Title:

The impact of extreme temperatures on respiratory mortality in Brazil: evaluating regional adaptations to different thermal environments

Short title:

Temperature and respiratory mortality in Brazil

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Abstract

We conducted a nationwide ecological time-series study to quantify the association between ambient temperature and respiratory mortality across Brazil's diverse climates. Using data from 520 municipalities (population ≥50,000) from 2010 to 2020, we analysed 1,008,157 respiratory deaths (ICD-10 J00–J99) using distributed-lag non-linear models (lags 0–21 days) with quasi-Poisson regression, adjusting for seasonality, time trends, and day of week. City-specific estimates were pooled by random-effects meta-analysis, and attributable fractions were calculated using the forward perspective method. Both cold and heat were associated with increased mortality risk, following a U-shaped relationship. Minimum mortality temperature varied by 6.3°C across regions. Relative risks at the 10th and 90th percentiles were 1.95 (IQR 1.44–2.88) and 1.82 (IQR 1.39–2.81), respectively. Non-optimal temperatures accounted for 2.89% of deaths nationally (approximately 2,650 annually), with the highest fractions in the North (8.2%). Adults aged ≥65 years and Black individuals (for heat) showed the most significant vulnerability. Temperature extremes increase respiratory mortality across Brazil, with tropical regions exhibiting heightened vulnerability to cold despite warmer baseline climates. These findings support region-specific

warning systems addressing both thermal extremes, with priority for older adults and Black populations.

Introduction

Respiratory diseases rank among the leading causes of global mortality, accounting for an estimated 4.2 million deaths annually, with disproportionate burden in low- and middle-income countries where the temperature–mortality relationship remains poorly characterized [1]. Climate change is intensifying these challenges by altering seasonal patterns and increasing the frequency of temperature extremes, directly and indirectly affecting respiratory health through physiological and infectious disease pathways [2–6].

The biological mechanisms underlying these associations are well documented. Cold temperatures and reduced absolute humidity enhance the stability and transmission of respiratory viruses, particularly influenza, contributing to pronounced seasonality in temperate climates [7,8]. Cold exposure damages the respiratory epithelium, impairs mucociliary clearance, increases susceptibility to infection, and exacerbates chronic respiratory diseases, with effects persisting for weeks [9–11]. Heat exposure triggers hyperventilation, airway desiccation, and elevated concentrations of ground-level ozone and particulate matter, aggravating asthma and chronic obstructive pulmonary disease, particularly among elderly populations [12–14]. Systematic reviews confirm that respiratory mortality exhibits a U- or J-shaped relationship with temperature, with elevated risk at both extremes [15–17]. However, most evidence derives from temperate, high-income settings, whereas tropical and subtropical regions—home to 40% of the global population—remain understudied [18–20].

Brazil offers a valuable setting to address this gap. The country spans equatorial to subtropical climates, and respiratory diseases account for 11–12% of national mortality, with a substantial burden among elderly and urban populations [21,22]. The demographic transition and the increasing frequency of extreme weather events are heightening vulnerability to temperature-related mortality [23–25]. Prior Brazilian research has been limited to single cities—São Paulo and Rio de Janeiro—or short observation periods, precluding national assessment of regional adaptation patterns [26,27].

We conducted a nationwide ecological time-series study across 520 municipalities from 2010 to 2020 to quantify the association between ambient temperature and respiratory mortality, estimate the attributable burden by geographic region, and examine effect modification by age, sex, and race/ethnicity. These findings aim to inform targeted climate-health policies and Brazil's National Adaptation Plan to Climate Change.

Methods

Study design and setting

We conducted a nationwide ecological time-series study in accordance with the STROBE guidelines for observational research. The study investigated the association between ambient temperature and daily respiratory mortality across Brazil from January 1, 2010, to December 31, 2020. We included 520 municipalities with populations of at least 50,000, selected for data completeness, reliable vital registration, and availability of meteorological data. These municipalities represent all five major geographic regions and span climatic zones from equatorial to subtropical.

Data sources

Mortality and meteorological data were obtained from the ClimatErna platform (www.climaterna.com.br; data extraction: October 10, 2025), which integrates information from the Brazilian Mortality Information System (SIM) and the National Institute of Meteorology (INMET). Daily counts of deaths from respiratory diseases (ICD-10 codes J00–

J99) and demographic variables (age, sex, race/ethnicity) were extracted from death certificates. Daily meteorological variables included mean temperature and relative humidity. For 223 municipalities, daily mean concentrations of particulate matter ($PM_{2.5}$) and ozone (O_3) were obtained from the Copernicus Atmosphere Monitoring Service to assess potential effect modification by air pollution.

Exposure and outcome definitions

The primary exposure was daily mean ambient temperature, calculated as the average of minimum and maximum temperatures recorded at municipal weather stations. Extreme cold and heat were defined as the 10th and 90th percentiles of each city's temperature distribution for the study period, respectively. The primary outcome was the daily count of deaths from respiratory diseases.

Statistical analysis

City-specific associations between temperature and respiratory mortality were estimated using distributed lag non-linear models (DLNM) with quasi-Poisson regression to account for overdispersion. Temperature–mortality associations were modelled using natural cubic splines for temperature (3 degrees of freedom) and for lag up to 21 days (4 degrees of freedom), adjusting for long-term time trends, seasonality, day of the week, and public holidays [10,28]. City-specific exposure–response curves were pooled using multivariate random-effects meta-analysis to obtain national and regional estimates [28]. Heterogeneity across regions was assessed using Cochran's Q and I^2 statistics. Attributable fractions and numbers for respiratory deaths due to non-optimal temperatures were calculated using the forward perspective method, with empirical confidence intervals estimated by Monte Carlo simulation [10].

Subgroup and sensitivity analyses

Stratified analyses were conducted by age group (<5, 5–64, ≥65 years), sex, and race/ethnicity (White, Black, Mixed, Indigenous, Asian) as reported on death certificates. Effect modification by urbanization level and air pollution ($PM_{2.5}$, O_3) was examined where data were available. Sensitivity analyses included alternative lag structures, different temperature metrics (minimum and maximum), exclusion of 2020 (COVID-19 pandemic), and varying degrees of freedom for splines.

Patient and public involvement

This study used secondary, de-identified administrative data. Patients and the public were not involved in the design, conduct, or reporting of this research.

Sex, gender, and race/ethnicity reporting

Sex and age were recorded as documented on death certificates. Race and ethnicity classifications were based on Brazilian census categories, as reported by next of kin or healthcare personnel. Limitations regarding the accuracy and completeness of these variables are addressed in the Discussion.

Ethics approval

This study used exclusively de-identified, publicly available aggregate mortality counts from Brazil's Ministry of Health (DATASUS) and environmental monitoring data. According to Brazilian National Health Council Resolution 510/2016, research involving only publicly available, de-identified data does not require approval from an institutional review board. No individual-level identifiable information was accessed or reported.

Results

Study population and descriptive characteristics

Our analytical sample comprised 520 Brazilian municipalities (population ≥50,000), representing 61% of the national population and spanning all five major geographic regions (Fig. 1, Table 1). Over the 11-year study period (2010–2020), 1,008,157 respiratory deaths were recorded, corresponding to an annual mortality rate of 73.1 per 100,000 population. The Southeast region contributed the largest share of deaths. Mean temperatures ranged from 20.5°C in the South to 26.8°C in the North and Northeast (Table 1).

Fig 1. Geographic distribution of study municipalities across Brazil's five regions.

Temperature–mortality associations

Nationally, exposure–response analyses revealed a U-shaped association between daily mean temperature and respiratory mortality, with risk increasing at both cold and hot extremes relative to the minimum mortality temperature (Fig. 2). The median minimum mortality temperature (MMT) was 24.0°C, varying by 6.3°C across regions: from 20.5°C in the South to 26.8°C in the North and Northeast (Table 2, Fig 3A). At the 10th percentile of each city's temperature distribution (cold), the median relative risk (RR) was 1.95 (IQR 1.44–2.88). At the 90th percentile (heat), the median RR was 1.82 (IQR 1.39–2.81), compared with the MMT as reference (Table 2).

Fig 2. National exposure–response curve showing the U-shaped relationship between temperature and respiratory mortality.

Fig 3. Regional variation in (A) minimum mortality temperature, (B) cold-associated relative risks, and (C) heat-associated relative risks.

Regional heterogeneity

Cold-associated relative risks were highest in the North and Northeast regions (median RRs > 2.2), which also had the highest mean temperatures (Table 2, Fig. 3B). Heat-associated relative risks were highest in the Center-West and North regions (median RRs > 2.4) (Table 2, Fig. 3C). Within-region variability in relative risks was greater than between-region variability for both cold and heat exposures (Figs 3B and 3C).

Attributable mortality burden

Overall, 2.89% of respiratory deaths (29,166; approximately 2,651 annually) were attributable to suboptimal temperatures during the study period (Table 3). Cold temperatures (below MMT) accounted for 1.44% of deaths nationally, and heat (above MMT) for 1.51%. Regional attributable fractions were highest in the North (4.02% for cold; 4.22% for heat) and lowest in the South (0.98% for cold; 1.12% for heat) (Table 3). In absolute numbers, the Southeast region accounted for the most attributable deaths (12,634), reflecting its larger population (Table 3).

Subgroup analyses

Adults aged ≥65 years accounted for 77% of all respiratory deaths. In this age group, cold-associated RR was 1.23 and heat-associated RR was 1.17, both higher than in younger age groups (Table 4).

Children aged <5 years and working-age adults (5–64 years) had lower relative risks for both exposures (Table 4). By sex, males had higher cold-associated RR (1.37) and females had higher heat-associated RR (1.33) (Table 4). By race/ethnicity, White individuals had the highest cold-associated RR (1.35), followed by Black (1.28), Mixed (1.25), Indigenous (1.18), and Asian (1.15) individuals. For heat, Black individuals had the highest RR (1.34), followed by Mixed (1.29), White (1.27), Indigenous (1.22), and Asian (1.19) individuals (Table 4).

Effect modification by air pollution

Among the 223 municipalities with $PM_{2.5}$ data, we observed no significant interaction between temperature and air pollution tertiles in the association with respiratory mortality (p for interaction = 0.34) (Table 5). Cold- and heat-associated relative risks remained elevated across all pollution tertiles. Adjustment for $PM_{2.5}$ and O_3 did not materially change the temperature–mortality associations (Table 5).

Sensitivity analyses

Results were robust across alternative model specifications, including varying degrees of freedom for temperature and lag splines, alternative lag structures, and the use of minimum or maximum temperature rather than mean temperature. Excluding 2020 (the COVID-19 pandemic) did not materially alter the estimates. Attributable fractions and relative risks varied minimally across all sensitivity analyses.

Discussion

In this nationwide ecological time-series study, we found that both cold and heat exposure were associated with increased respiratory mortality across Brazil, with a U-shaped exposure–response relationship. The associations varied substantially by geographic region, age, and race/ethnicity. These findings contribute evidence from a large middle-income tropical country to a literature dominated by temperate, high-income settings.

The median minimum mortality temperature varied by 6.3°C across regions, ranging from 20.5°C in the South to 26.8°C in the North/Northeast. This regional variation is consistent with patterns observed in multi-country studies. It may reflect differences in population acclimatization, built environment, or behavioural responses to local climate, although our study design does not allow us to distinguish among these mechanisms [10,18].

Cold-associated mortality was most substantial in the North and Northeast—the warmest regions—where relative risks exceeded 2.2. This finding aligns with previous observations that populations in warmer climates may experience greater relative increases in mortality during cold periods, possibly due to less frequent exposure. However, the specific mechanisms remain unclear [10,18]. We did not directly measure adaptation, and alternative explanations, including differences in housing quality, heating availability, or healthcare access, cannot be excluded. Heat-associated mortality was highest in the Central-West and North regions, which may be attributable to differences in urbanization patterns and infrastructure, although these factors were not directly assessed [14,22].

The magnitude of temperature–mortality associations observed in Brazil was comparable to or exceeded those reported in studies from Europe, North America, and East Asia [10,15]. This observation indicates that factors beyond climatic conditions may influence population vulnerability, though our study was not designed to identify specific determinants.

We observed racial/ethnic differences in temperature-associated mortality: White individuals had the highest cold-associated relative risk (1.35), while Black individuals had the highest heat-associated relative risk (1.34). Racial/ethnic disparities in temperature-associated mortality have also been reported in the United States, though differences in racial classification systems and social contexts limit direct comparisons [29]. Furthermore, race/ethnicity on Brazilian death certificates is reported by third parties and is subject to misclassification. Race/ethnicity in Brazil correlates strongly with socioeconomic status, and we could not adjust for individual-level confounders. These subgroup findings should therefore be interpreted cautiously and require confirmation in studies with individual-level data.

We did not find significant effect modification by air pollution among the 223 municipalities with available $PM_{2.5}$ data. However, the limited geographic coverage of air quality monitoring may have reduced statistical power, and we cannot exclude the possibility of temperature–pollution interactions in highly polluted urban areas not adequately represented in our subsample.

Strengths and limitations

This study has several strengths: a large sample size (over one million deaths), broad geographic coverage (520 municipalities across all five regions), an 11-year observation period, use of well-established statistical methods (DLNM with meta-analysis), and extensive sensitivity analyses.

However, significant limitations must be acknowledged. First, as an ecological study, our findings reflect population-level associations and do not establish causality. Individual-level confounders—including comorbidities, medication use, smoking status, and indoor environmental conditions—could not be assessed. Second, we lacked data on influenza circulation and other respiratory virus activity, which are established confounders of temperature–respiratory mortality associations. Third, we did not assess short-term mortality displacement (harvesting), in which some temperature-associated deaths may reflect delayed mortality among frail individuals. Fourth, the restriction to municipalities with populations ≥50,000 may limit generalizability to rural areas. Fifth, outdoor temperature measurements may not accurately reflect individual thermal exposure, particularly for individuals who spend extended time indoors. Sixth, cause-of-death coding for respiratory diseases may include misclassification, and the completeness of race/ethnicity data on death certificates varies across regions. Finally, although sensitivity analyses excluding 2020 yielded similar results, the residual effects of the COVID-19 pandemic on respiratory mortality patterns cannot be entirely ruled out.

Policy implications

Given the observed cold-associated mortality in tropical regions, early warning systems in Brazil may benefit from addressing both thermal extremes rather than focusing solely on heat. Adults aged 65 years and older, who accounted for 77% of respiratory deaths, represent a priority population for targeted interventions [6,24].

Conclusion

In summary, this study provides nationwide estimates of temperature-associated respiratory mortality in Brazil. Both cold and heat were associated with increased mortality, with regional variation in vulnerability and the highest attributable fractions in the North. These findings inform climate adaptation planning in Brazil and other tropical countries with similar characteristics.

Acknowledgments

We thank the Brazilian Ministry of Health for making mortality data publicly available through DATASUS, the National Institute of Meteorology (INMET) for meteorological data, and the Copernicus Atmosphere Monitoring Service for air quality data.

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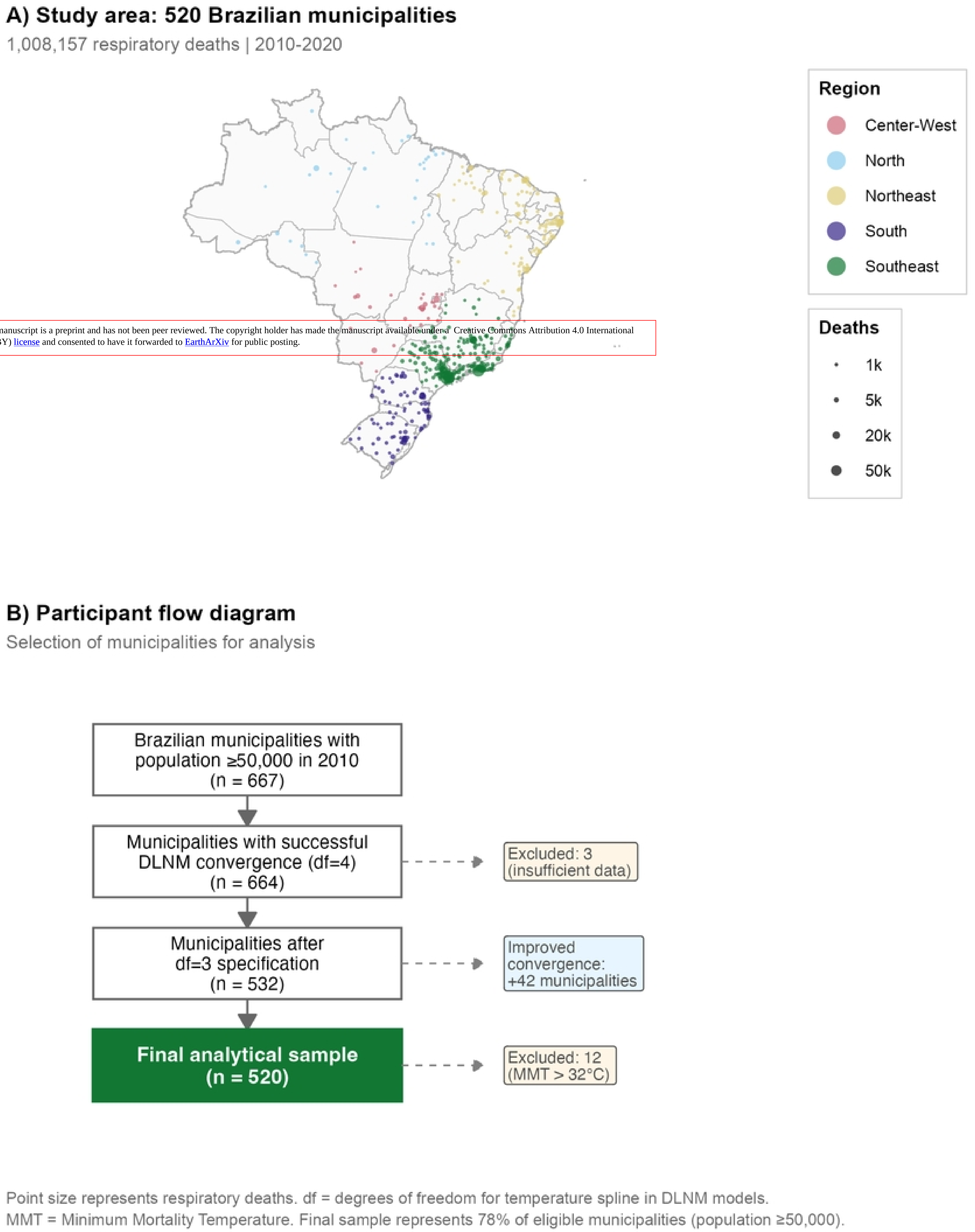
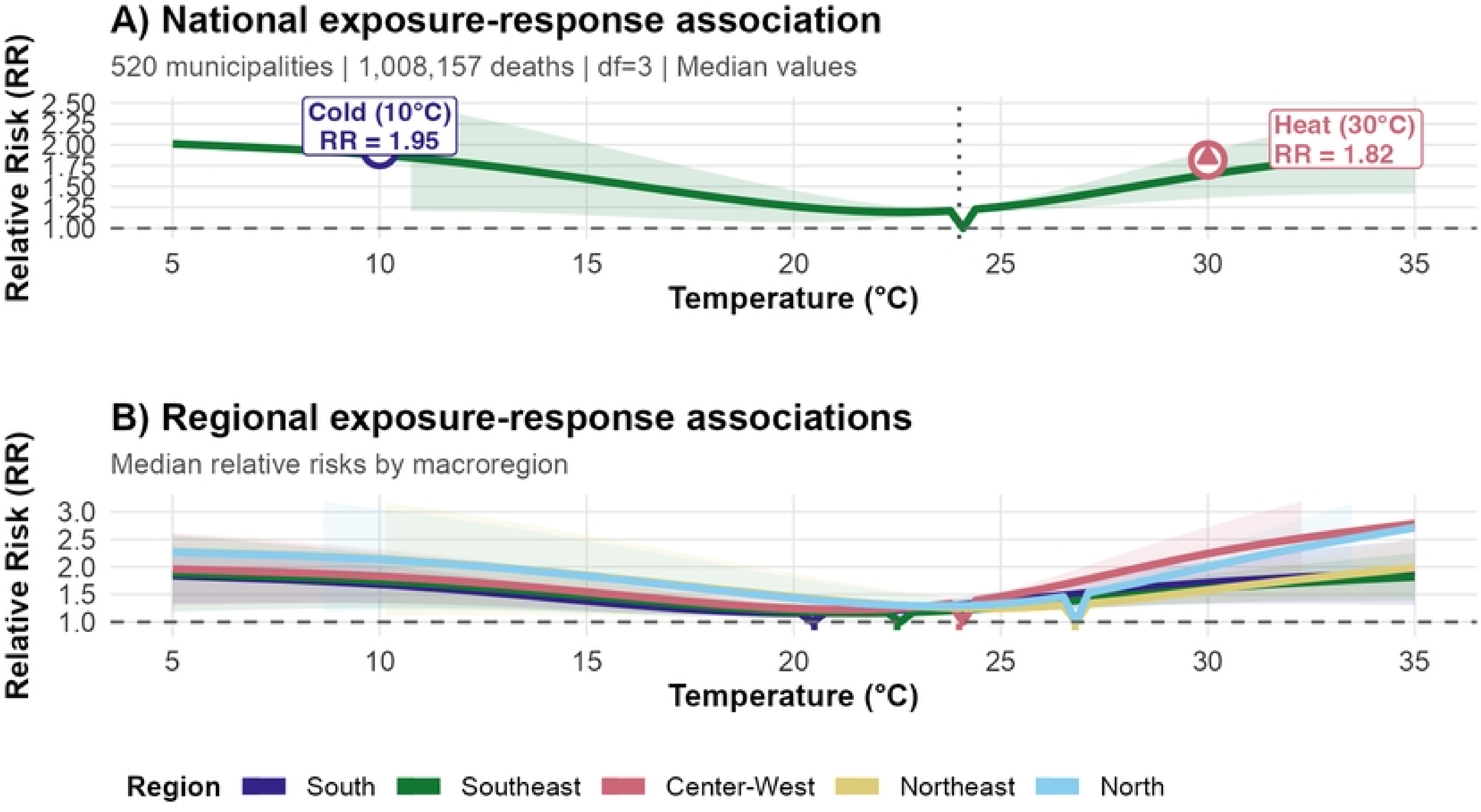
Supporting information

S1 Checklist. STROBE checklist for observational studies.


A) Study area: 520 Brazilian municipalities
1,008,157 respiratory deaths | 2010-2020
Region
Center-West
North
Northeast
South
Southeast
Deaths
1k
5k
20k
50k
B) Participant flow diagram
Selection of municipalities for analysis
Brazilian municipalities with population ≥50,000 in 2010 (n = 667)
Municipalities with successful DLNM convergence (df=4) (n = 664)
Excluded: 3 (insufficient data)
Municipalities after df=3 specification (n = 532)
Improved convergence: +42 municipalities
Final analytical sample (n = 520)
Excluded: 12 (MMT > 32°C)
Point size represents respiratory deaths. df = degrees of freedom for temperature spline in DLNM models.
MMT = Minimum Mortality Temperature. Final sample represents 78% of eligible municipalities (population ≥50,000).

Figure



Curves based on median relative risks from 520 municipalities. Shaded areas represent approximate 95% confidence intervals.
Curves constructed using cubic splines through median MMT (RR=1.0) and extreme temperature RRs (10°C and 30°C).
MMT = Minimum Mortality Temperature. Based on df=3 specification (2010-2020). Reference RR = 1.0.

Figure

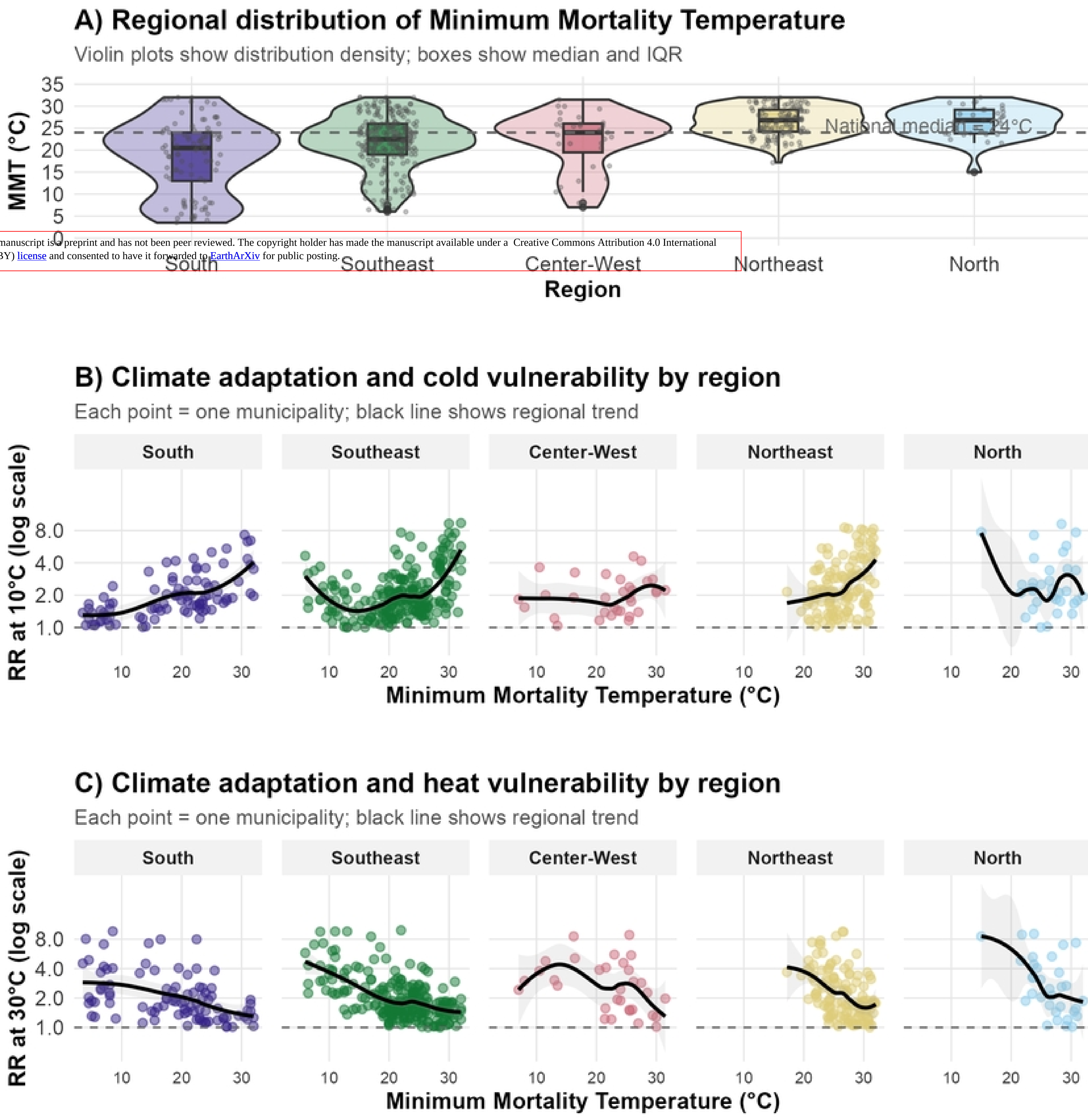


Figure shows geographic and climatic heterogeneity in temperature-mortality associations across 520 Brazilian municipalities. Panel A: Distribution of MMT by macroregion showing clear south-north gradient. Panels B-C: Regional relationships between local climate (MMT) and vulnerability to temperature extremes. Points represent individual municipalities; smooth lines show trends within each region. RR presented on log scale. Based on df=3 specification (2010-2020).

Figure