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Spatial Analysis of Cerebrovascular Hospitalization Risk and Particulate Matter Effects: Evidence from Northern Spain

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Abstract

Cerebrovascular diseases are among the leading causes of mortality and disability worldwide. This study aimed to identify geographic patterns and sex differences in unplanned hospital admissions for cerebrovascular diseases, and to assess their association with ambient air pollution within small areas of Asturias, a northern region of Spain that exhibits elevated rates of mortality and morbidity from these pathologies. The study included 20,305 unplanned hospital admissions recorded between 2016 and 2023. Standardized admission ratios, smoothed relative risks, and posterior risk probabilities were estimated using reparameterized Besag–York–Mollié models at the census tract level. Global and Local Moran's I statistics were computed to evaluate the spatial correlation of admissions. Subsequently, estimates of PM_{10} and $PM_{2.5}$ concentrations were incorporated into the models, adjusting for average net income per person, to assess their association with admission risk and their contribution to the geographical patterns observed. Spatial analysis revealed marked inequalities in cerebrovascular admissions both between sexes and across small areas. High-risk clusters were consistently identified in the north-central coastal area for both sexes. For men, higher PM_{10} and $PM_{2.5}$ levels were statistically significantly associated with hospitalizations (PM_{10}: RR = 1.08, 95% CI: 1.02–1.14; $PM_{2.5}$: RR = 1.22, 95% CI: 1.07–1.40, per 5 $\mu g/m^3$ increase) and explained part of the spatial variability observed. For women, neither pollutant showed statistically significant associations nor appeared to be associated with the geographic patterns. Integrating both geographic and sex-related factors is essential for identifying high-risk areas and potential risk factors in the burden of cerebrovascular disease. In men, exposure to PM_{10} and $PM_{2.5}$ was associated with cerebrovascular hospitalizations and explained part of the spatial variability observed, while no such association was found in women.

Keywords: cerebrovascular disorders; hospital admissions; spatial inequalities; disease mapping; particulate matter

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1. Introduction

Circulatory diseases, including cerebrovascular and cardiovascular diseases, are the leading cause of death worldwide. The World Health Organization (WHO) estimated 19.8 million deaths from these conditions in 2022, of which more than 80% were attributable to strokes and myocardial infarctions [1]. Globally, stroke was the second cause of death in 2016 and 2019 (after ischemic heart disease) and the third in 2021 (after ischemic heart disease and COVID-19) according to the Global Burden of Disease [2,3]. There were 7.3 million stroke deaths in 2021, representing approximately 11% of all deaths, and 160.5 million disability-adjusted life years (DALYs), representing roughly 6% of all DALYs across all causes [3]. In Europe, stroke-related burden decreased during the years 1990–2019; however it remained the third cause of DALYs in Western Europe and the second in Central and Eastern Europe [4]. Spain is no exception. According to the latest data from the National Institute of Statistics, cerebrovascular diseases were the second cause of death in Spain in 2023 and the third in 2024 [5]; however, mortality rates have shown a downward trend over the past decades [6].

The Principality of Asturias (hereinafter Asturias), an autonomous community in northern Spain, is among the Spanish regions with the lowest decline in cerebrovascular mortality for both sexes. In 2024, cerebrovascular diseases accounted for 4.93% of all deaths in this region, ranking as the second leading cause of death among women (5.62%) and the third among men (4.17%). Notably, Asturias recorded the highest cerebrovascular mortality rate per 100,000 inhabitants among all Spanish regions in 2023 and the second highest in 2024 [5]. Despite the apparent downward trend in mortality rates, the number of hospital discharges has increased in recent years. In particular, Asturias had the highest cerebrovascular morbidity rate in Spain in 2023, with 371 per 100,000 [5].

The region is of particular concern regarding environmental risk factors, particularly ambient air pollution, given the historical presence of heavy industry and thermal power stations [7]. Although air quality has improved in Asturias in recent years, important challenges remain, particularly in urban areas where population exposure to air pollutants remains substantial [8]. In 2014, Asturias recorded the highest $PM_{2.5}$-attributable cardiovascular mortality rate in Spain, with the majority of deaths caused by myocardial infarctions, strokes, and heart failure [9]. In addition, this region has the oldest population in Spain [5]; a demographic characteristic associated with increased susceptibility to the adverse effects of air pollution [10]. At the regional level, some studies have examined stroke code activations and highlighted inequalities in emergency care across different areas of Asturias. Peripheral areas, which tend to have older populations, accounted for a low proportion of these activations [11,12]. In addition, López-Martínez et al. showed sex differences in age, symptoms, severity, treatment, and subsequent complications among patients with stroke in a rural healthcare area of Asturias [13]. Previous studies have identified spatial disparities associated with other diseases in this region, highlighting the existence of geographical health inequalities and supporting the need for further spatial epidemiological research studies [14,15]. Despite the considerable burden of cerebrovascular disease in the region and its industrial activity, the number of studies conducted on this topic remains limited. This highlights the importance of examining the geographical distribution of the disease and the environmental factors that may be contributing to its burden in Asturias.

Spatial analysis has proven valuable not only for visualizing disease distribution, but also for identifying patterns and variations, including the detection of vulnerable high-risk areas [16]. Furthermore, spatial approaches can help identify environmental and social determinants that inform decision-making, guiding interventions, distributing resources, and reducing health inequalities [17]. This is particularly relevant for stroke, a largely preventable condition; in 2021, more than 80% of its burden was attributable to

modifiable risk factors such as high systolic blood pressure, air pollution, high outdoor temperatures, smoking, unhealthy diet, and physical inactivity, with environmental and behavioral determinants substantially contributing to disease burden [18].

In particular, ambient air pollution is considered one of the principal risk factors, responsible for more than 14% of stroke deaths worldwide [19]. Ambient air pollution consists of particulate matter (PM) and toxic gases. PM is classified by particle size: $PM_{2.5}$ refers to particles with a diameter of less than 2.5 μm and PM_{10} to those less than 10 μm, both largely derived from industrial emissions and traffic [20]. Numerous studies have reported associations between PM exposure and cerebrovascular outcomes [21,22]. The geographic variability of PM exposure is a critical factor in health risk assessment, as its spatial distribution is heterogeneous and exhibits marked geographical patterns [23]. In this context, approximately 70% of the Asturian population is concentrated in the central part of the region, which includes important transport networks, industrial activities, and urban areas that may contribute to spatial heterogeneity in air pollution exposure in the region.

Socioeconomic status may influence both the distribution of exposure to pollutants and health inequalities. Previous studies have shown that lower socioeconomic groups often have a higher prevalence of cardiovascular risk factors such as hypertension, diabetes, and obesity, contributing to a greater burden of cerebrovascular disease. These groups may also be differentially exposed to air pollution [24–26]. Therefore, socioeconomic status is regarded as an important potential confounder in studies assessing the association between air pollution and health outcomes.

In this context, this study aimed to analyze the spatial distribution of unplanned hospital admissions due to cerebrovascular diseases across small areas in Asturias, to identify geographic patterns, high-risk clusters, and sex differences in their distribution. It also aimed to assess the association between ambient particulate matter exposure ($PM_{2.5}$ and PM_{10}) and admission risk, adjusting for income as a socioeconomic indicator. The ultimate goal was to better understand the spatial inequalities in the burden of cerebrovascular disease in Asturias.

2. Materials and Methods

2.1. Study Area and Reference Population

The study region was Asturias (Figure S1), which had a population of 1,042,608 inhabitants in 2016 [27], the year used as reference for population data. This was an ecological study in which the units of analysis were the 868 census tracts in 2016, covering the entire territory of the region. These territorial units vary considerably in surface area but provide a relatively homogeneous population size, making them suitable for spatial analysis. They are commonly used in epidemiological research to examine spatial disparities and identify geographic patterns and health inequalities [28,29].

Asturias is divided into 78 municipalities, which are larger administrative areas comprising varying numbers of census tracts. To support the interpretation of results, a map showing the names of the municipalities is provided in the Supplementary Materials (Figure S2 and Table S1).

The population by census tract was obtained from the 2016 Municipal Register of Inhabitants provided by the Asturian Society of Economic and Industrial Studies (SADEI). This population was stratified by sex and age group (0–14, 15–39, 40–64, 65–84 and 85 years and over).

2.2. Health Data

The health data analyzed correspond to unplanned hospital admissions for cerebrovascular diseases in Asturias between 2016 and 2023, retrieved from the Minimum Basic Data

Set (MBDS). Table S2 provides a detailed description of the International Classification of Diseases (ICD-10) [30] codes used in the study. All codes were analyzed together due to the small number of cases in some groups.

The individual pseudonymized records were georeferenced by assigning geographical coordinates to the postal address of each record and grouping them by census tracts, alongside population data from the municipal census of residents. For the entire period, 90.1% of the records were successfully geocoded, with the remaining 9.9% excluded owing to missing or incomplete addresses. A more detailed description of the study population and geocoding procedure is provided in Martínez-Pérez et al., which followed the same process but was limited to the central area of Asturias [14]. The records were aggregated over the entire study period to estimate long-term spatial patterns of cerebrovascular hospitalization risk at the census tract level and to obtain stable risk estimates for these small geographic areas.

2.3. Air Pollution Assessment

Estimates of PM_{10} and $PM_{2.5}$ at the census tract level were obtained using a spatiotemporal land use model based on random forest algorithms. First, daily values were estimated on 1 km × 1 km grids for the entire Spanish territory excluding Canary Islands, Ceuta, and Melilla for the study period. A full description of the model development is provided in [31,32]. Subsequently, for census tracts greater than 1 km^2, PM concentrations were estimated as the average of the 1 km^2 grids intersecting each census tract. For census tracts smaller than 1 km^2, a downscaling process based on random forest models was applied, incorporating variables such as population, land use, road, industrial activity, elevation, slope, nighttime light intensity, surface brightness, and impermeability to improve the accuracy of PM_{10} and $PM_{2.5}$ estimates as previously described in [33], with full details available in the Supplementary Materials. Finally, daily estimates were aggregated to obtain long-term average concentrations of PM_{10} and $PM_{2.5}$ for each census tract over the study period (2016–2023). The predictive performance of the downscaling models was assessed using 10-fold cross-validation by comparing observed and predicted PM concentrations at monitoring stations. Across the study period, the model's mean cross-validated R^2 was 0.72 for PM_{10} and 0.79 for $PM_{2.5}$, with corresponding RMSE values of 6.29 $\mu g/m^3$ and 2.89 $\mu g/m^3$.

2.4. Statistical Analysis

Spatial Distribution

For each sex and census tract, the standardized admission ratios (SARs) were calculated, defined as the ratios of observed to expected hospital admissions, obtained using the indirect method adjusting by age group and taking the total population of Asturias as the reference.

The use of SARs may result in overdispersion, particularly in small population areas, where observed variability may exceed what is expected. This extra variability can be attributed to two factors: correlation between neighboring areas and non-spatial variables affecting relative risk [34]. Therefore, spatial smoothing methods were applied to improve the accuracy of morbidity estimates by reducing the extra variability [14]. Conditional autoregressive models, specifically iCAR [35] and BYM2 [36]—a reparametrized version of the Besag–York–Mollié (BYM) [37]—were fitted using the simplified Laplace approximation within the INLA (integrated nested Laplace approximation) framework for Bayesian inference [38,39]. These models are commonly used in spatial epidemiology; BYM2 model combines the structured spatial effects of the iCAR model, which captures the correlated spatial variability, with an unstructured random effect capturing residual variability unex-

plained by the neighborhood structure. Both models were fitted using the INLA library (R version 4.5.0) [40] and compared using the Deviance Information Criterion (DIC) [39] and the Watanabe–Akaike information criterion (WAIC).

The smoothed relative risk (SRR) and the posterior risk probability (PP) were estimated using the selected models. The SRR is a modified form of the SAR that captures spatial variability across neighboring areas and random effects. The PP is defined as the probability that the SRR exceeds 100, indicating a higher-than-expected risk of hospitalization.

Global and Local Moran's I were calculated to assess the spatial correlation of admissions in Asturias. Global Moran's I was used to test the null hypothesis of spatial randomness against the alternative hypothesis of spatial correlation (positive or negative). Local Moran's I detects spatial correlation at a local level [41]. A statistically significant (p-value < 0.05) and positive value indicates the presence of a cluster of similar values, such as high values surrounded by high values, or low values surrounded by low values. Conversely, a statistically significant but negative value suggests that census tracts with high values are surrounded by low-value tracts, and vice versa. The results were presented in maps; the legend interpretation and color scheme are provided in Table S3.

To incorporate PM exposure, it was first determined whether including PM_{10} and $PM_{2.5}$ estimates in the BYM2 models explained part of the spatial variability in admissions, as reflected by changes in the model's variance components, given that BYM2 quantifies overall variability across areas and the proportion attributable to spatial versus non-spatial components. Then, the association between PM exposure and admissions was examined, reporting relative risks (RRs) and 95% credible intervals (CIs). To determine the most appropriate model specification, it was evaluated whether allowing the effect of PM to vary across space improved model fit by fitting spatially varying coefficient (SVC) models [42]. If the variability of the PM coefficient given by the model is very small, there will be little evidence that the effects vary across space, whereas a large variability will indicate that the effect of PM on the risk of hospitalization differs between census tracts. All models were adjusted, to avoid a potential confounding effect by socioeconomic status, by the average net income per person (per €1000 increase) in 2016 [5]. In addition, separate models were estimated for each sex.

The analyses were carried out in R (version 4.5.2) using RStudio (version 2026.01.0).

3. Results

During the study period, there were 20,305 unplanned hospital admissions for cerebrovascular diseases, corresponding to a mean annual rate of 243.44 admissions per 100,000 inhabitants. The sex distribution of hospitalizations between 2016 and 2023 was well balanced: 51% in men and 49% in women. The distribution of hospitalization by age group varied between sexes (Table 1). In men, more than 50% of hospitalizations occurred in the 65–85 age group, followed by those aged 40–65 (24%). Among women, 45% of hospitalizations occurred in the 65–85 age group, followed by those aged 85 and over (43%).

For both men and women, the BYM2 model showed lower DIC and WAIC values than the iCAR model (Table S4). The differences exceeded 17 points for DIC and 70 points for WAIC, providing strong support for the BYM2 model over the iCAR model. This suggests that modeling both spatially structured and unstructured random effects provided a better representation of the observed variability than a model including only spatially structured effects. Therefore, the maps were generated using the BYM2 model. The distribution of SARs also differed between men and women, although some areas in the center of the region showed high admission rates for both sexes (Figure S3). The SAR map reflects the raw data prior to smoothing and it is useful to understand the original data

structure. The SRR maps, shown in Figure 1, also revealed that the spatial distribution of cerebrovascular admissions differed between sexes. Although some areas, mainly in the central zone, showed elevated risks for both sexes, the number of these areas was greater for women. The spatial distribution of the PP was similar to that of the SRR (Figure 2), clearly showing low risk probabilities in the peripheral areas of the region for both sexes and higher probabilities in the center. The proportion of census tracts exceeding a PP value of 0.8 was 18.78% in men and 19.35% in women. The Global Moran's I analysis (Table S5) indicated moderate, statistically significant positive spatial correlation in the distribution of admissions for both sexes.

Table 1. Distribution by age and sex of the number of hospitalizations for cerebrovascular diseases. In addition, the population of 2016 by age group is also shown.

	Men			Women		
Age Group	**Nº Cases**	**% Cases**	**Population**	**Nº Cases**	**% Cases**	**Population**
≤14	7	0.07	58,807	4	0.04	55,691
(14–40)	86	0.83	135,547	87	0.87	132,327
[40–65)	2434	23.57	198,382	1121	11.24	207,279
[65–85)	5627	54.49	91,279	4510	45.20	117,743
≥85	2173	21.04	13,837	4256	42.65	31,716

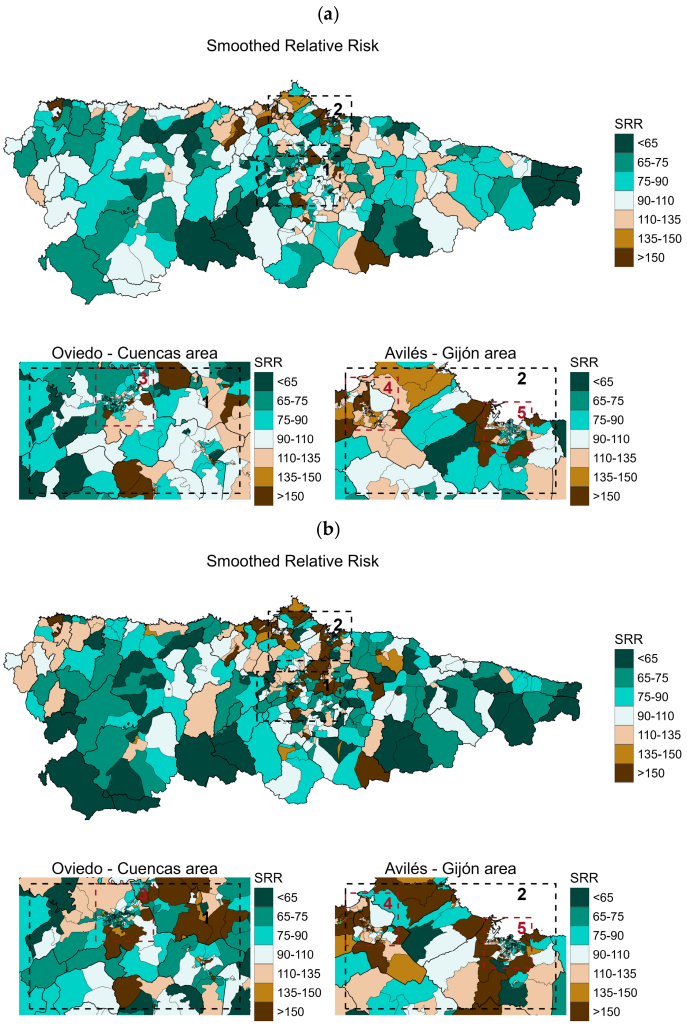


Figure 1. Smoothed relative risk (SRR) for cerebrovascular diseases in Asturias. The maps with the zoom on areas 3, 4 and 5 are presented in Figures S4 and S5. (**a**) Men, (**b**) women.

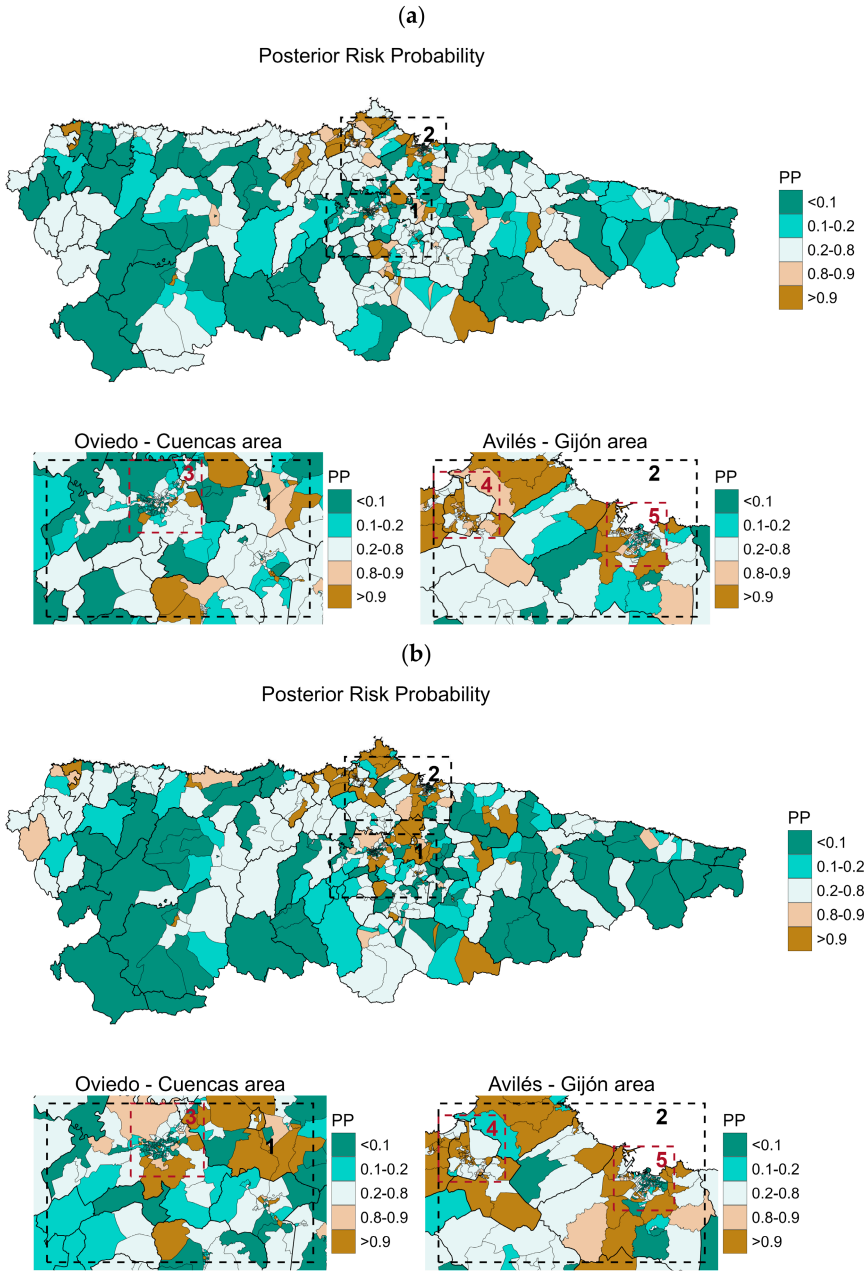


Figure 2. Posterior risk probability (PP) for cerebrovascular diseases in Asturias. The maps with the zoom on areas 3, 4 and 5 are presented in Figure S4 and S5. (**a**) Men, (**b**) women.

High-risk clusters, shown in red in Figure 3, were identified particularly in the north-central area of Asturias—specifically in the municipalities of Avilés, Castrillón, Gozón, Corvera de Asturias and Gijón—for both sexes. Low-risk clusters were found in the center and east of the region for men, while for women, only one low-risk cluster was identified in Allande, in the western part of Asturias. Census tracts with low-risk surrounded by high-risk areas, shown in light blue, were identified for both sexes in the central area. High-risk areas surrounded by low-risk ones, shown in orange, were found only in men, in Oviedo, located in the central part of the region.

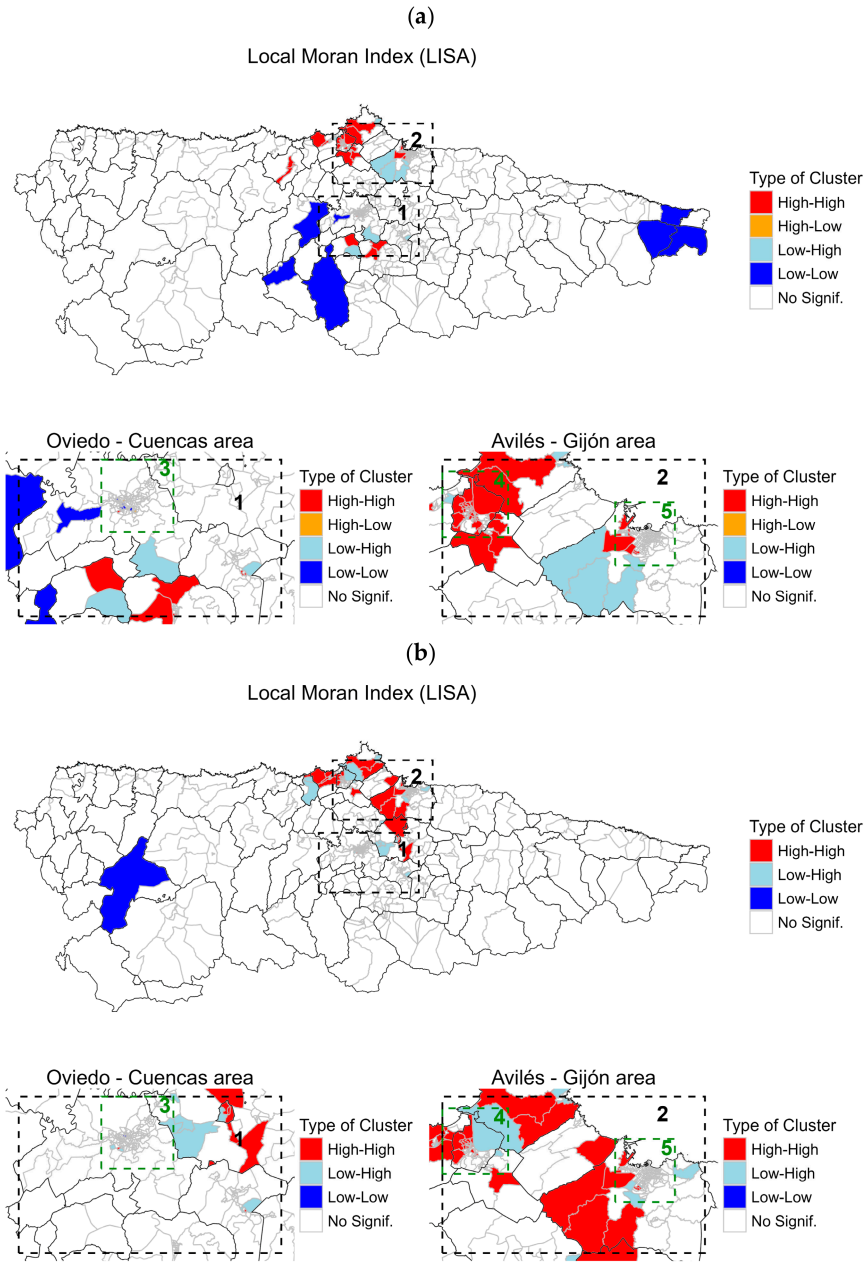


Figure 3. Local Moran's I (LISA) for cerebrovascular diseases in Asturias. The maps with the zoom on areas 3, 4 and 5 are presented in Figures S4 and S5. (**a**) Men, (**b**) women.

Enlarged maps of the smaller census tracts in Oviedo, Gijón, and Avilés for both sexes are provided in the Supplementary Materials for better visualization (Figures S4 and S5).

Over the whole study period, the mean PM_{10} concentration was 19.56 $\mu g/m^3$ (range across census tracts: 8.89–28.40 $\mu g/m^3$), while the mean $PM_{2.5}$ concentration was 9.92 $\mu g/m^3$ (range across census tracts: 5.27–13.89 $\mu g/m^3$). For PM_{10}, 77.19% of the census tracts exceeded the WHO annual recommended level of 15 $\mu g/m^3$, and for $PM_{2.5}$, all census tracts exceeded the recommended level of 5 $\mu g/m^3$ (Tables S6 and S7) [43]. The spatial distribution maps of PM_{10} and $PM_{2.5}$ showed that areas with higher pollutant levels were located in the central area of the region, while peripheral areas showed the lowest concentrations (Figures S6 and S7).

When PM_{10} and $PM_{2.5}$ concentrations were included in the BYM2 models adjusted for average net income per person, the proportion of spatial variability was reduced in men, indicating that PM exposure accounted for part of the spatial variability observed (Table 2).

For women, overall variability remained similar while spatial variability increased slightly (Table 2).

Table 2. Comparison of overall variability across areas and proportion of spatial variability before and after including covariates, together with RR per 5 μg/m^3 increase and 95% CI for each pollutant and each sex.

	Men			Women		
	BYM2	**BYM2, PM_{10}**	**BYM2, $PM_{2.5}$**	**BYM2**	**BYM2, PM_{10}**	**BYM2, $PM_{2.5}$**
RR, mean (95% CI)		**1.08 (1.02, 1.14)**	**1.22 (1.07, 1.40)**		1.05 (0.98, 1.12)	1.15 (0.98, 1.36)
Overall variability	0.1442	0.1406	0.1409	0.2227	0.2231	0.2231
Spatial variability (%)	26.5	22.4	23.6	24	25.2	25.6

The RR of hospital admissions differed markedly between men and women, being consistently higher in men than in women for both pollutants. In particular, in men, the risk increased by 8% for every 5 μg/m^3 increment in PM_{10} and by 22% for every 5 μg/m^3 increment in $PM_{2.5}$, both of which were statistically significant (Table 2). For women, the association was positive but not statistically significant for either pollutant (Table 2). When SVC models were fitted, there was little evidence that the effects of pollutants varied across space, given that the coefficients of variability for PM_{10} and $PM_{2.5}$ ranged from $3.18 \cdot 10^{-5}$ to $4.74 \cdot 10^{-5}$. Furthermore, BYM2 provided a better fit than SVC, according to the DIC and WAIC (Table S8).

4. Discussion

This ecological study revealed marked spatial clustering of hospital admissions for cerebrovascular diseases at the census tract level and suggested that ambient air pollution may explain part of the geographical differences observed, particularly among men. This is the first study to describe the spatial distribution of cerebrovascular diseases and their association with PM across Asturias using a small-area approach. The region represents a relevant setting not only due to its high disease burden, but also because of its heterogeneous exposure to air pollution, driven by the coexistence of industrial activity, heavy traffic, and rural areas with markedly different pollution levels.

The sex distribution of hospital admissions during the study period was consistent with the findings summarized in the review by Rexrode et al. [44], according to which the incidence tends to be higher in men throughout middle age and in women from the age of 80 onwards. In Asturias, the distribution of admissions varied considerably across the study area. Most areas in the west and east of the region, where rural areas predominate, showed lower risk of hospitalization. Areas of elevated risk were concentrated in the north-central coastal zone, which combines high population density with considerable industrial activity and heavy traffic. Notably, these clusters encompassed both urban and rural census tracts, and some also showed elevated risks of hospitalization for asthma, chronic obstructive pulmonary disease, and ischemic heart disease [14,15,45]. The same areas additionally exhibited the highest concentrations of PM_{10} and $PM_{2.5}$ in the region [8]. This spatial coincidence suggests that differences in air pollution exposure may contribute to the geographic patterns observed in cerebrovascular hospitalizations.

In men, prior to the inclusion of PM concentrations in the model, more than a quarter of the geographical variability in admissions was attributable to spatial structure. After incorporating PM concentrations, overall variability decreased only slightly; however, spatial

variability was further reduced, indicating that air pollution exposure was associated with the geographic patterns observed and that part of what had been interpreted as a spatial effect may be related to PM concentrations. In women, overall variability did not change when PM concentrations were incorporated in the model, while the unexplained spatial variability increased slightly. These findings suggest that the geographical distribution of admissions in women may be driven by factors other than air pollution. Previous studies have shown that geographical variation in cerebrovascular disease risk is a complex phenomenon not attributable to a single cause. Beyond environmental factors and income, part of the variation observed is also attributable to unmeasured factors such as traditional vascular risk factors, genetic predisposition, lifestyle, access to health services, education level, or other local conditions [46,47]. It should be noted that no evidence was found to suggest that the effect of PM on the risk of cerebrovascular hospitalization varies geographically, indicating that the impact of air pollution on cerebrovascular events is relatively homogeneous across the census tracts of the region.

The analysis of the association between PM_{10} and $PM_{2.5}$ exposure and cerebrovascular hospitalizations showed positive associations in men, while findings in women were less evident. These findings are consistent with previous literature. A 2022 global review found an increased risk of stroke associated with long-term $PM_{2.5}$ exposure in both sexes, although a slight publication bias was detected in analysis of studies including women [48]. Similarly, a review of ambient PM pollution in China found a positive association between PM exposure and ischemic stroke DALYs in males, while in women the burden was more strongly associated with a diet high in sodium, smoking, and household air pollution from solid fuels [49]. In addition, the health effects of ambient air pollution on the cardiovascular system may be modified by several biological differences between men and women, including hormonal influences, differences in the respiratory tract and differences in metabolism [50]. Behavioral and occupational factors may also contribute to the observed sex differences. For example, men and women may differ in occupational exposure profiles, smoking patterns and other cardiovascular risk factors, which could influence both exposure and susceptibility to the effects of air pollution [51,52]. However, these factors could not be evaluated in the present ecological study because individual-level information was unavailable, and therefore, the sex-specific associations observed in this study should be interpreted with caution.

Beyond PM, previous evidence from Asturias has also linked cerebrovascular diseases to other pollutants, particularly NO_2 and SO_2 [53], suggesting that PM may not fully capture the impact of air pollution on cerebrovascular risk in the region. Thus, the residual spatial variability observed after including PM concentrations in the models may partly reflect exposure to other pollutants not considered in the present analysis, as well as the combined effects of complex pollution mixtures. Meteorological factors may also partially account for some of the findings of this study; Motlogeloa et al. [54] reviewed the association between climate and health, reporting that cerebrovascular disease showed a substantial association with factors such as temperature and rainfall in most of the studies reviewed. Given that urban areas are particularly vulnerable to the effects of climate change [55], these meteorological factors may be especially relevant in the context of this study, as the highest-risk clusters in this study were identified mainly in urban and sub-urban areas. Taken together, although the evidence suggests that exposure to air pollution is related to cerebrovascular events, further epidemiological investigations are needed—particularly studies disaggregated by stroke subtype, which remain scarce [56].

Some limitations should be acknowledged. First, the study relied on the place of residence recorded on the health card at the time of hospital admission, which may not have reflected the individual's actual residence, potentially leading to exposure misclassification.

Second, temporal trends could not be assessed because analyses were based on aggregated data for the entire study period. Future spatiotemporal studies may help determine whether the observed spatial patterns remained stable over time. Third, the procedure used to estimate PM concentrations across the entire region of Asturias may have introduced uncertainty, particularly in areas lacking nearby monitoring stations. Fourth, as with most single-pollutant models, we cannot rule out the possibility that the observed associations partly reflect exposure to correlated co-pollutants rather than particulate matter alone. Future studies using multi-pollutant models could help disentangle the independent contribution of each pollutant. Moreover, because data on other relevant cerebrovascular risk factors were unavailable at the census-tract level, models could only be adjusted for average net income. Therefore, residual confounding cannot be excluded, and the observed associations should be interpreted with caution and should not be considered evidence of causality. Finally, the ecological design of the study, with data aggregated at the census tract level, does not allow inference at the individual level and raises the possibility of ecological fallacy.

Despite these limitations, the present study also has notable strengths. It included hospital admission data covering the entire population of Asturias, ensuring comprehensive population-level representation. PM exposure estimates were generated for all census tracts in the region, allowing complete spatial coverage. The use of census tracts as spatial units enabled the analysis of areas with relatively homogeneous populations, thereby enhancing the internal comparability of spatial estimates. In addition, the analyses accounted for socioeconomic context through area-level income indicators.

Overall, these findings contribute to a better understanding of the spatial distribution of cerebrovascular disease and its relationship with air pollution. However, some spatial variability remains unexplained, and future research should explore additional environmental and contextual factors that may help account for these patterns. These results may inform the development of targeted preventive strategies and support public health policies aimed at reducing particulate matter-related cerebrovascular morbidity.

5. Conclusions

Differences were found in the spatial distribution of cerebrovascular diseases between sexes and across census tracts in the Principality of Asturias. High-risk clusters were identified, particularly in the north-central coastal area for both sexes, where pollution levels were also higher. PM exposure may partially explain the geographic patterns observed and was associated with increased hospitalization risk in men, while its association with spatial patterns was less evident in women. These findings highlight the importance of integrating geographic and sex-related perspectives into public health strategies aimed at reducing the burden of cerebrovascular disease.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/environments13080435/s1, Figure S1: Study area; Figure S2: Municipalities; Figure S3: Standardized admission ratios; Figure S4: Standardized admission ratio zoom for men; Figure S5: Standardized admission ratio zoom for women; Figure S6: PM_{10} distribution; Figure S7: $PM_{2.5}$ distribution; Table S1: Municipality codes; Table S2: Disease classification; Table S3: Map legends; Table S4: Model fit (BYM2 vs iCAR); Table S5: Global Moran's I; Table S6: PM_{10} summary statistics; Table S7: $PM_{2.5}$ summary statistics; Table S8: Model fit (BYM2 vs SVC).

Author Contributions: I.G.-C.: formal analysis, investigation, methodology, visualization, writing—original draft, writing—review and editing. I.M.-P.: formal analysis, methodology, investigation, visualization, writing—review and editing. R.F.-I.: conceptualization, investigation, methodology, supervision, writing—review and editing. S.P.: methodology, writing—review and editing; M.G.: methodology, writing—review and editing. A.V.: methodology, writing—review and editing. A.F.-S.:

conceptualization, investigation, methodology, project administration, funding acquisition, supervision, writing—review and editing. All authors have read and agreed to the published version of the manuscript.

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Informed Consent Statement: Patient consent was waived as no individual-level data were used in the analyses.

Data Availability Statement: Summary statistics and the statistical code used for the analysis may be available upon reasonable request to the corresponding author. Hospitalization data was provided by the Asturias Government Health Service and cannot be shared for confidentiality reasons.

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