When the Weather Turns Cold: Seasonal Patterns of Subarachnoid Hemorrhage in a Tropical Country

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Abstract

Background

Subarachnoid hemorrhage (SAH) carries high mortality worldwide. Seasonal patterns have been documented in temperate regions, but evidence from tropical and subtropical populations remains limited.

Objectives

We investigated associations between meteorological variables and SAH hospital admissions in Brazil across diverse climate zones.

Methods

We conducted an ecological time-series analysis linking nationwide SAH hospitalizations (ICD-10: I60.0–I60.9) from Brazil's Unified Health System with meteorological data from the National Institute of Meteorology, 2020–2024. Generalized additive models with distributed lag structures were used to assess the relationships between temperature, humidity, atmospheric pressure, and monthly SAH incidence. Air pollution analysis was attempted but revealed critical surveillance gaps. Stratified analyses explored effect modification by season, age, and region.

Results

Among 3,323 SAH admissions, incidence peaked during autumn (26.4%) and winter (25.4%) when mean temperatures were 3.4°C lower than summer. Temperature showed inverse associations with admissions in autumn ($\beta = -8.3$ per °C; 95% CI: −11.2, − 5.4) and winter ($\beta = -7.1$ per °C; 95% CI: −9.8, − 4.4). Effects were stronger in southern regions and among individuals aged 65 years or older. Air quality data were available for only three months, which precluded analysis and highlighted infrastructure deficiencies.

Discussion

SAH admissions in Brazil increase during colder months with a dose-response relationship. Findings align with cold-induced sympathetic activation and blood pressure elevation. The absence of integrated air pollution monitoring represents a major surveillance gap. Results support the incorporation of meteorological indicators into neurocritical care planning and underscore the urgent need for an environmental health data infrastructure in Latin America.

Introduction

Subarachnoid hemorrhage (SAH) is a catastrophic cerebrovascular event accounting for approximately 5% of all strokes worldwide, with case fatality rates around 35% and long-term disability affecting up to half of survivors (1–3). Beyond established risk factors such as hypertension, smoking, and aneurysm characteristics, emerging evidence suggests that environmental factors—particularly meteorological variables—may modulate SAH risk through both physiological and behavioral pathways (4–6).

Temperature fluctuations induce sympathetic nervous system activation, peripheral vasoconstriction, and blood pressure elevation that may destabilize aneurysmal walls (7). Cold exposure specifically triggers noradrenergic-mediated cutaneous vasoconstriction, increasing systemic vascular resistance and arterial pressure (8,9). Additionally, cold temperatures promote prothrombotic changes, including elevated fibrinogen levels, increased platelet aggregation, and higher blood viscosity (10). These hemodynamic and hemostatic alterations create conditions conducive to aneurysm rupture, particularly in individuals with pre-existing hypertension or unruptured aneurysms.

International studies consistently demonstrate seasonal SAH patterns, with peak incidence during colder months in temperate climates (11–13). A European meta-analysis of 18,714 patients found a 0.4% increase in risk per 1°C decrease in temperature (14). Similar associations have been reported in Asian cohorts, particularly among younger populations (15). However, evidence from tropical and subtropical regions remains limited, leaving uncertainty about whether moderate thermal variations in warmer climates exert comparable effects.

Air pollution represents another potential environmental trigger (16,17). Particulate matter exposure induces systemic inflammation, endothelial dysfunction, and autonomic imbalance—mechanisms that could compromise vascular integrity and precipitate rupture (18,19). Some studies suggest temporally lagged associations between $PM_{2.5}$ peaks and SAH occurrence (18–20), although findings remain heterogeneous, and data from low- and middle-income countries are notably sparse.

The climate-SAH relationship likely involves complex interactions between physiological responses and behavioral adaptations (21,22). While seasonal blood pressure elevations during winter months are well-documented, ranging from 3 to 30 mmHg in population studies (23,24), behavioral contributions remain less certain. Smoking patterns exhibit seasonal variability, with outdoor smoking decreasing in cold weather but indoor exposure potentially increasing due to reduced ventilation, especially in lower-income households (25,26). These behavioral pathways require further investigation with direct observational data.

Brazil provides a unique epidemiological context for examining environmental determinants of SAH (27). The country encompasses diverse climate zones—from equatorial in the north to subtropical in the south—with marked seasonal temperature variations in the southern regions (28,29). Brazil's Unified Health System (SUS) serves approximately 75% of the population, providing comprehensive hospitalization data, yet significant regional disparities persist in healthcare access and stroke outcomes (30–32). Critically, environmental health surveillance infrastructure remains underdeveloped, with fragmented air quality monitoring that limits comprehensive risk assessment.

This study examined the relationships between meteorological variables and SAH hospital admissions across Brazil from 2020 to 2024, employing an ecological time-series design with nationwide hospitalization data. We examined seasonal patterns, temperature-related trends, and attempted to analyze air pollution to characterize environmental risk factors in a middle-income country with substantial climate diversity. Given the limitations encountered in accessing air quality data, this work also highlights critical gaps in environmental health surveillance infrastructure that impede evidence-based public health planning in Latin America.

Study Design and Data Sources

We conducted an ecological time-series analysis of nationwide hospitalizations for subarachnoid hemorrhage (SAH) in Brazil from January 2020 to December 2024, examining associations with meteorological variables.

Hospitalization Data

SAH admissions (International Classification of Diseases, 10th Revision [ICD-10] codes I60.0–I60.9) were obtained from Brazil's Department of Informatics of the Unified Health System (DATASUS) (33), which captures all public hospital admissions representing approximately 75% of the Brazilian population. We extracted monthly admission counts, including patient age, sex, and state of residence. Population denominators for incidence rate calculations came from the Brazilian Institute of Geography and Statistics (IBGE) (34). Data completeness was verified by checking for implausible values and temporal discontinuities; no substantial gaps were identified.

Meteorological Data

Climate variables were obtained from the National Institute of Meteorology (INMET) (35), Brazil's official meteorological service. We extracted monthly averages of maximum and minimum temperature (°C), relative humidity (%), atmospheric pressure (hPa), and total precipitation (mm) from all operational weather stations nationwide. Complete spatial coverage with adequate station density across Brazil's five geographic regions became available only from 2020 onward; therefore, our analysis focused on this five-year period, despite the availability of hospitalization records dating back to 2015.

Station-level data were aggregated to state-level monthly means weighted by population distribution using inverse distance weighting. Outliers exceeding 3 standard deviations from the station-specific long-term mean were flagged and removed after manual verification (affecting $< 0.5\%$ of observations). Missing values ($< 2\%$ of station-months) were imputed using linear interpolation between adjacent months within the same station. For stations with gaps exceeding 2 consecutive months, we used spatial interpolation from neighboring stations within a 200 km radius.

Air Pollution Data and Surveillance Infrastructure Limitations

We attempted to incorporate air quality data from OpenAQ (36), a global, open-access platform that aggregates real-time measurements from monitoring stations. However, systematic nationwide particulate matter monitoring data were unavailable for Brazil during the study period. Only three months of PM_{10} measurements from selected urban monitoring stations in 2023 could be retrieved (April–June 2023, covering São Paulo, Rio de Janeiro, and Brasília), representing < 5% of the study period and < 20% of the national population.

These limited data were aggregated to monthly means and are presented descriptively (Table 1) to document critical deficiencies in environmental health surveillance infrastructure; however, they were not included in statistical models due to insufficient temporal and spatial coverage for meaningful inference. This data gap reflects broader challenges in Brazil's environmental monitoring capacity and represents a major limitation for integrated environmental health risk assessment in Latin America.

Statistical Analysis

Primary Models

We used generalized additive models (GAMs) with quasi-Poisson distributions to assess associations between meteorological variables and monthly SAH incidence, accounting for overdispersion commonly observed in count data (37). The base model structure incorporated a penalized cubic regression spline for long-term temporal trends (7 degrees of freedom per year of observation), cyclic cubic splines for seasonal patterns (12 knots), state-specific effects to account for regional baseline differences, and a population offset term (log-transformed)

Meteorological exposures (temperature, humidity, atmospheric pressure, precipitation) were modeled as smooth terms using thin-plate regression splines. To assess potential delayed effects, we implemented distributed lag non-linear models (DLNMs) using cross-basis functions that simultaneously model non-linear exposure-response relationships and lagged effects up to 3 months (37). The temperature-lag cross-basis function utilized natural cubic splines with three internal knots placed at the 10th, 50th, and 90th percentiles of the temperature distribution, and a natural cubic spline for the lag dimension with three equally spaced knots.

All continuous meteorological variables were standardized (z-scores: [x - mean]/SD) to enable direct comparison of effect sizes across different measurement scales.

Seasonal Stratification

We examined effect modification by season according to Southern Hemisphere meteorological definitions: summer (December–February), autumn (March–May), winter (June–August), and spring (September–November). Season-specific linear regression models assessed temperature-SAH associations within each period:

SAH admissions = $\beta_0 + \beta_1 \cdot$mean temperature + $\beta_2 \cdot$temperature range + ε

where β_1 represents the change in monthly admissions per 1°C increase in mean temperature, and β_2 captures the effect of diurnal temperature variation (maximum - minimum). Models were adjusted for precipitation and humidity as potential confounders.

Subgroup Analyses

Stratified analyses were performed to identify vulnerable populations and regional variations, age group: <65 years vs. ≥65 years (assessing thermoregulatory vulnerability in the elderly), sex: male vs. female (exploring potential differences), geographic region: North (equatorial/tropical), Northeast (tropical/semi-arid), Central-West (tropical savanna), Southeast (tropical/subtropical transition), and South (subtropical, coldest winters), relative risks (RR) and 95% confidence intervals (CI) were estimated for each stratum, with interaction terms tested using likelihood ratio tests ($p < 0.05$ considered significant),

Sensitivity Analyses

Model robustness was evaluated through, varying degrees of freedom for time trends (5–10 df/year), Testing alternative lag periods (0–6 months), Excluding the first and last 6 months of observations to evaluate boundary artifacts, Comparing quasi-Poisson with, negative binomial regression models, Testing models with and without correlated variables (e.g., removing humidity/precipitation when examining temperature), re-running analyses after excluding months with extreme SAH counts (> 2 SD from mean)

Model Diagnostics

We assessed model adequacy through Examination of deviance residuals for temporal patterns and heteroscedasticity, Partial autocorrelation function (PACF) plots to detect residual serial correlation (up to 12 lags), Quantile-quantile (Q-Q) plots comparing observed vs. theoretical residual distributions, Mean absolute percentage error (MAPE) between observed and fitted values, Variance inflation factors (VIF < 5) to assess multicollinearity among meteorological covariates, and Dispersion parameter φ from quasi-Poisson models ($\varphi > 1$ indicates overdispersion)

Software and Reproducibility

All analyses were performed in Python version 3.11 using statsmodels (v0.14), scipy (v1.11), pandas (v2.0), and pygam (v0.8) libraries. Graphical outputs were generated using matplotlib (version 3.7) and seaborn (version 0.12). Complete analysis code and aggregated data are available from the corresponding author upon reasonable request. Individual-level data cannot be shared due to data protection regulations, but aggregated monthly counts by state, age group, and sex are available.

Ethical Considerations

This study utilized anonymized, publicly available aggregate data that precluded individual identification. The study was exempt from institutional review board approval under Brazilian National Health Council Resolution 510/2016, which exempts research using de-identified public databases. No individual consent was required, given the use of aggregate administrative data.

Results

Between January 2020 and December 2024, a total of 3,323 hospital admissions for subarachnoid hemorrhage (SAH) were recorded in Brazil's public health system. Mean monthly admissions were 55.4 (SD = 12.3, range: 28–89). The highest seasonal incidence occurred in autumn (26.4%, n = 877) and winter (25.4%, n = 844), compared to spring (23.9%, n = 794) and summer (24.3%, n = 808). The mean age at admission was 54.7 years (SD = 13.2), with 58.3% of patients being female. Regional distribution showed the highest admission rates in the Southeast (42.1%) and South (28.6%) regions.

Temporal and Seasonal Patterns

Monthly time-series analysis revealed consistent peaks in SAH admissions during colder months, particularly from May to July (Fig. 1). Seasonal temperature patterns showed marked differences: the mean winter temperature (22.2°C, SD = 2.8°C) was 3.4°C lower than the summer temperature (25.6°C, SD = 2.1°C). The temporal correspondence between lower temperatures and higher SAH incidence is visually apparent throughout the study period (Fig. 1).

Temperature-SAH Associations

Season-stratified linear regression analyses demonstrated significant negative associations between temperature and SAH admissions in autumn ($\beta = -8.3$ admissions per °C; 95% CI: −11.2, − 5.4; $p < 0.001$) and winter ($\beta = -7.1$ per °C; 95% CI: −9.8, − 4.4; $p < 0.001$). In spring, the association was weaker and marginally significant ($\beta = -3.2$ per °C; 95% CI: −6.8, 0.4; $p = 0.08$), while summer showed no meaningful relationship ($\beta = -0.4$ per °C; 95% CI: −3.1, 2.3; $p = 0.64$) (Fig. 2).

Standardized analyses confirmed the inverse temperature-SAH relationship, with correlation coefficients of $r = -0.42$ ($p = 0.02$) for maximum temperature and $r = -0.38$ ($p = 0.04$) for minimum temperature (Fig. 3). The quasi-Poisson GAM showed adequate fit (dispersion parameter $\varphi = 1.32$, indicating moderate overdispersion), with no substantial residual autocorrelation (PACF < 0.15 for all lags).

Distributed Lag Analysis

DLNM analysis revealed that the strongest temperature effect occurred within the same month (lag 0), with a relative risk of 1.18 (95% CI: 1.09–1.28) per 1°C decrease below the median temperature. Cumulative effects persisted for up to 2 months, though effect sizes diminished at longer lags. No significant non-linear temperature effects were detected beyond the linear relationship.

Subgroup Analyses

Stronger temperature-SAH associations were observed in the South region ($\beta = -12.4$ per °C; 95% CI: −17.8, − 7.0; $p < 0.001$) compared to other regions (p for interaction = 0.03). Age-stratified analysis showed amplified effects among individuals ≥ 65 years (RR = 1.24 per 1°C decrease; 95% CI: 1.12, 1.37) compared to younger adults (RR = 1.11; 95% CI: 1.03, 1.20; p for interaction = 0.04). No significant sex differences were detected ($p = 0.42$).

Air Pollution Data Limitations

Air quality data were severely limited. Only three months of PM_{10} measurements from urban stations were available (April–June 2023), precluding time-series analysis (Table 1). These sparse data are presented to document surveillance infrastructure deficiencies rather than to draw epidemiological inferences.

Discussion

This five-year nationwide ecological analysis reveals a clear inverse relationship between ambient temperature and subarachnoid hemorrhage (SAH) hospital admissions in Brazil, with a peak incidence during the colder autumn and winter months. These findings extend evidence from temperate regions (8,9,11,15) to tropical and subtropical settings, demonstrating that even moderate seasonal temperature variations (a mean difference of 3.4°C between winter and summer) significantly influence SAH risk. The results support the hypothesis that environmental factors modulate cerebrovascular vulnerability beyond established individual risk factors (4,19).

The observed temperature-SAH association is biologically plausible through well-established physiological pathways. Cold exposure triggers sympathetic nervous system activation, leading to peripheral vasoconstriction and increased systemic vascular resistance, which in turn elevates arterial blood pressure and may destabilize aneurysmal walls (7,38). Cold temperatures also promote prothrombotic changes, including elevated fibrinogen levels, increased platelet aggregation, and higher blood viscosity (10), creating conditions conducive to aneurysm rupture. These mechanisms, extensively documented in European and Asian populations (11,15), appear to be consistent with the patterns observed in our Brazilian cohort.

The stronger associations in southern Brazil, where winters are more pronounced, and among elderly individuals (≥ 65 years), who have diminished thermoregulatory capacity, support the cold-exposure hypothesis. The immediate effect (lag 0) and short persistence (up to 2 months) align with acute hemodynamic responses rather than cumulative exposures.

The near-complete absence of air pollution data represents a critical limitation—not primarily of this study, but of Brazil's environmental health surveillance infrastructure. Despite evidence from other countries linking particulate matter exposure to cerebrovascular events through systemic inflammation, endothelial dysfunction, and autonomic imbalance (13,18–20), we were unable to evaluate this pathway. Only three months of PM_{10} data were retrievable, exemplifying broader challenges in environmental health monitoring across Latin America, where integrated air quality surveillance remains fragmented and geographically limited (Table 1).

This surveillance gap has substantial implications beyond research limitations. The inability to assess synergistic effects between temperature and air pollution on SAH risk represents a missed opportunity for comprehensive environmental health risk assessment. Future studies integrating long-term, high-resolution air quality data with health outcomes are essential, but first require investment in monitoring infrastructure.

These findings have important implications for neurocritical care planning in Brazil. The consistent seasonal pattern suggests opportunities for targeted capacity planning, with neurocritical care resources accounting for predictable autumn/winter surges in SAH admissions, particularly in southern states where temperature effects are most pronounced (39). Integrating meteorological data—including temperature drops, atmospheric pressure changes, and humidity shifts—into public health surveillance could enable proactive capacity adjustments (40,41). Such environmental early warning systems could alert healthcare facilities to periods of elevated SAH risk, facilitating the preparation of staffing and resources before seasonal peaks (41,42).

Climate change adds further complexity to this scenario. Increasing temperature variability and extreme weather events may amplify seasonal disease burdens (14,24,40). While long-term warming might reduce winter-associated peaks in some areas, increased climate volatility and abrupt temperature transitions could trigger acute hemodynamic stresses in vulnerable populations (43,44). Given Brazil's regional heterogeneity, climate change impacts on SAH incidence are likely to be uneven, potentially exacerbating existing health inequalities between northern tropical and southern subtropical regions (40).

This study has inherent limitations. The ecological design precludes individual-level causal inference and cannot determine whether specific patients were exposed to cold immediately before rupture. Data were restricted to public system admissions (~ 75% of the population), potentially missing privately insured patients with different risk profiles. We lacked individual-level confounders (hypertension control, aneurysm characteristics, medications). Monthly aggregation may obscure the acute effects of temperature fluctuations. Air pollution analysis was impossible due to infrastructure deficiencies. The five-year period, while capturing robust seasonal patterns, may not reflect long-term climate trends. Despite these constraints, this nationwide analysis provides novel evidence that moderate climatic fluctuations meaningfully influence SAH occurrence in a climatically diverse middle-income country, with implications for environmental health surveillance and neurocritical care preparedness across Latin America.

Conclusion

SAH admissions in Brazil increase during colder months, with a consistent inverse association between temperature and incidence. This pattern is biologically plausible, reflecting cold-induced sympathetic activation, peripheral vasoconstriction, and prothrombotic changes. These findings extend evidence from temperate regions to tropical and subtropical settings, demonstrating that even moderate seasonal temperature variations can meaningfully influence SAH risk in climatically diverse populations.

The critical gap in air pollution monitoring infrastructure represents a significant impediment to comprehensive environmental health risk assessment in Brazil, highlighting the urgent need for investment in environmental surveillance across Latin America. Findings suggest the need to incorporate seasonal considerations into neurocritical care planning and integrate meteorological indicators into health surveillance systems. As climate variability intensifies, adaptive surveillance strategies and seasonal preparedness will be crucial in preventing disproportionate impacts on vulnerable regions and populations. Future research should prioritize establishing comprehensive air quality monitoring networks and examining individual-level interactions between environmental exposures and cerebrovascular risk.

Declarations

Compliance with Instructions to Authors: The authors confirm that this manuscript complies with all instructions to authors provided by the *Neurocritical Care* journal, including formatting, word count, figure/table specifications, reference style, and ethical requirements.

General Statement: All authors have read and approved the submitted manuscript. This manuscript has not been submitted elsewhere nor published elsewhere in whole or in part. All authors confirm the integrity of the work and take responsibility for the content and conclusions presented herein.

Authors' Contributions: All authors meet the ICMJE criteria for authorship and have approved the final manuscript. Individual contributions were as follows: Daniela Laranja Gomes Rodrigues (DLGR): Study conceptualization, design, data collection coordination, data analysis, manuscript drafting, and project supervision. João Brainer Clares de Andrade (JBCA): Study design, critical review of manuscript, methodological supervision, and approval of final version. Gisele Sampaio Silva (GSS): Study design, critical revision for important intellectual content, and approval of final version for submission.

All authors contributed to the interpretation of data and critical revision of the manuscript. All authors approved the final version and agree to be accountable for all aspects of the work.

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Conflicts of Interest: The authors declare no competing interests, financial or otherwise, related to the study design, execution, analysis, interpretation, writing, or decision to publish this manuscript.

Ethics Approval and Informed Consent: The study utilized only aggregated, de-identified service data without individual patient identifiers. Individual informed consent was not required due to the use of non-identifiable aggregated data. No patient-level data were collected or analyzed.

Use of Generative AI and AI-Assisted Technologies: During the preparation of this manuscript, the authors used ChatGPT (OpenAI, GPT-4) to assist with English language editing, grammar review, and translation of Portuguese content into English. All AI-generated content was thoroughly reviewed, edited, and verified by the authors to ensure accuracy, clarity, and scientific rigor. The authors take full responsibility for the content and integrity of this publication. AI tools were not used for data analysis, interpretation, or the generation of scientific conclusions.

Data Availability: Hospitalization data are publicly available from DATASUS (http://datasus.saude.gov.br/). Meteorological data are available from INMET (https://portal.inmet.gov.br/). Limited air pollution data were obtained from OpenAQ (https://openaq.org/). Aggregated analysis datasets and code are available from the corresponding author upon reasonable request, subject to data protection regulations.

Guarantor: Daniela Laranja Gomes Rodrigues serves as the guarantor for this manuscript and accepts full responsibility for the work, including the study design, access to data, and the decision to submit for publication.

Justification:

- Study conducted without external funding through institutional social responsibility initiatives
- No access to publication budgets or research grants
- Authors from a middle-income country (Brazil), where APC represents a substantial barrier
- Findings address critical knowledge gap with direct implications for neurocritical care planning globally
- Commitment to open data/code sharing to maximize impact

We believe this research contributes important evidence from underrepresented populations to the neurocritical care literature. A waiver would enable maximum dissemination to clinicians and policymakers in resource-limited settings who would benefit most.

Authors' Contributions

All authors meet the ICMJE criteria for authorship and have approved the final manuscript. Individual contributions were as follows: Daniela Laranja Gomes Rodrigues (DLGR): Study conceptualization, design, data collection coordination, data analysis, manuscript drafting, and project supervision. João Brainer Clares de Andrade (JBCA): Study design, critical review of manuscript, methodological supervision, and approval of final version. Gisele Sampaio Silva (GSS): Study design, critical revision for important intellectual content, and approval of final version for submission.

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Tables

Table 1: Limited PM_{10} data available in Brazil (2023)

Month	PM_{10} (µg/m³)	SAH Admissions
April 2023	18.1	186
May 2023	20.6	204
June 2023	29.6	153

Legend. Limited PM_{10} data available for Brazil (April-June 2023 only). Data from selected urban monitoring stations (São Paulo, Rio de Janeiro, Brasília) represent <5% of the study period and <20% of the national population. PM_{10}, particulate matter ≤10 micrometers; SAH, subarachnoid hemorrhage.

Figures

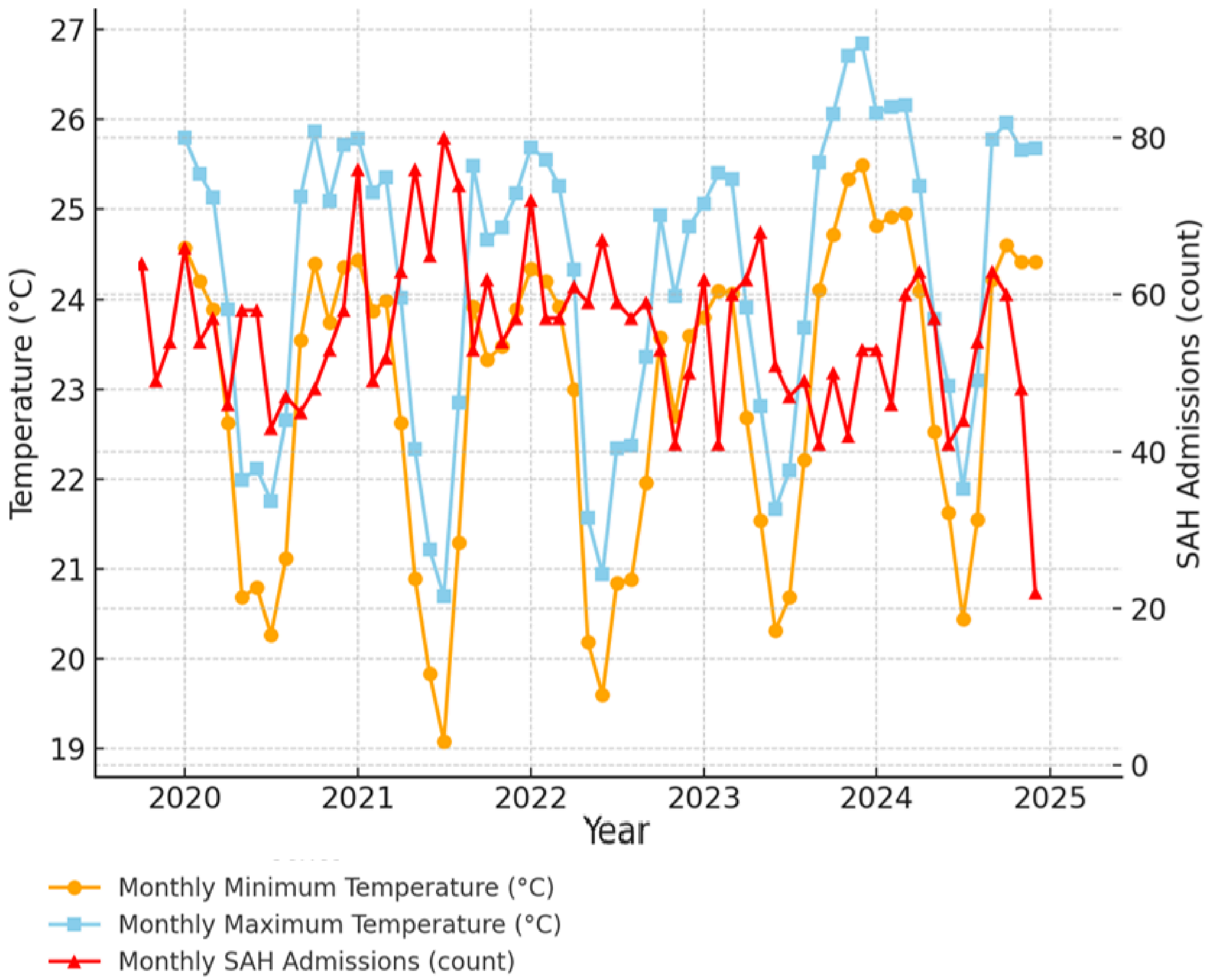

Figure 1

Time series of monthly subarachnoid hemorrhage admissions and temperature variations in Brazil (2020-2024).

Monthly SAH admissions (blue line, left axis) and mean maximum (red) and minimum (orange) temperatures (right axis). Vertical dashed lines indicate seasonal transitions. Peak admissions occurred during May–July (autumn-winter). SAH, subarachnoid hemorrhage.

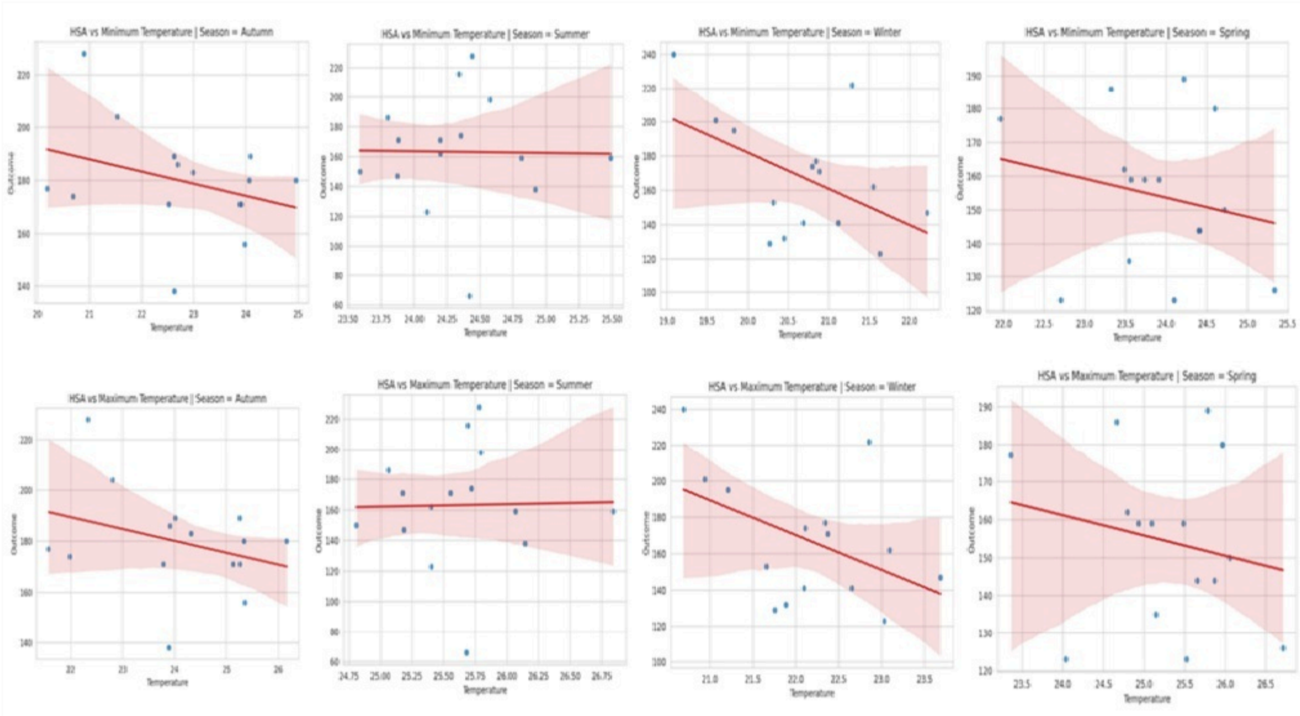

Figure 2

Seasonal stratification of the relationship between temperature and subarachnoid hemorrhage admissions in Brazil (2020-2024).

Monthly SAH admissions versus mean temperature by season: (A) Autumn, (B) Winter, (C) Spring, (D) Summer. Points represent observations; lines show linear fits with 95% CI (shaded). Regression coefficients and p-values are shown in panels. CI, confidence interval.

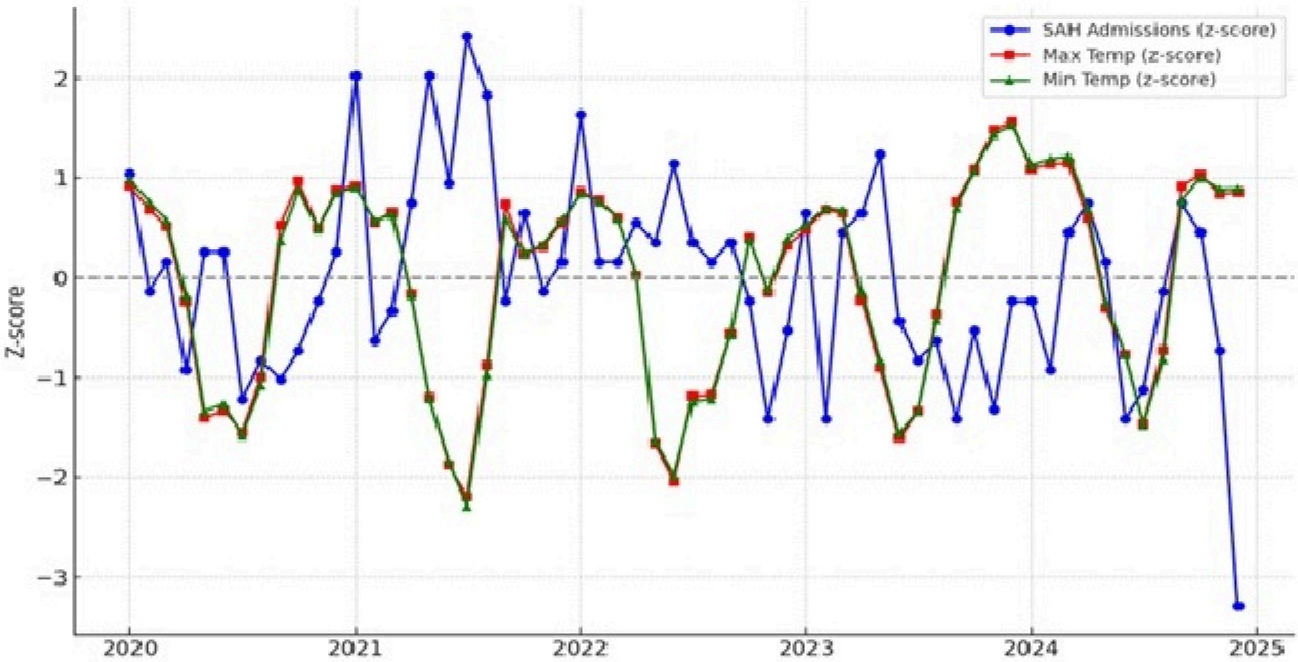

Figure 3

Standardized trends comparing SAH admissions and annual temperature anomalies in Brazil (2020-2024).

Z-scores for monthly SAH admissions (blue) and temperatures (maximum: red dashed; minimum: orange dashed) relative to period means. Gray bands indicate ±1 SD. Correlation: r = −0.42 (p = 0.02). SD, standard deviation.