial resolution of $0.0025° \times 0.0025°$ (approximately 250 m × 250 m at the Equator), for 1975, 1990, 2000, and 2015.[29] Annual population estimates were derived from both datasets using linear extrapolation and interpolation: this is justified because the rate of population change has varied little between the times for which data are available (Appendix Section 5).

Exploratory data analysis

Outliers were investigated and removed in cases where it could be established that they were unconnected with the aims of the study (Appendix Section 6.1). Historical mortality and hospitalisations showed systematic variations associated with time, seasonality (e.g., higher rates in cold months, i.e., May–September and lower rates in warm months i.e., December–March), region, sex (e.g., females had higher all-cause hospitalisation rates than males, but males had higher rates than females in all-cause and CVT mortality and CVT hospitalisations), and age categories. Also, the relationship between the outcome and any one of these variables itself potentially varies with the others, so that their potential effects must be considered in combination rather than individually. The relationship between health outcomes and population-weighted temperature indices showed that the effects of temperature indices may be considered separately from those of the other variables, with no obvious indication that the effects vary, for example, between regions, sexes, or age categories (Appendix Section 6).

Estimation of exposure-response relationships

For each response variable (all-cause mortality, CVT mortality, all-cause hospitalisations, and CVT hospitalisations), models were fitted to estimate the time trend and seasonality, together with variation associated with region, sex, age categories (5-year groups), ICD change (from ICD-9 to ICD-10 in 1997, only for CVT mortality), and population-weighted temperature indices derived from the ERA5 reanalysis.

We used Negative Binomial Generalised Additive Models (GAMs) with log link functions due to their flexibility and ability to capture relationships in the data, without imposing specific assumptions on the forms of those relationships.[30] The Negative Binomial distribution was chosen primarily to model the data's inherent variance-mean relationship (heteroscedasticity), ensuring reliable inference. The models were fitted using penalised smoothing splines, with the degree of smoothing determined using generalised cross-validation as implemented in the bam function[31] from the R package mgcv.[32] Time trends, included to represent long-term temporal variation that cannot otherwise be attributed to the climatic covariates, and seasonality were modelled using tensor product interaction smooths with cubic and cyclic cubic regression spline, respectively, and with a basis dimension of 10 in both cases. Region, sex, age category, and ICD change (from ICD-9 to ICD-10 in 1997) were included as factor variables (treatment coding), and the effect of population-weighted temperature indices was considered linear on the log scale. Covariate selection followed an iterative approach,[33,34] in which covariates were considered in groups successively expanding the model and then removing individual redundant terms.

Redundant terms were identified based on the Akaike information criterion (AIC),[35] the Bayesian information criterion (BIC),[36] and their effect on the model's predictions and the associated standard errors (Appendix Section 7). The latter criterion is intended to protect against the tendency of AIC to overfit when using large datasets[37]: a complex model may be selected using AIC despite its predictions being very similar, for practical purposes, to those from a much simpler model.

The final models for each health outcome are detailed in Appendix Section 8. Various checks were performed to verify the ability of the model to capture the structure in the data, along with checks to ensure that the spline basis dimensions were adequate (Appendix Section 9).

The models' predictive performance was then assessed using a five-fold cross-validation approach that has been suggested for use in similar contexts (Appendix Section 9).[38,39] The datasets were divided into five temporally-ordered, non-overlapping subsets. For each subset and response variable, the selected model structure was refitted to the remaining four subsets and then used to obtain out-of-sample predictions.[39] Prediction performance was assessed using the root mean squared error (RMSE), the mean absolute error (MAE), the mean and standard deviation of the standardised prediction error, and the log-likelihood.

Results from the cross-validation for the first and last subsets showed that it would be inappropriate to use the models for projecting health outcomes beyond the time period used for model fitting; however, the stability of the coefficients across the cross-validation suggests that the models could be used to explore the hypothetical effects of temperature indices associated with different climate change scenarios.

Assessment of potential consequences of future climate change on health outcomes

To assess the potential consequences of future climate change on health outcomes, the fitted historical models were used to generate predictions under different climate scenarios. This was achieved by replacing the historical temperature indices with the corresponding bias-corrected outputs from climate model simulations: this will lead to changes in the model predictions of health outcomes, which are solely attributable to the climate scenarios.

All-cause and CVT deaths and hospitalisations were estimated under two climate scenarios of bias-adjusted temperature indices across two future periods: i) RCP2.6 in the short-term, that is, between 2031 and 2060 (named S26 hereafter), ii) RCP8.5 between 2031 and 2060 (named S85), iii) RCP2.6 in the long-term, between 2061 and 2090 (named L26), and iv) RCP8.5 between 2061 and 2090 (named L85).

It is important to clarify that these scenario-based estimates i) represent the predicted difference in total health outcomes associated with the scenario-specific temperature regimes, compared to predictions using historical temperatures; and ii) are not absolute forecasts of future mortality or hospitalisation counts (i.e., these are hypothetical estimates, representing what health outcomes might have been observed during our historical study period if ambient temperatures had corresponded to those projected in each specific scenario).

Based on the similarities between some estimates and to align with age categories commonly used in public health in Chile, results were aggregated to five age categories (i.e., 0–4, 5–19, 20–39, 40–59, 60+). Model-based point estimates, standard deviation of the prediction errors, and 95% prediction intervals were obtained as described in Appendix Section 10.

Role of the funding source

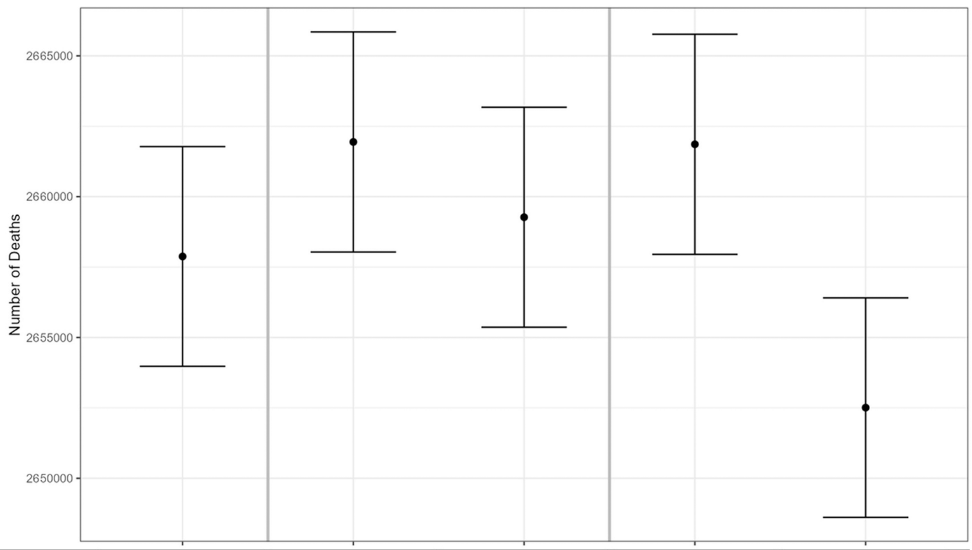
The funders did not have any role in study design, data collection, data analysis, interpretation, writing of the report.

Results

Overall, estimated outcomes vary by health outcome, region, climate scenario. Mortality shows slight increases or decreases depending on the scenario and the cause, while hospitalisations consistently increase across all scenarios at the national level. Seasonal patterns of health outcomes also slightly change depending on the region, age category, and climate scenario. Differences by sex mirror historical observations, and estimates for CVT outcomes are driven primarily by adults aged 20+ due to low rates in younger groups. All details in Appendix Section 11.

All-cause mortality

Overall, all-cause mortality is higher in S26 (+0.15%), S85 (+0.05%), and L26 (+0.15%), but lower in L85 (−0.2%) compared to the historical climate (Fig. 1). However, scenario-related changes compared to the historical climate show a marked decreasing gradient from north to south. From Arica to O'Higgins (except for Valparaíso), there is an increase in mortality across most of the scenarios, ranging from +2.3% (Tarapacá, L85) to +0.1% (Metropolitana, L85): see Appendix Figure 1A for region locations. Then, from Maule to Magallanes, there is a consistent decrease in mortality, ranging from −0.1% (Maule, S26) to −2.1% (Aysén, L85) (Fig. 2). Seasonally, estimates for the 60+ age group, particularly from Arica to Metropolitana regions, show slight increases during summer months (i.e., December–March) and slight decreases during winter months (i.e., June–August) across all scenarios



Scenario / Estimates	Historical 1990-2019	RCP2.6 2031-2060	RCP8.5 2031-2060	RCP2.6 2061-2090	RCP8.5 2061-2090
Point estimate	2,657,877	2,661,944	2,659,271	2,661,861	2,652,508
PI95%: LL	2,653,977	2,658,035	2,655,366	2,657,952	2,648,611
PI95%: UL	2,661,777	2,665,853	2,663,176	2,665,770	2,656,405

Fig. 1: Model-based estimates of all-cause mortality by scenarios. Points represent point estimates and horizontal bars represent the upper limit (UL) and the lower limit (LL) of the 95% prediction interval (PI 95%).

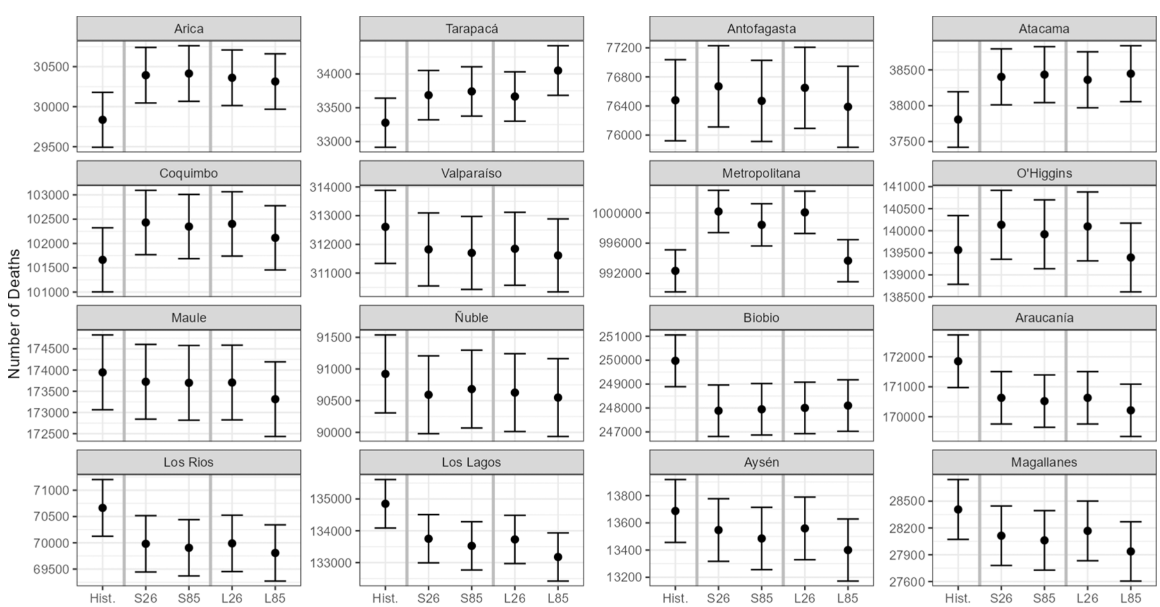


Fig. 2: Model-based estimated number of all-cause deaths for the historical climate (Hist.) and hypothetical scenarios by region. NB: these plots are not on the same vertical scale because of the variation between regions. Plot layout (from top to bottom and left to right) reflects the north-south alignment of the regions. Points represent point estimates and horizontal bars represent the upper limit and the lower limit of the 95% prediction interval.

compared to the historical climate (Appendix Figures 51A–66A).

Cardiovascular and temperature-related mortality

Overall, CVT mortality across all scenarios is between 0.5% and 0.8% lower than the historical climate, particularly in S85 and L85 (Fig. 3). However, this overall decrease is reversed in the northernmost regions: Arica and Tarapacá show CVT mortality increases up to almost 30% higher in L85 (Fig. 4). From Arica to Metropolitana region, CVT mortality over summer months is markedly higher in warmer scenarios (S85 and L85) compared to the historical climate, particularly for age category 40–59 and 60+. In southern regions, there is a slight decrease in winter months (Appendix Figures 67A–82A).

All-cause hospitalisations

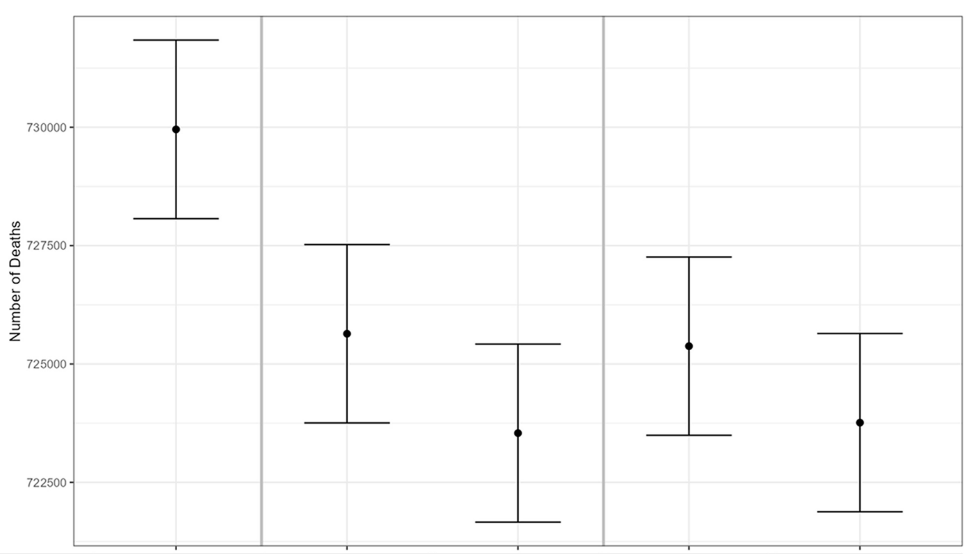
Overall, all-cause hospitalisations are significantly higher across all scenarios than the historical climate, with the highest estimates in S85 (+3.6%) and L85 (+4.2%) (Fig. 5). In general, estimates are between 0.2% (Araucanía, S26) and 7.2% (Metropolitana, L85) higher across all scenarios compared to the historical climate in northern, central, and central-south regions (i.e., from Arica to Araucanía); and between 0.3% (Los Rios, S85) and 2.5% (Magallanes, L85) lower in southern regions (i.e., from Los Rios to Magallanes) (Fig. 6). There are also seasonal variations in these changes. In northern regions (from Arica to Atacama) estimates are higher in summer and lower in winter in S85 and L85, particularly for age categories 20–30 and above. In central regions (from Coquimbo to Biobio), all scenario-related hospitalisations are higher over most of the year compared to the historical climate (Appendix Figures 83A–98A).

Cardiovascular and temperature-related hospitalisations

Similar to all-cause hospitalisations, CVT hospitalisations are between 1.5% and 2% higher across all scenarios than the historical climate (Fig. 7). Overall, CVT hospitalisations increase compared to the historical climate in northern and central regions (i.e., from Antofagasta to Biobio), and decrease in southern regions (i.e., from Araucanía to Magallanes) (Fig. 8). In terms of seasonality, northern-central (i.e., from Atacama to O'Higgins) regions show a slight increase in CVT hospitalisations from autumn to spring months across all scenarios compared to the historical climate, while southern regions, CVT hospitalisations are lower over most of the year across all scenarios (Appendix Figures 99A–114A).

Discussion

This study is the first to estimate the potential temperature-related health consequences associated



Scenario / Estimates	Historical 1990-2019	RCP2.6 2031-2060	RCP8.5 2031-2060	RCP2.6 2061-2090	RCP8.5 2061-2090
Point estimate	729,955	725,639	723,540	725,377	723,761
PI95%: LL	728,069	723,755	721,660	723,494	721,878
PI95%: UL	731,841	727,523	725,420	727,260	725,644

Fig. 3: Model-based estimates of CVT mortality by scenarios. Points represent point estimates and horizontal bars represent the upper limit (UL) and the lower limit (LL) of the 95% prediction interval (PI 95%).

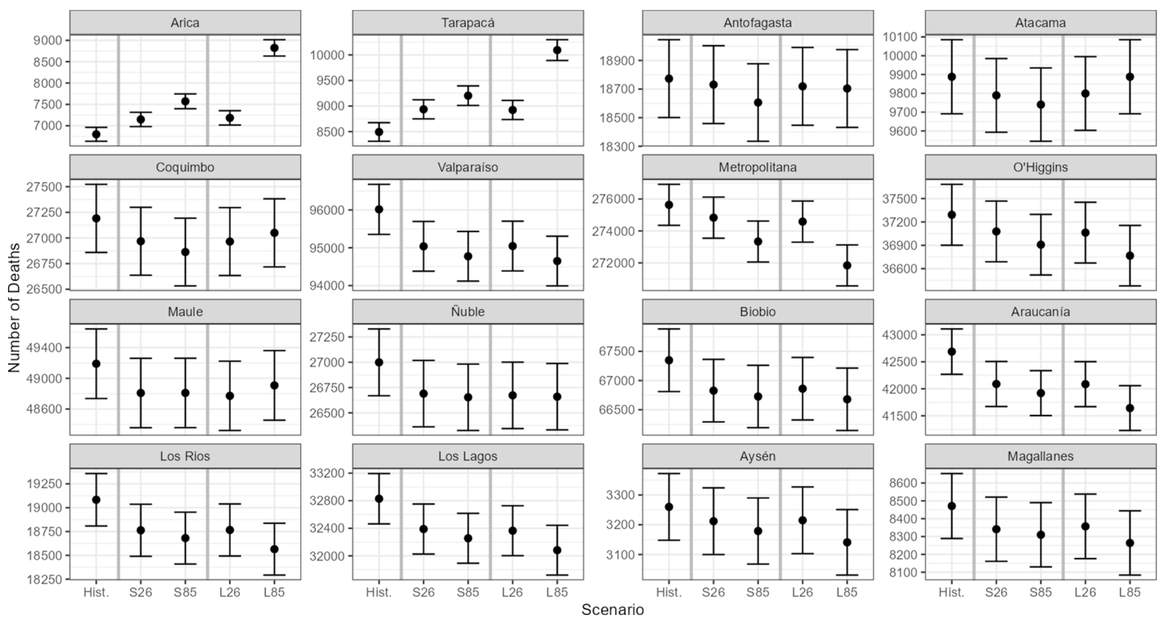
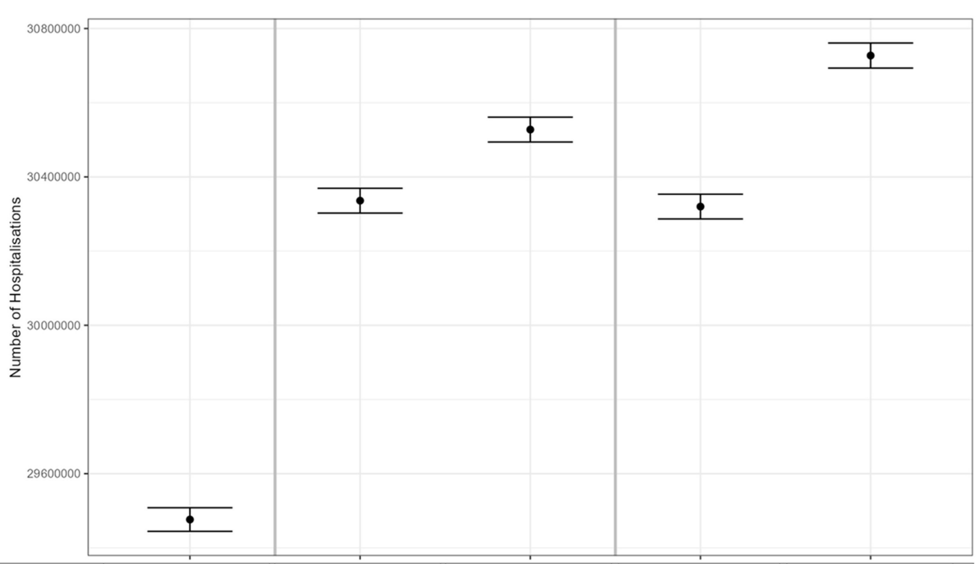


Fig. 4: Model-based estimated number of CVT deaths for the historical climate (Hist.) and hypothetical scenarios by region. NB: these plots are not on the same vertical scale because of the variation between regions. Plot layout (from top to bottom and left to right) reflects the north-south alignment of the regions. Points represent point estimates and horizontal bars represent the upper limit and the lower limit of the 95% prediction interval.

with climate change at a regional level in Chile. Overall, the variation in estimates between scenarios and regions reflects a combination of factors: the magnitude of projected temperature changes, underlying regional demographics, and the issue that most of historical mortality and morbidity burden has been associated with low, rather than high, temperatures.[40]



Scenario / Estimates	Historical 1990-2019	RCP2.6 2031-2060	RCP8.5 2031-2060	RCP2.6 2061-2090	RCP8.5 2061-2090
Point estimate	29,476,304	30,335,878	30,527,529	30,319,945	30,727,092
PI95%: LL	29,444,458	30,302,476	30,493,943	30,286,551	30,693,311
PI95%: UL	29,508,150	30,369,280	30,561,115	30,353,339	30,760,873

Fig. 5: Model-based estimates of all-cause hospitalisations by scenarios. Points represent point estimates and horizontal bars represent the upper limit (UL) and the lower limit (LL) of the 95% prediction interval (PI 95%).

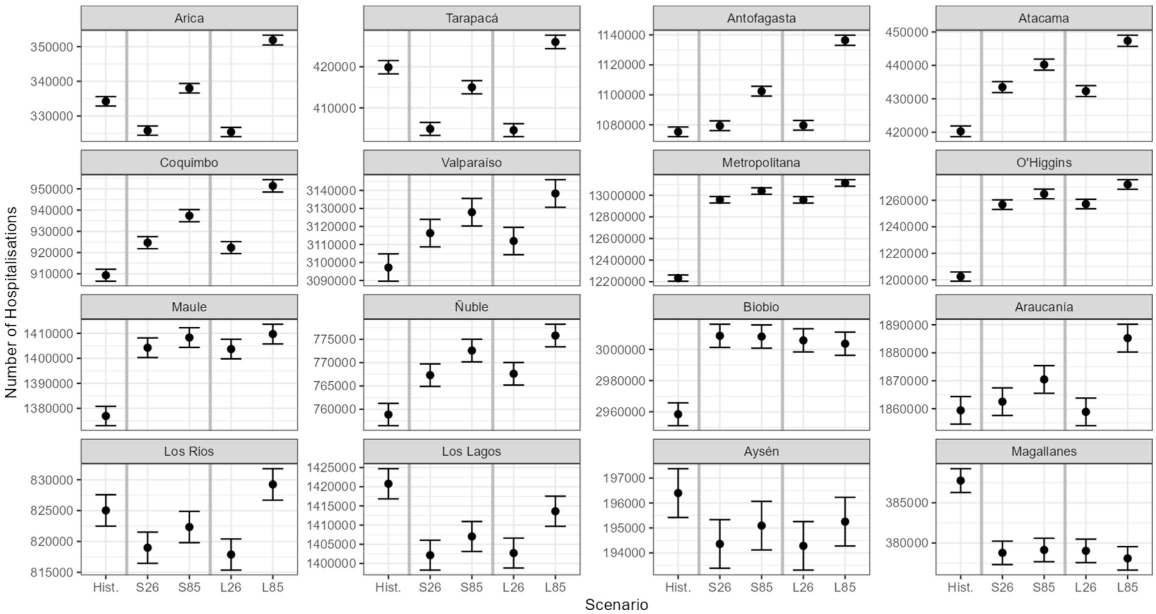
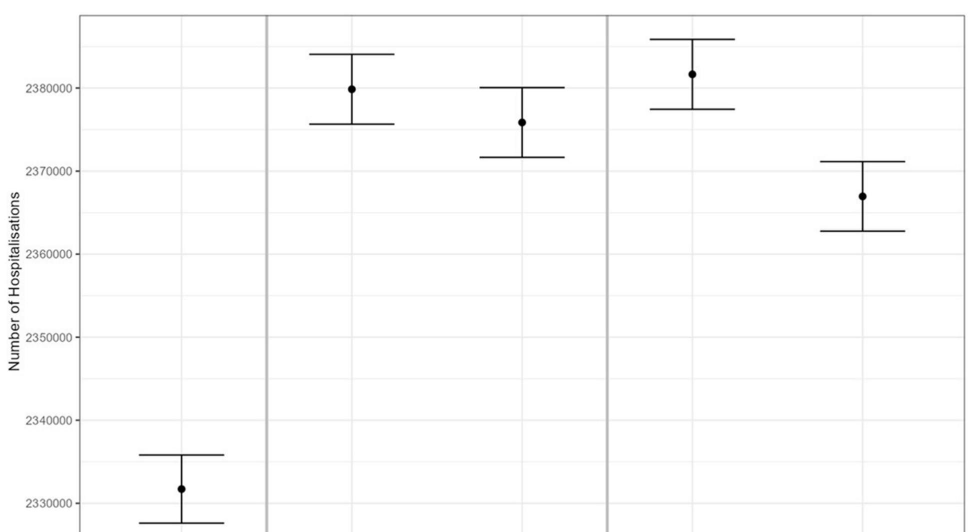


Fig. 6: Model-based estimated number of all-cause hospitalisations for the historical climate (Hist.) and hypothetical scenarios by region. NB: these plots are not on the same vertical scale because of the variation between regions. Plot layout (from top to bottom and left to right) reflects the north-south alignment of the regions. Points represent point estimates and horizontal bars represent the upper limit and the lower limit of the 95% prediction interval.

High temperature indices show a considerable warming pattern across the country, particularly in northern regions (i.e., from Arica to Coquimbo), which are considered arid to warm temperate regions.[41] For example, the median of the ambient temperature increases by approximately 5 °C and monthly warm nights (TN90p) triple in L85 by 2090 compared to the historical climate. Less intense warming trends of these



Scenario / Estimates	Historical 1990-2019	RCP2.6 2031-2060	RCP8.5 2031-2060	RCP2.6 2061-2090	RCP8.5 2061-2090
Point estimate	2,331,710	2,379,857	2,375,856	2,381,653	2,366,955
PI95%: LL	2,327,608	2,375,652	2,371,658	2,377,445	2,362,767
PI95%: UL	2,335,812	2,384,062	2,380,054	2,385,861	2,371,143

Fig. 7: Model-based estimates of CVT hospitalisations by scenarios. Points represent point estimates and horizontal bars represent the upper limit (UL) and the lower limit (LL) of the 95% prediction interval (PI 95%).

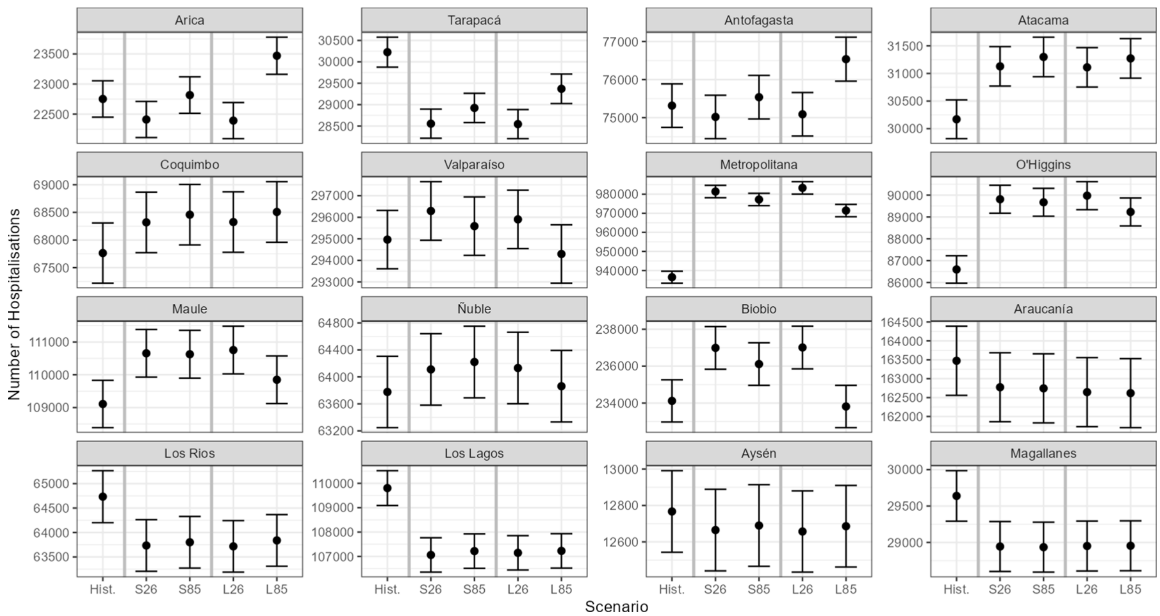


Fig. 8: Model-based estimated number of CVT hospitalisations for the historical climate (Hist.) and hypothetical scenarios by region. NB: these plots are not on the same vertical scale because of the variation between regions. Plot layout (from top to bottom and left to right) reflects the north-south alignment of the regions. Points represent point estimates and horizontal bars represent the upper limit and the lower limit of the 95% prediction interval.

indices are observed in central to southern regions, which are considered warm temperate to polar regions.[41] Low temperatures also show a warming pattern, meaning fewer events of cold temperatures. These shifts in temperature indices are reflected in the changes in health outcomes.

Differences in health outcomes across the country likely relate to physiological limits of heat tolerance.[2,42] In the northern and central zones, projected warming may exceed the body's heat tolerance capacity, particularly during summer. Conversely, warming levels in the central-south, southern, and austral zones might reduce the significant historical risk from cold exposure without reaching dangerous heat thresholds, potentially lowering cold-related mortality and morbidity. Our findings suggest mortality estimates are highly sensitive to reduced cold exposure, while hospitalisation estimates appear more responsive to warming. Consequently, the overall national estimates presented here represent a net balance between these competing effects: significant reductions in cold burden can lead to net mortality decreases, while increased warming appears to drive net hospitalisation increases. This balance varies by region, outcome, and scenario intensity, explaining nuances like the S85 vs L85 all-cause mortality difference or patterns between RCP2.6 and RCP8.5.

Evidence from 2001 to 2020 in the United Kingdom indicates a net mortality decrease linked to milder winters, alongside net increases in hospital admissions (including injuries) on warmer days compared to colder ones.[43] Complementary evidence suggests that intentional injuries and violence increase on warmer days and nights,[44–46] which might be triggered by physiological discomfort, frustration, and changes in daily activities.[47] Two additional studies suggest that all-cause hospital admissions and respiratory-related intensive care demand increase under warmer climate scenarios.[48,49]

Based on this evidence, the current study suggests one possible explanation for the increased rate of hospitalisations under warmer scenarios in Chile. In northern and in some central and central-south zones, this increase, particularly in summer, may be associated to heat-related causes. In south and austral zones, however, this increase might be more influenced by changes in social behaviour that lead to a rise in hospitalisations due to injuries. As our models are not capable of distinguishing between heat-related causes and behavioural-mediated factors, this interpretation represents just one possible explanation of the results. Overall, the analysis identified five distinct zones in Chile based on varying patterns of temperature indices and estimated health outcomes (Table 1), which carry significant public health and social implications for Chile, particularly given existing socio-economic disparities.

In northern regions, already burdened with high poverty rates,[50] the estimated increases in all-cause mortality (~2%) and CVT mortality (up to 30%) has

Zones	Characteristics
Northern zone	The northern zone includes northern regions (i.e., Arica, Tarapacá, Antofagasta, Atacama, and Coquimbo), generally characterised by similar projected changes in climate indices. However, two sub-zones emerge based on estimated health outcomes. The first covers Arica and Tarapacá (sub-tropical regions) where warmer scenarios are associated with higher estimated mortality and hospitalisations compared to the historical period, with notable increases under L85 in summer, autumn, and spring. The difference in estimated all-cause mortality between these two regions might relate to a decrease in estimated deaths in winter in Arica under L85, not seen in Tarapacá. In Arica, scenarios S26 and L26 correspond to lower estimated hospitalisations, contrasting with the increases estimated under warmer scenarios S85 and L85. The second sub-zone covers Antofagasta, Atacama, and Coquimbo. Here, estimated deaths under S26 and L26 are higher than under S85 and L85, respectively, which might be linked to projected increases in some low-temperature indices (cold nights/days) in S26/L26; however, overall warming is associated with estimated increases in summer deaths and decreases in winter deaths. Estimated hospitalisations increase with warmer projected temperatures, and estimated CVT hospitalisations also appear sensitive to more extreme warming, with Antofagasta (L85) showing a marked increase compared to Atacama and Coquimbo. In summary, projected extreme warming in northern regions is associated with potentially significant increases in overall estimated rates of human mortality and morbidity. Differences in estimated health outcomes between geographically contiguous regions (e.g., Antofagasta vs Atacama) may reflect differences in population characteristics and distribution.
Central zone	The central zone (from Valparaíso to O'Higgins) also shows two sub-zones. Valparaíso (first sub-zone), with population concentrated coastally, shows a warming pattern, but less intense than the north, alongside significant decreases in low-temperature indicators. This aligns with estimated health outcomes: warmer scenarios are generally associated with decreases in estimated all-cause deaths, CVT deaths, and CVT hospitalisations, especially in winter. However, estimated all-cause hospitalisations show the opposite pattern, increasing with warmer temperatures particularly in autumn and winter. This potential mortality benefit aligns with evidence suggesting people in moderate cold climates could benefit from reduced cold-related outcomes under warming.[48] The contrasting pattern for all-cause hospitalisations might be explained by increases in other temperature-sensitive causes (e.g., gastrointestinal) or by behavioural changes leading to illness/injury requiring admission under warmer conditions (discussed further below). The second sub-zone (Metropolitan and O'Higgins regions) shows overall warming but also slight increases in cold night/day indices, especially in L85. Overall, the warmest scenario (L85) is associated with lower estimated all-cause deaths, CVT deaths, and CVT hospitalisations compared to other scenarios, likely linked to the reduction in cold-related outcomes. Here, estimated deaths and CVT deaths slightly increase in summer but decrease notably in winter/spring under L85, driving the overall reduction. Estimated CVT hospitalisations increase across the whole year, although L85 shows summer reductions. Estimated all-cause hospitalisations, however, are higher in autumn/spring under L85 compared to other scenarios, consistent with the behavioural change hypothesis.
Central-South zone	This zone includes Maule, Ñuble (forming one sub-zone), and Biobío (another sub-zone). Maule and Ñuble show significant warming and decreases in cold indices. These changes correspond to lower estimated mortality, especially in winter, although estimated mortality increases in summer under S85/L85, consistent with their hot summer/cold winter climate.[49] Similar to other zones, warmer temperatures (S85, L85) are associated with estimated increases in all-cause hospitalisations. Estimated CVT hospitalisations appear to reflect a balance between cold/warm indices, with significantly lower estimates from January to June under L85. Biobío, though contiguous, shows less intense warming but significant decreases in cold indices, similar perhaps to Valparaíso (with population also concentrated coastally). Here, warmer scenarios are associated with lower estimated mortality, especially in autumn, winter, and spring. Although estimated hospitalisations are higher than the historical period (mainly April–September), they show a decreasing trend under warmer scenarios, notably for CVT hospitalisations in L85 due to spring/summer reductions. These results support the idea that warming scenarios in such regions can reduce cold-related health burdens.
South zone	This zone (Araucanía, Los Ríos) shows warming and significant decreases in cold indices. These changes correspond to lower estimated all-cause deaths, CVT deaths, and CVT hospitalisations. All-cause hospitalisations show mixed results (associated mainly with estimated increases in summer/autumn for ages 5+). The warmest scenario (L85) and its associated reduction in cold indices correspond to significantly lower estimated deaths, especially in winter/spring. However, this pattern does not correspond to a similar reduction in estimated CVT hospitalisations (though spring shows reduction). As these regions have Mediterranean climates, it is plausible that warmer scenarios would be associated with an overall decrease in climate-sensitive mortality and morbidity estimates.
Austral zone	The final zone (Los Lagos, Aysén, Magallanes) shows warming (less difference between scenarios except L85) and significant reductions in cold indices. These changes correspond to lower estimates for all health outcomes across all scenarios compared to the historical period. As expected in cold climates, the warmest scenario (L85) is associated with lower estimated mortality, especially in winter. Estimated all-cause hospitalisations follow a pattern similar to northern zones (increase, except Magallanes), which might also be related to social behaviour changes under warmer scenarios.

Table 1: **Zones in Chile based on variations in temperature indices and health outcomes.**

important social implications. The potential loss of healthy and working-age individuals in a society reduces the labour force, negatively affecting local and national productivity and economic growth, and leads to broader and cascading social challenges.[51] Families may lose a primary breadwinner, potentially worsening mental health, increasing the risk of financial strain and poverty, limiting educational opportunities, and exacerbating existing health and social inequalities.[52,53]

The estimated increase in hospitalisations across the country presents further public health and social challenges. Higher demand for healthcare services pressures an already overburdened and under-resourced healthcare system,[54] requiring more resources, infrastructure and equipment, and health personnel. This added to unequal access and resources available in different regions, might exacerbate health inequities, worsen population health outcomes, and even further increase mortality rates.[55] Seasonal shifts in hospitalisations, with an increased demand in warmer months and decreased demand in winter months, require health systems to adjust resource allocation strategies, ensuring that healthcare services and delivery is responsive to changing demands across the year. Additionally, higher rates of hospitalisation are also linked to greater rates of work absence, lower quality of life, and potential long-term disabilities,[56] all affecting families' wellbeing and income, exacerbating health-poverty traps (i.e., poor health leads to poverty and vice versa)[57] and impacting productivity and economic development at a national scale.

Conversely, the estimated reduction in mortality and hospitalisations associated with fewer cold events, especially in southern regions, might offer some public health benefits. Fewer deaths and hospitalisations might lead to less pressure on healthcare systems, allowing for re-allocation of resources to other activities that promote and protect people's health. Additionally, communities might remain socially and economically active for longer, contributing to further development at individual and societal levels.[58] However, it is possible that temperature increases might trigger changes in social behaviour, which in turn might lead to higher rates of injuries derived from outdoor activities or violence. If this happened to be the case, appropriate public health surveillance and responses would be required.

Overall, these findings highlight the need for region-specific public health strategies in Chile. Northern regions might require heat plans that reduce the risk of heat-related mortality and morbidity, while southern regions might adjust healthcare demand and potential shifts in healthcare needs.

It is important to note that the estimates of this study may be conservative, as they do not fully account for potential cascading and broader health impacts of climate change, including those related to water and food insecurity derived from climate change-influenced drought.[59]

This study complements and expands the evidence already published. A study that used A1b SRES scenario (in which the CO_2 emissions are lower than those for RCP8.5 but much higher than RCP2.6[60]) and non-accidental hospital admissions showed that warmer scenarios are linked to higher hospital admissions, qualitatively agreeing with our findings. However, estimates are not fully comparable as it compared projected estimates only with those for the year 2008 and did not disaggregate the estimations by age or seasonality.[4] Further studies by the Multi-Country Multi-City (MCC) Collaborative Research Network also qualitatively aligns with our findings, showing that warmer scenarios would decrease cold-related deaths and increase heat-related deaths (0.2% decrease in excess mortality by 2050–59 compared to 2010–19).[6,10] However, MCC analyses for Chile relied on only four land-based monitors in the central zone of the country, providing limited insight into the substantial regional heterogeneity demonstrated here. Methodological differences, including our use of multiple extreme temperature indices versus primarily mean temperature, also limit direct comparison of specific risk estimates.[2,61]

This study has some limitations. The cross-validation results demonstrated that the underlying time trend, representing the effects of social and other changes that are unrelated to the temperature indices considered in the study, could not be extrapolated reliably beyond the period used for model fitting: thus, it was not possible to produce true projections of health outcomes into the future. Instead, the results represent what could have occurred in the past if temperatures had been as projected under the hypothetical scenarios: they suggest the potential impacts of climate change considered in isolation, therefore. This hypothetical, comparative approach helps explain why results sometimes appear counterintuitive (e.g., lower mortality under more extreme warming scenarios or compared to historical levels), as they reflect the modelled net balance of changing risks (discussed earlier) rather than absolute future forecasts. Nonetheless, health outcomes in the future might be different as social variables have an important role in modulating the impact of environmental change. For example, the presented models do not explicitly include variables related to population adaptation or acclimatisation to ambient temperatures, or the use of air conditioning, which may have an important impact on health.[62] A statistical approach considering such effects would require extensive data on relevant covariates which, at present, are not available. In view of this, the approach of this study can be seen as a pragmatic one that seeks to maximise the use of the data that are available.

This study has been further limited by the absence of ethnicity in the original health databases, and the lack of availability of high-resolution climate projections for South America: the relevant CORDEX archive provides projections from only one Regional Climate Model (RCM) at the resolution required. As more high-resolution projections become available, it will be of interest to place the current results within the context of those obtained from an ensemble of different RCMs that could potentially have different biases and patterns of change.

Conclusion

This is the first study that estimated the effects of climate change scenarios on temperature-related mortality and hospitalisations at a regional level in Chile, revealing seasonal, regional, and age-related differences. The findings not only contribute to the evidence on the field, but also provide information for potential health and climate adaptation policies in Chile.

Contributors

YPS conceptualised the idea, led the project, collected all datasets, performed the analyses, interpreted and prepared the results for publication, wrote the draft of the manuscript, and wrote the final manuscript. REC supported and guided all the study, developed the non-standard parts of the statistical methodology, and provided critical feedback for statistical analyses. IK gave feedback during the study, writing process, and final manuscript. All authors agreed on the final manuscript and the decision to submit the study for publication. YPS was responsible for submitting it to the journal.

Data sharing statement

All databases used in this study are publicly available and we have provided the sources where we obtained them.

Editor note

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Declaration of interests

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.lana.2025.101151.

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