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Research article

Wildfires impact on $PM_{2.5}$ concentration in galicia Spain

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ABSTRACT

Wildfire intensity and severity have been increasing in the Iberian Peninsula in recent years, particularly in the Galicia region, due to rising temperatures and accumulating drier combustible vegetation in unmanaged lands. This leads to substantial emissions of air pollutants, notably fine particles ($PM_{2.5}$), posing a risk to public health. This study aims to assess the impact of local and regional wildfires on $PM_{2.5}$ levels in Galicia's main cities and their implications for air quality and public health. Over a decade (2013–2022), $PM_{2.5}$ data during wildfire seasons were analyzed using statistical methods and Lagrangian tracking to monitor smoke plume evolution. The results reveal a notable increase in $PM_{2.5}$ concentration during the wildfire season (June–November) in Galicia, surpassing health guidelines during extreme events and posing a significant health risk to the population. Regional wildfire analyses indicate that smoke plumes from Northern Portugal contribute to pollution in Galician cities, influencing the seasonality of heightened $PM_{2.5}$ levels. During extensive wildfires, elevated $PM_{2.5}$ concentration values persisted for several days, potentially exacerbating health concerns in Galicia. These findings underscore the urgency of implementing air pollution prevention and management measures in the region, including developing effective alerts for large-scale events and improved wildfire management strategies to mitigate their impact on air quality in Galician cities.

1. Introduction

Climate change is a driver of the increasing trend in the frequency and intensity of wildfires all over the globe (Jolly et al., 2015; Couto et al., 2022; Celis et al., 2023; Caballero, 2015). These fires originate from the intersection of dry and warm meteorological conditions, biomass availability (fuel), and ignition sources (Moritz et al., 2014), with atmospheric conditions considered the predominant factors in fire spread at regional level (Abatzoglou and Kolden, 2013). The Mediterranean region, especially the Iberian Peninsula, is a focal point of climate change, with projections indicating a warmer and drier climate in the future (Calheiros et al., 2020). These conditions could significantly increase wildfire risk, especially in late spring and early autumn, leading to a longer and more severe fire season (Pereira et al., 2005; Ruffault et al., 2020; Calheiros et al., 2021). Likewise, extreme weather conditions are expected to persist, potentially surpassing the response capacities of local authorities and diminishing the effectiveness of firefighting operations (Mallinis et al., 2016; Castellnou et al., 2018). However, changes in climate-induced fire behavior could be mitigated by vegetation combustion capacity through land management activities, such as prescribed fires or forest thinning (Dupuy et al., 2020).

Wildfires release to the atmosphere a significant amount of air fine particles (e.g., $PM_{2.5}$), that will generate air pollution, although this impact is not limited to its area of origin but can be transported over long distances, endangering multiple populations (Baars et al., 2019; Sicard et al., 2019; Salgueiro et al., 2021). In particular, wildfires in Portugal have impacted air quality across Europe, especially the Iberian Peninsula (Brito et al., 2017, 2021; Turco et al., 2019; Augusto et al., 2020; Tarín-Carrasco et al., 2021). Previous studies have linked air pollution related to these fires with increased mortality risk (Augusto et al., 2020; Tarín-Carrasco et al., 2021). Hence, it is crucial to investigate the connection between air pollutants and wildfires in the area since this relation could have significant consequences for human health and the design of public policies. Several studies demonstrated that there is a solid connection between wildfires and $PM_{2.5}$ concentration during Portugal's fire season (Cattani et al., 2006; Isabel Miranda et al., 2010; Fernandes et al., 20215; de Souza Fernandes Duarte et al., 2023; Barbosa et al., 2024), emphasizing the severe degradation of air quality they can

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cause. However, few studies have focused on analyzing the impact of severe wildfire events in Portugal, such as those observed in 2016, 2017, and 2022. These incidents showed daily $PM_{2.5}$ levels surged beyond two standard deviations from the daily average calculated, affecting almost the entire Iberian Peninsula and potentially posing health risks to its inhabitants.

The Northwest of the Iberian Peninsula region (NIP) shown in Fig. 1a, which includes Galicia in Spain and the central-north area of Portugal, is renowned for its significant wildfire activity (Barreal et al., 2012; Barreal and Loureiro, 2015; de Diego et al., 2021, 2023). Previous studies have indicated a relative increase in the total burned area and the severity of fires in recent years (Chas-Amil et al., 2020). Despite the escalating frequency and projected rise in fires across Portugal and Galicia, research on the impact of these wildfires on air quality and public health remains relatively sparse compared to other European countries. As the number and extent of wildfires continue to increase, there is a growing concern about their potential implications for air pollution. Therefore, there is an urgent need for more comprehensive studies focused on this region.

Different atmospheric models have been used to assess the impact of long-range transport (LRT) of pollutants due to wildfires. Previous studies have relied on the Hybrid Single-Particle Lagrangian Integrated Trajectory model (HYSPLIT) since it is easy to use and has good precision (Adame et al., 2012; Mendez-Espinosa et al., 2020; Casallas et al.,

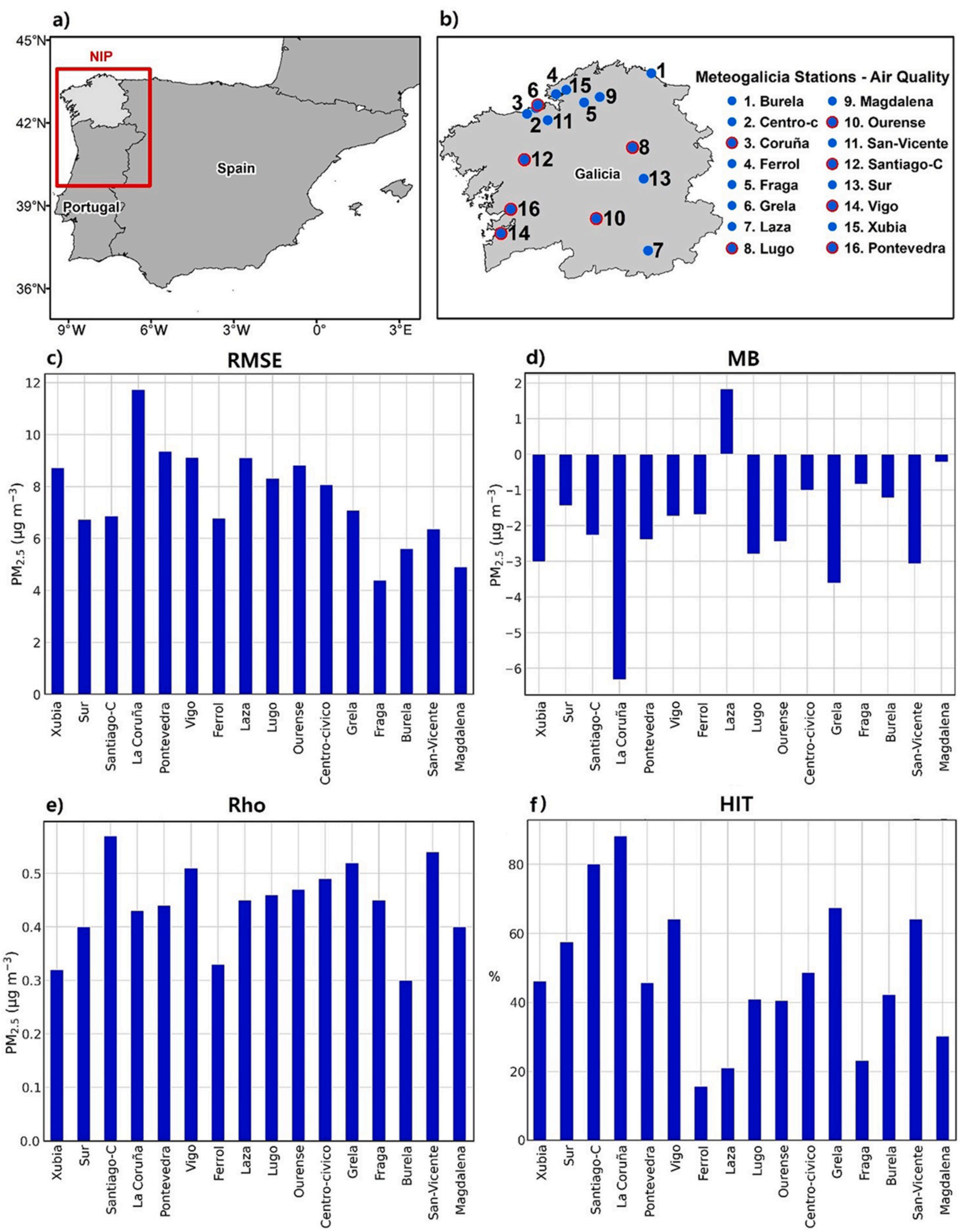

Fig. 1. Northwest Iberian Peninsula location (NIP) (a). Spatial distribution of air quality stations from Meteogalicia ($PM_{2.5}$) in blue and with red mask the cities with a higher population density in Galicia (b). Reanalysis evaluation for the root mean square error (RMSE) (c), mean bias (MB) (d), The Spearman correlation coefficients (Rho) (e), and the hit rate (HIT) (f).

2023a; Gili et al., 2024). However, HYSPLIT has limitations, as it assumes transport solely from the point of origin (fires) to the monitoring station, disregarding factors like turbulence or dispersion (Pouyaei et al., 2020). As a result, numerous researchers have leaned towards employing Lagrangian methods for tracking pollution plumes. These methods enable the quantification of pollutant concentration, smoke onset, and transport, facilitating the calculation of robust correlations between fires and air pollution (e.g., Wernli and Bourqui, 2002; Putero et al., 2018; Pouyaei et al., 2020; Casallas et al., 2023b). Therefore, to assess the impact of pollution developed in Portugal on the air quality of Galicia, it is essential to use a Lagrangian framework that analyzes the onset, trajectory, and magnitude of the smoke plumes produced by the wildfires. Then, this study aims to analyze the correlation between wildfires and $PM_{2.5}$ levels in the NIP by focusing on extreme wildfire occurrences to analyze plume behavior and assess pollution concentration reaching the major Galician cities and producing acute exposure. This assessment encompasses mean and maximum $PM_{2.5}$ values, coupled with the duration of exposure to exceptionally high $PM_{2.5}$ levels experienced by the population.

2. Data and method

2.1. Study area

Our study focuses on the NIP, where we investigate the specific dynamics of wildfires and their impact on air quality in Galicia. The NIP, encompassing provinces in northern Portugal and the autonomous community of Galicia in Spain, is characterized by homogeneous wildfire activity. Several authors have detailed the characteristics of fires in this area (e.g., Moreno et al., 2014; Sousa et al., 2015; Trigo et al., 2016; Jiménez-Ruano et al., 2019). The NIP stands out as one of the regions most affected by wildfires in Europe, with approximately 280,000 ha burned annually. Studies indicate that this high incidence of fires is directly related to the region's environmental factors, which significantly influence the structure of its forest mass. In this area, forests cover about 70% of the territory, while the remaining land consists of shrubs and grasslands. This territorial composition not only significantly contributes to the economic activity of wood production demanded by the European Union (de Diego et al., 2019), but also favors the spread of fires. During the 21st century, the NIP has recorded the highest number of wildfires in Spain, highlighting the severity of the situation (Barreal et al., 2012; Barreal and Loureiro, 2015).

Regarding wildfire seasonality in the NIP, meteorological variables are crucial in seasonal and monthly variations in wildfire patterns (Carmo et al., 2022; Carnicer et al., 2022; Williams et al., 2023). Therefore, our study adheres to the standard seasonal divisions identified by several authors. The region has two distinct fire seasons: a more active season covering boreal summer and autumn (JJA and SON, respectively), and a second season with less activity spanning boreal winter and spring (DJF and MAM, respectively) (Trigo et al., 2016; Sousa et al., 2015).

In terms of population (Fig. 1b), Galicia has approximately 2.7 million inhabitants spread across 313 municipalities (INE, 2023). La Coruña is the province with the most inhabitants (~1,125,000), followed by Pontevedra, and Lugo. Ourense is the province with the fewest residents in Galicia despite being the second with the most municipalities. In the analyses derived from this study, we will refer to six of the most densely populated municipalities in Galicia: Vigo, La Coruña, Ourense, Santiago de Compostela (hereafter Santiago-C), Lugo, and Pontevedra (Bruña-García and Marey-Pérez, 2018). In these municipalities, we also find air quality monitoring stations, which provide us with precise and up-to-date data on air quality in these densely populated areas.

2.2. Data

2.2.1. VIIRS data

The Visible Infrared Imaging Radiometer Suite (VIIRS) is one of the instruments on board the NASA/NOAA Suomi National Polar Orbiting Partnership (S-NPP) and NOAA-20 and 21, which were launched in October 2011, November 2017, and November 2022, respectively. The instruments acquired data at nominal resolutions of 375 m (I bands) and 750 m (M bands) (Schroeder et al., 2014). We used the VNP14IMG thermal anomalies product, which provides information about the thermal anomalies at 375 m spatial resolution, including the detection time, coordinates of the fire, FRP measurement (MW), brightness temperature of the I4 and I5 bands, the confidence value, and the type of thermal anomaly (biomass fires are type 0). The data were downloaded in vector format from the Fire Information for Resource Management System (FIRMS) (https://firms.modaps.eosdis.nasa.gov), which offers data covering the period from 2012 to the present.

The thermal anomalies product from VIIRS at 375 m (Schroeder et al., 2014) was used to determine wildfire events in Galicia for 10 years, from January 1, 2013, to December 31, 2022. The thermal anomalies product provided by VIIRS has a higher detection rate than MODIS, is more sensitive to smaller fires (Schroeder et al., 2014; Miura et al., 2021) and has proven to be the most accurate for verifying the start date of a fire, in contrast to burned area data (Neves de Oliveira et al., 2023).

2.2.2. Regional grid data

We used the data from Copernicus Atmospheric Composition Reanalysis 4 (EAC4) of the CAMS, managed by the European Centre for Medium-Range Weather Forecasts (ECMWF) (Inness et al., 2019) to analyze atmospheric conditions over the study area. CAMS reanalysis data products have a spatial resolution of $0.75^{\circ} \times 0.75^{\circ}$ for the study period and provide data every 3 h.

From this regional database, we focused on the analysis of surface $PM_{2.5}$ due to its high health risk associated with exposure to elevated concentrations (Chow et al., 2011). EAC4 dataset can ensure good spatiotemporal coherence of pollution, as seen in recent studies analyzing air pollutant concentrations in Iberian Peninsula (Royé et al., 2024) or in South America (Santos et al., 2021; Casallas et al., 2020). Nevertheless, an analysis of the dataset is performed in this study to account for its uncertainties.

2.2.3. Galician data

To represent local air quality conditions, we utilized data from background air quality stations provided by the Official Meteorological Agency of Galicia (Meteogalicia, 2023). We selected a 10-year period (2013–2022) for our analysis, aligning with the timeframe used for VIIRS and CAMS data. Out of a total of 50 weather stations, we selected those with less than 20% missing data, resulting in 16 stations distributed throughout the territory of Galicia (Fig. 1b).

To define Galicia's population density and distribution, we relied on information regarding the political-administrative boundaries of Spain and Portugal, as well as the municipal division of Galicia, provided by the Spanish National Geographic Institute platform (IGN, 2024). Additionally, we utilized population density data at the municipal administrative level provided by the National Statistics Institute of Spain (INE, 2023).

2.3. Methods

2.3.1. CAMS data evaluation

To evaluate CAMS reanalysis, we first compare the daily $PM_{2.5}$ from the reanalysis with the daily averages obtained from the time series of Meteogalicia monitoring stations. This analysis aims to verify if the CAMS data accurately captures the evolution, magnitude, and capacity to recreate extreme events of $PM_{2.5}$. We applied various statistical measures to assess the effectiveness of the CAMS data (Boylan and Russell, 2006; Cobourn, 2010; Tzanis and Alimissis, 2021; Mogollón-Sotelo et al., 2021; Liao et al., 2021; Paunu et al., 2024). We computed the root mean square error (RMSE), the mean bias (MB), the Spearman correlation coefficient (Rho), the index of agreement (IOA), the factor of two (FAC2), the normalized mean bias (NMB), as well as categorical statistics including the hit rate (HIT), the false alarm rate (FAR), and the proportion of correct (POC) (Chas-Amil et al., 2020; Sayeed et al., 2022) (for details about all the evaluation parameters, see Celis et al., 2022). We computed statistical parameters and also compared these values with benchmarks established in previous studies (e.g., Boylan and Russell, 2006; Emery et al., 2017; Casallas et al., 2020; Mogollón-Sotelo et al., 2021), aiming to determine acceptable error ranges across various metrics.

2.3.2. Tracking pollution

To evaluate the LRT of pollution from fires, we applied the lagrangian tracker developed by Casallas et al. (2024), which is based on a watershed algorithm of Scikit-image library version 0.2 (Virtanen et al., 2020) using Python 3.9. The process involves first segmenting the image, where each segment represents an object or unique part based on distinctive features. Then, it identifies and labels objects within image segments by applying a threshold. For example, it can label areas where pollutant concentration exceeds a predefined threshold, which can be statically or dynamically adjusted based on percentiles or magnitudes in time and space.

After the algorithm identifies objects, it is crucial to track them over time (Müller et al., 2023). Casallas et al. (2024) tracker computes object trajectories by assigning labels at the initial time step. Subsequently (every 3 h for CAMS), it calculates the Euclidean distance of the objects and the object overlap to discern whether an object is new and warrants a new label or if it's the same as in the previous step, in which case it retains the same label. In this context, the Lagrangian tracker traces objects from origin to dissipation, providing a comprehensive characterization throughout their trajectory from wildfire locations to various urban centers. That facilitates the establishment of a direct connection between wildfires and pollution, enabling the quantification of the amount of pollution transported from wildfire emission regions to urban areas. In addition, it assesses the degree to which pollution increments within cities can be attributed to associated pollution plumes from fires. We applied a spatial and temporal threshold set at the 90th percentile to ensure precise identification of wildfire pollution plumes. This threshold was determined using a randomized search method following the procedure outlined by Casallas et al. (2024). We tested various percentiles to identify the one that captures the majority of wildfire events while excluding those caused by industrial activities or road transport, since our focus is solely on long-range and short-range transport resulting from wildfires.

Although the Lagrangian method can be very beneficial, it also has important limitations. The framework does not consider turbulence within objects, which could introduce errors. Additionally, the threshold may cause uncertainties, necessitating other filters to exclude small or short-lived events not related to wildfires or volcanic activity. The results, especially the composites that can be constructed within the framework, are sensitive to data resolution, particularly in areas with complex wind flow. Moreover, an hourly or 3-hourly data output is essential to accurately capture plume behavior, as a daily resolution might yield misleading results. While not a limitation, this characteristic is crucial when selecting the dataset, given the sensitivity of results to data resolution.

2.3.3. Hazardous events and exposure to pollution

To identify and characterize $PM_{2.5}$ pollution events from wildfires, we adhered to the WHO (2021) guidelines, which set annual average $PM_{2.5}$ concentrations below 5 μg/m^3, with 24-h averages below 15 μg/m^3. An extreme $PM_{2.5}$ event is defined when concentrations exceed 15 μg/m^3 for at least three consecutive days. Additionally, we confirmed that wildfires caused these events by verifying that at least 50 active fires were detected by VIIRS between 1 and 3 days before the start of the pollution events in the NIP.

To obtain a more detailed description of the wildfires that occurred in the NIP during our study period, we employed Roteta et al. (2021) freely accessible global automatic algorithm for calculating burned area (BA) at medium spatial resolution. This method delineates the BA boundaries using reflectance images from Sentinel-2 sensors, which provide an average spatial resolution of 20 m. By applying this approach, we created predefined geometry layers for each year, enabling us to identify the wildfires that occurred during each wildfire season manually.

3. Results and discussion

3.1. CAMS reanalysis evaluation

To assess the CAMS reanalysis dataset, we initially calculated daily $PM_{2.5}$ concentrations and compared them with data from 16 meteorological stations in Galicia (Fig. 1b). The results of this analysis are presented in Fig. 1c–f and Table SM1 (supplementary material). The assessments of statistics measuring pollutant evolution, such as Rho (Fig. 1e) and IOA (Table SM1), provided crucial insights into CAMS ability to depict temporal data variability and its agreement with in-situ observations. Rho values revealed an acceptable relationship between reanalysis and observations, although some cities exhibited a lower correlation. Nonetheless, they were close to the acceptable threshold (Rho>0.4), showing that CAMS had sufficient precision to recreate the pollutant evolution. IOA values mostly exceeded 0.48 across all cities, indicating good agreement between datasets, especially in Fraga and Ferrol (>0.7), which are considered high statistical values in terms of precision (Casallas et al., 2021).

The assessments focused on data magnitude included RMSE, MB (Fig. 1c–d), FAC2, and NMB (Table SM1). These metrics aimed to measure the accuracy of CAMS predictions regarding the magnitude of forecasted values compared to observed ones. RMSE revealed that CAMS achieves excellent precision (Mogollón-Sotelo et al., 2021) across all cities, consistently below 10 μg/m^3, except for La Coruña. Despite exceeding this criterion, La Coruña still showed good precision with an RMSE below 15 μg/m^3 (Emery et al., 2017). We considered the benchmark value of 50% for the FAC2 statistic as Celis et al. (2022). We found that all stations exceed this value, suggesting that prediction errors are relatively consistent with the variability of observed values, indicating moderate precision.

As for MB and NMB, most stations showed negative values, indicating slight underestimations, all falling within the range considered acceptable by previous studies (Boylan and Russell, 2006; Emery et al., 2017; Mogollón-Sotelo et al., 2021), demonstrating the overall reliability of CAMS predictions in terms of magnitude. However, the Laza station stood out with an overestimation, showing MB values of 1.2 and NMB of 18.7 (see Table 1 SM), possibly influenced by factors such as inadequate representation of local pollution sources like industry and traffic, as well as specific terrain features and meteorological conditions, although a more detailed study is needed to fully understand the reasons behind the uncertainties in Laza. Additionally, the resolution of CAMS data may have contributed to this discrepancy.

Regarding HIT and FAR (taking the threshold reference value of 15 μg/m^3 as in Celis et al., 2022), HIT provides insights into the model's ability to identify extreme events accurately. The values shown in Fig. 1f accurately represent >40%, which is considered adequate (Casallas et al., 2020), except for the Ferrol, Laza, Fraga, and Magdalena stations. On the other hand, all 16 stations showed FAR values > 30% for the events recorded by monitoring systems, with six cities having low FAR values. Those results indicated that CAMS could represent extreme values corresponding to air quality alert situations with acceptable accuracy. Finally, concerning POC, the reference point is set at 50% to establish the accuracy of predictions in extreme events. We found that most stations exceed these values, indicating an acceptable representation. These findings underscore the utility and reliability of $PM_{2.5}$ forecasts regarding extreme events. Consequently, CAMS data can be used to study air pollution evolution, magnitude, and extreme events with acceptable precision in this region, although conclusions need to account for uncertainties.

3.2. WildFires and $PM_{2.5}$ seasonality evolution

Fig. 2 analyzes the temporal and seasonal distribution of wildfires in the Iberian Peninsula over the past decade. This region is known for its susceptibility to wildfires, particularly pronounced between June and October, coinciding with the warmest and driest period of the year (JJA). August records a relatively high frequency of wildfires during the study period (Fig. 2a), while October shows unusually high values, possibly related to large-scale events. These months of heightened biomass burning activity generate significant peaks in the distribution of fires (de Diego et al. 2019, 2021; Gili et al., 2024).

Fig. 2b–e shows the average number of wildfires produced per season, calculated by first summing the hotspots between 2013 and 2022 per pixel for every month and then averaging them per season across the Iberian Peninsula. Most biomass burning activity is concentrated in the NIP, with some events detected in the central and southwestern regions of the peninsula, as well as in eastern Spain, especially during the boreal summer and autumn months (Fig. 2d and e). This analysis matched the results reported by previous studies in the same region (Moreno et al.,

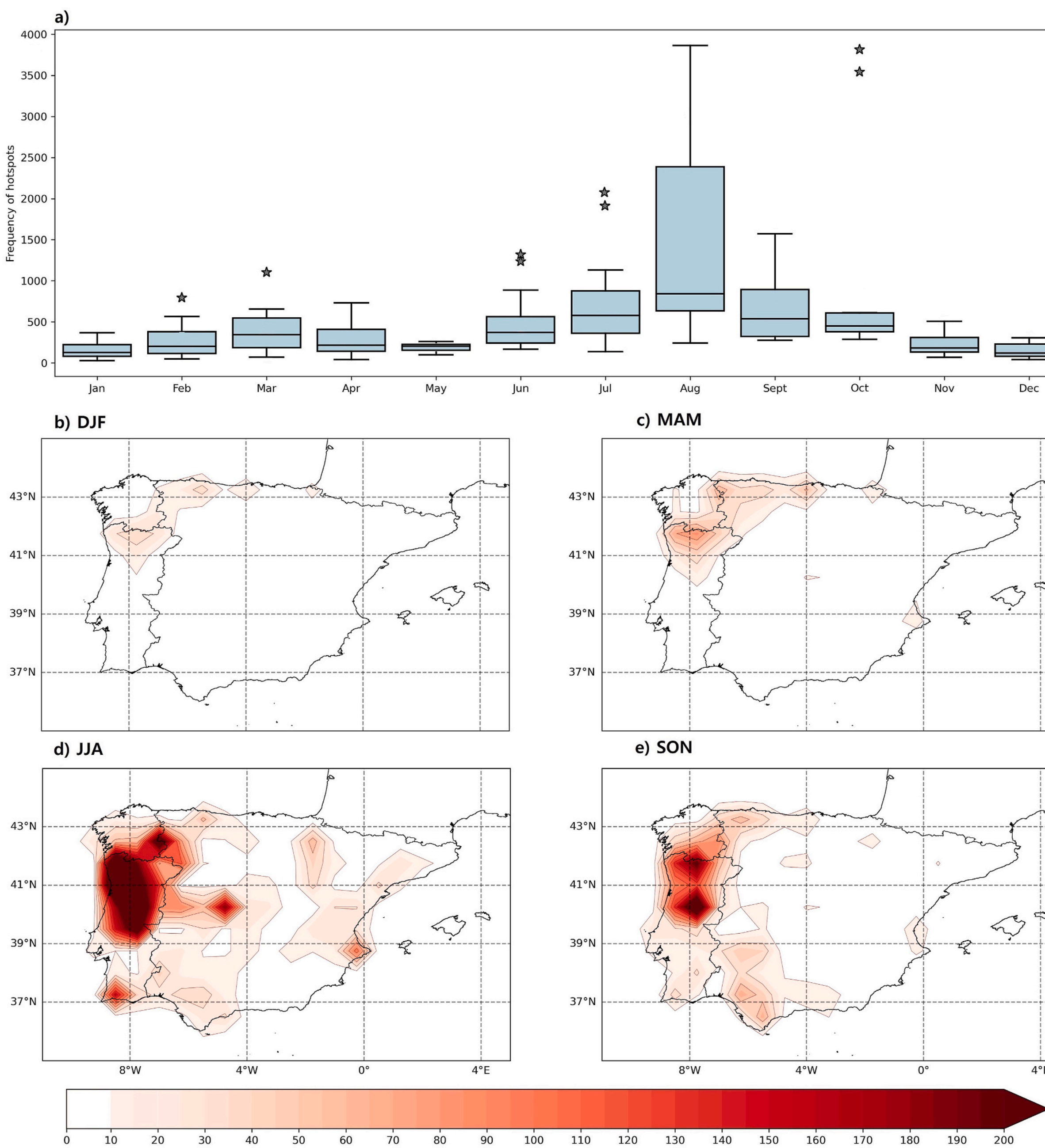

Fig. 2. Multi-annual monthly boxplot (with the stars depicting fliers) of VIIRS active fires in the Iberian Peninsula (a).Spatial distribution of the average number of fire detections by VIIRS during the DJF seasons: December to February (b), MAM: March to May (c), JJA: June to August (d), and SON: September to November (e) between 2013 and 2022. The map panels were created using the Cartopy Python package (Met Office, 2010).

2014; Vanesa Moreno et al., 2016; Viedma et al., 2018). Wildfire activity during boreal winter and spring tends to be lower, as observed in Fig. 2b–c, where fires are less frequent. However, notable activity is observed in March, primarily linked to agricultural and pasture burns in the northern part of the peninsula, significantly contributing to the total number of detected fires (Rodríguez-Vicente and Marey-Pérez, 2010; García-Llamas et al., 2020).

The boreal summer and autumn seasons experience a high incidence of wildfires. Since we want to identify the relationship between these fires and air pollution, we focus on examining the pollution events detected by the Lagrangian tracker during these seasons. For that we created a composite (Fig. 3a–b) of all the pollution events identified by this tracking method and investigated their correlation with the presence of wildfires. Results show that across the Iberian Peninsula, average $PM_{2.5}$ concentrations exceeded 10 μg/m^3 during both JJA and SON, with particularly elevated pollution levels (>15 μg/m^3) observed in central-northern Portugal and southern Galicia. The eastern region recorded average $PM_{2.5}$ values ranging between 12 and 15 μg/m^3. Notably, the areas with the highest pollution coincided with regions prone to wildfires, suggesting a strong correlation between fire activity and pollution levels (Zhang et al., 2019; Barbosa et al., 2024).

To analyze this in more detail, we computed the Pearson correlation between the number of fires and the composite of pollution plumes (Fig. 3c–d). The results unveiled a significant relationship between these variables, with Pearson correlation exceeding 0.8 in various regions of the Iberian Peninsula during boreal summer/autumn (Fig. 3) and boreal winter/spring (Figure SM1), in line with previous studies (Nunes et al., 2021). However, upon closer examination of the elevated pollution levels observed in the southeastern part of the Iberian Peninsula during JJA (Fig. 3a), we found no correlation with wildfires (Fig. 3c). That suggests that these pollution events may originate from sources unrelated to fire activity, such as anthropogenic sources like maritime transport (Rodríguez et al., 2020), or local urban sources, as for example, industries and traffic (Pey et al., 2013).

Conversely, high fuel loads often characterize regions exhibiting a high correlation between fires and pollution (Aragoneses and Chuvieco, 2021). In the SON season, fires were more prevalent in the northern part of the Iberian Peninsula, coinciding with regions experiencing high $PM_{2.5}$ concentrations, thus resulting in a high correlation between the two. However, in the southern region, elevated $PM_{2.5}$ levels are not linked to fires, suggesting that these areas are more affected by local pollution sources, rather than long-range transport (LRT) of pollution (Querol et al., 2019). We noticed that the mean pollution levels attributed to fires exceeded the guidelines set by the WHO (2021), suggesting potential health impacts for residents in the affected areas.

3.3. *Analyzing the characteristics of pollution plumes develop from wildfires*

In this section, we utilize the Lagrangian tracker to identify the

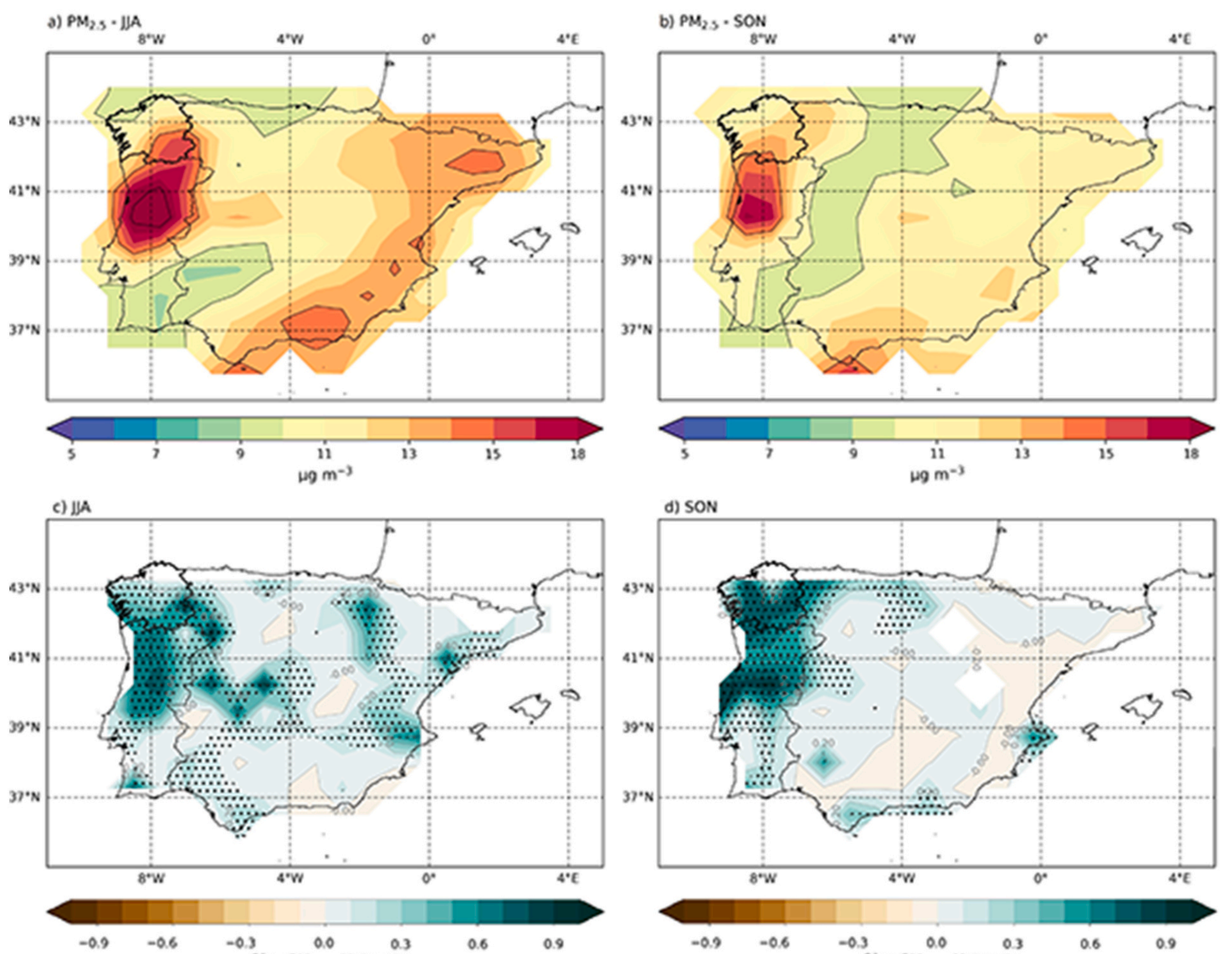

Fig. 3. Seasonal average 2013–2022 composites of $PM_{2.5}$ pollution events captured by the Lagrangian tracker across the Iberian Peninsula for the JJA (a) and SON (b). Colors and contour lines represent the magnitude of each pollutant. Pearson correlation (colors and contour lines) for JJA (c) and SON (d) between seasonal averages of $PM_{2.5}$ and the number of hot temperature points (VIIRS) (Fig. 1). The black dots in panels c and d represent locations where the Pearson correlation between the hotspots and the pollution plumes have statistical significance (p-value <0.05). The plot was made using the Cartopy Python package (Met Office, 2010).

initiation of pollution plumes and their proximity to the main cities of Galicia. Explicitly focusing on pollution events originating from wildfires, similar to Casallas et al. (2024), we filtered the pollution plumes identified by the Lagrangian tracker, selecting only those associated with wildfire hotspots, and also plumes with an area >70 km^2. The initiation of pollution plumes depends on when tracking begins, ensuring that the initial pixel (or group of pixels) is connected to a hotspot. We do not use the hotspot itself as the initiation point, since plumes can form after the hotspot appears, and not always simultaneously. We also excluded small events lasting less than a day to eliminate minor local pollution episodes. In addition, we narrowed our analysis to pollution plumes reaching the studied cities monitoring stations and resulting in elevated $PM_{2.5}$ levels since those events could potentially harm human health.

Fig. 4 depicts the number and location of events in relation to the studied cities. Generally, pollution emissions from biomass burning were less frequent during the DJF and MAM seasons. Conversely, during the boreal summer/autumn periods, the number of events detected in the six analyzed cities increased, coinciding with the high pollution depicted in Fig. 3.

Regarding the MAM season, we found that a significant number of events originate in the south and southeast of Santiago-C and La Coruña, approximately 200–300 km away (Figure SM3). By using land use coverages, such as the Corine Land Cover (CLC) map from the European Environment Agency (EEA, 2018), and overlaying them with fire hotspot coverages, we can identify that the smoke plumes mainly come from biomass burning (shown Figure SM4). This burning corresponds largely to agricultural areas located in southern Galicia and even northern Portugal during this time of year. Additionally, many events originating in the south and southeast of Santiago-C coincide with records from other authors (Verkerk et al., 2015; Fernández-González et al., 2022). These events could be related to factors such as agricultural or pastoral activities associated with socioeconomic development and the traditional use of fire as a management tool, such as agricultural burns and burns to expand pastures (De Diego et al., 2021).

During the JJA season, Galician cities experienced a significant increase in $PM_{2.5}$ pollution events, primarily attributable to wildfires located to the east and south (i.e., E, SE, S, SW). This suggests an association with fires developing in southern Portugal, western Asturias, and Galicia. These areas, easily identifiable in the CLC coverage, show forest zones where coniferous and broadleaf forests predominate (Molina Rodríguez, 2019; Chas-Amil et al., 2020). This attribute significantly influences the amount of emissions produced due to the high concentration of available biomass (Molina Rodríguez, 2019; Gómez-García, 2020; Chas-Amil et al., 2020). Furthermore, the proximity to the transitional zone between the Eurosiberian (or Atlantic) and Mediterranean climates generates more biomass, and with high summer temperatures, the risk of wildfires increases. The effects of these environmental conditions are exacerbated by limited forest management (Caballero, 2015; Fernández-González et al., 2022).

These results align with previous studies on fire regimes in the region, which report that fires increase due to fuel accumulation and favorable climatic conditions (Molina Rodríguez, 2019). The stations recording most of these high pollution events are located in Ourense, Pontevedra, Vigo, and Santiago-C, which are in southwest Galicia, an area prone to episodes of wildfires due to its arid conditions and strong winds (Gili et al., 2024). Conversely, La Coruña and Lugo report fewer events, likely due to their relative distance from the wildfire hotspots. The spatial distribution of these events underscores the importance of considering regional factors, such as agricultural activities and wildfire management practices, to understand pollution dynamics.

After describing the onset location of the pollution plumes related to the studied region, we determined the average distance the smoke plumes travel to reach the analyzed cities (Fig. 5). This analysis provides additional information on the evolution and impact of pollution plumes from fires far from Galician cities. For this analysis, we focused on seasons with higher pollution contributions, such as JJA and SON. The analysis of DJF and MAM seasons and the annual average of all events

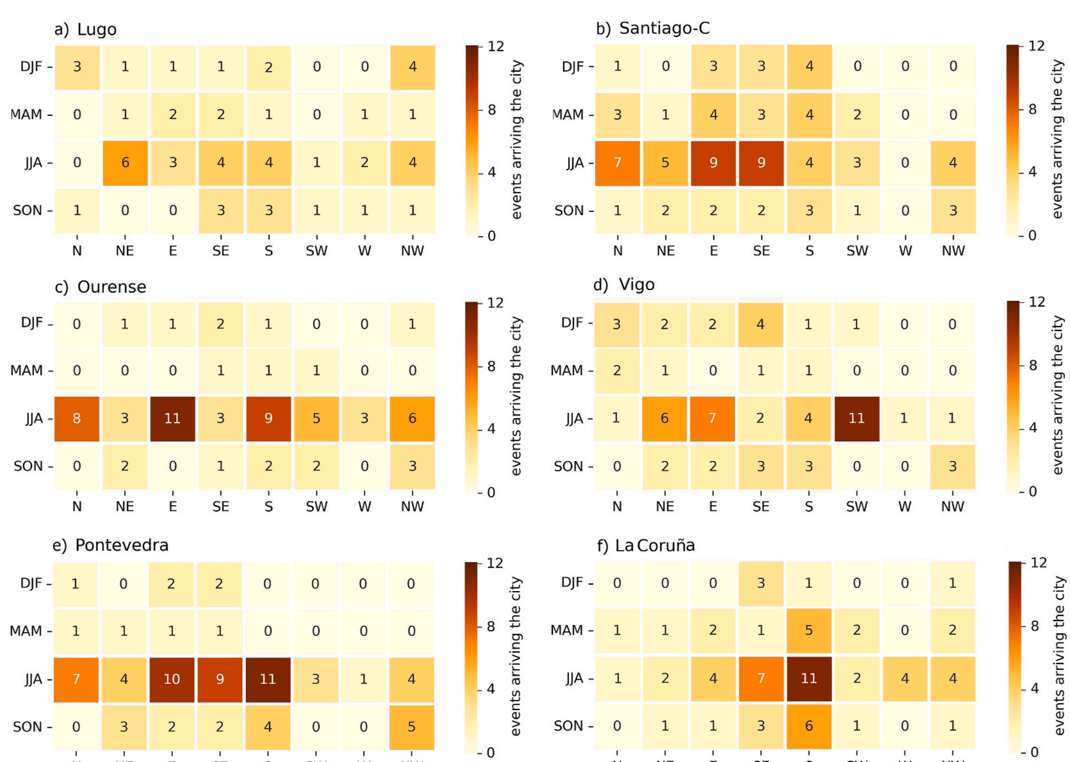

Fig. 4. Number of events that propagate to the city from each cardinal location and divided depending on the season, for (a) Lugo, (b) Vigo, (c) Santiago-C, (d) Pontevedra, (e) Ourense, and (f) La Coruña.

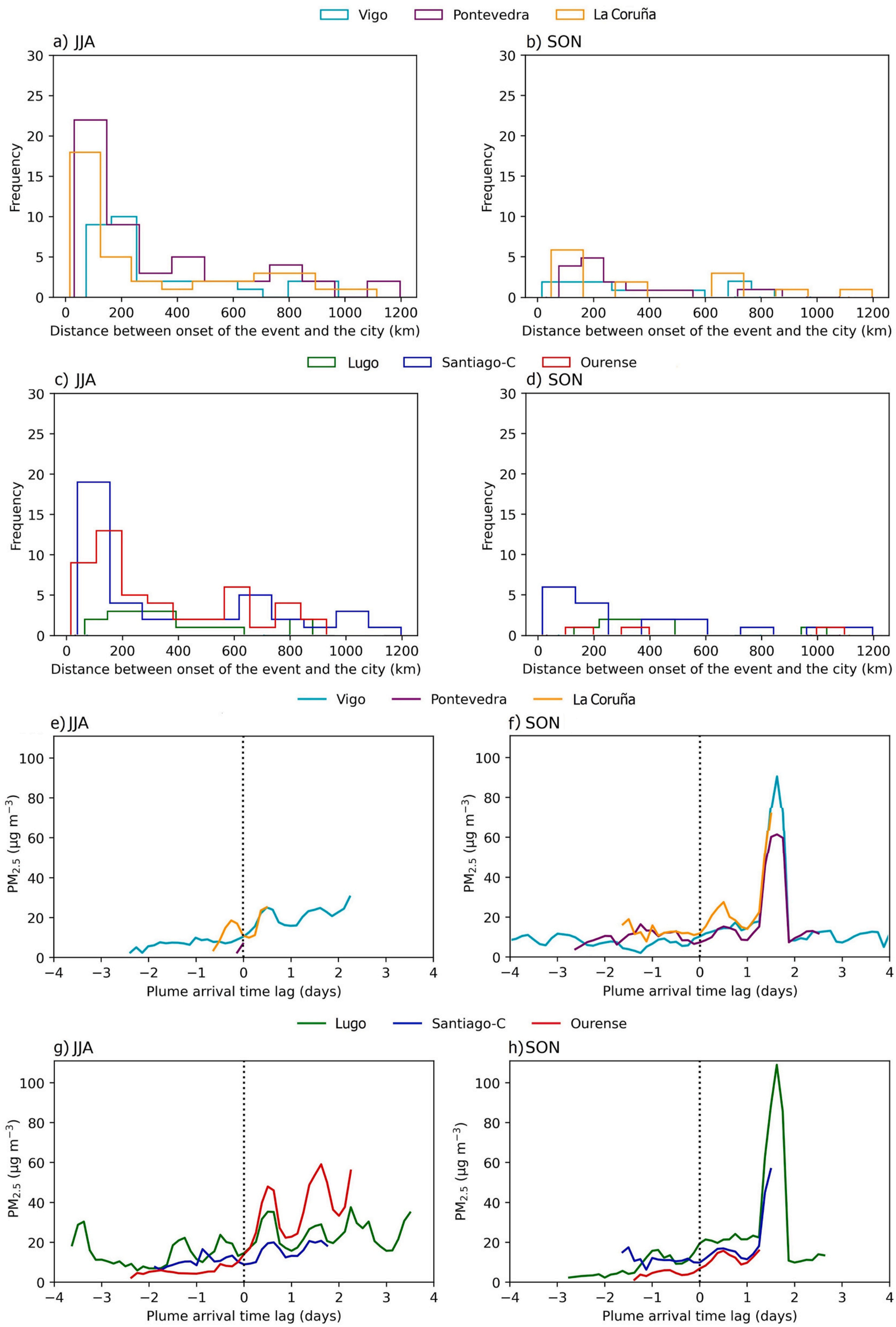

Fig. 5. Panels (a-b-c-d) show the frequency of geodesic distances between the event onset and the cities (Vigo, A La Coruña, Santiago-C, Pontevedra, Lugo, and Ourense) for the JJA average (a–c) and SON (c–d). (e-f-g-h) Composites of $PM_{2.5}$ (concentration) pollution plumes in Vigo, A La Coruña, Santiago-C, Pontevedra, Lugo, and Ourense. For the events that develop during (e–g) JJA, and (f–h) SON. The zero on the x-axis marks the arrival of the events in the cities.

are included as SM (Figures SM2). Upon examining the distances covered by pollution plumes (Fig. 5a–d), the JJA season reported a higher frequency of events than SON. Cities like Pontevedra, La Coruña, Ourense, and Santiago-C showed a frequency of more than ten events traveling shorter distances during this season, while Vigo had fewer, and Lugo barely registered two events covering distances exceeding 300 km.

During the SON season (Fig. 5b–d), there was a noticeable decrease in event frequency, with no more than six episodes, yet characterized by extensive travel distances, even exceeding 1200 km, as observed in Santiago-C, La Coruña, and Ourense. Consequently, pollution events spun almost the entire Iberian Peninsula, showcasing the importance of biomass burning pollution during this season, extending beyond Galicia. For instance, in October 2017, an extreme wildfire event occurred in northern Portugal, affecting the entire Iberian Peninsula. Therefore, during SON, long-distance events may be linked to rare yet intense wildfire episodes that develop in Portugal (Castellnou et al., 2018; Turco et al., 2019). Those events highlight the importance of international cooperation since fires that develop in one country can strongly affect others.

We created composites from the Lagrangian tracking results for each city analyzed to further our analysis. These composites estimated the evolution of the $PM_{2.5}$ related to pollution plumes that resulted from wildfires. Since this analysis aimed to approximate the amount of pollution that arrives in each Galician city due to the wildfire smoke plumes, we use the compositing method of Adams et al. (2013, 2015), where the zero on the x-axis represents the arrival of the event to the city.

Fig. 5e–h illustrates the progression of pollution plumes before, during, and after they traverse the urban areas of interest. This analysis shows that average pollution levels surpass 35 μg/m^3 during the boreal summer and autumn seasons, coinciding with the previous section results. Conversely, in the boreal winter and spring seasons (Figure SM3), $PM_{2.5}$ average values fluctuate between 15 and 20 μg/m^3 upon plume arrival in the cities. Elevated pollution levels, exceeding 60 μg/m^3 during autumn in most analyzed cities, could be attributed to exceptionally intense wildfire events, such as the one documented in October 2017, characterized by extraordinarily high pollution levels (Fig. 2).

In contrast to this specific event, a more gradual variation in pollution levels is observed in other cases over the first 2–3 days from their initial detection. For example, in the case of the Ourense monitoring station in boreal summer (Fig. 5f), multiple pollution peaks are recorded, indicating a recurrence of events where pollution levels fluctuate more dynamically over time. We observed that most events consistently occurred in specific locations and comparable distances. In the six cities depicted in Fig. 5, those events are closely associated with wildfires, highlighting the pronounced seasonality of pollution events. Those fire-prone areas should be considered priority areas for enacting policies regarding forest management. On the other hand, in the DJF and MAM seasons, the variation typically ranges between 1 and 2 days from their initial detection, with values generally not exceeding 20 μg/m^3.

3.4. Identification and characterization of dangerous pollution events

This section explores specific events of $PM_{2.5}$ pollution caused by forest fires that affected the inhabitants of Galicia between 2013 and 2022 due to an increase in the average concentration threatening public health. During this period, at least ten events exceeded the pollution threshold recommended by the WHO (2021) for three consecutive days, as shown in Fig. 6a. Fig. 6b shows the spatial distribution of burned areas for the extreme fire seasons to highlight the strong relation between wildfires and extreme air pollution events. The CAMS database and the temporal series of ground stations from Meteogalicia detected these high pollution levels (>25 μg/m^3), reaffirming the consistency between these data sources.

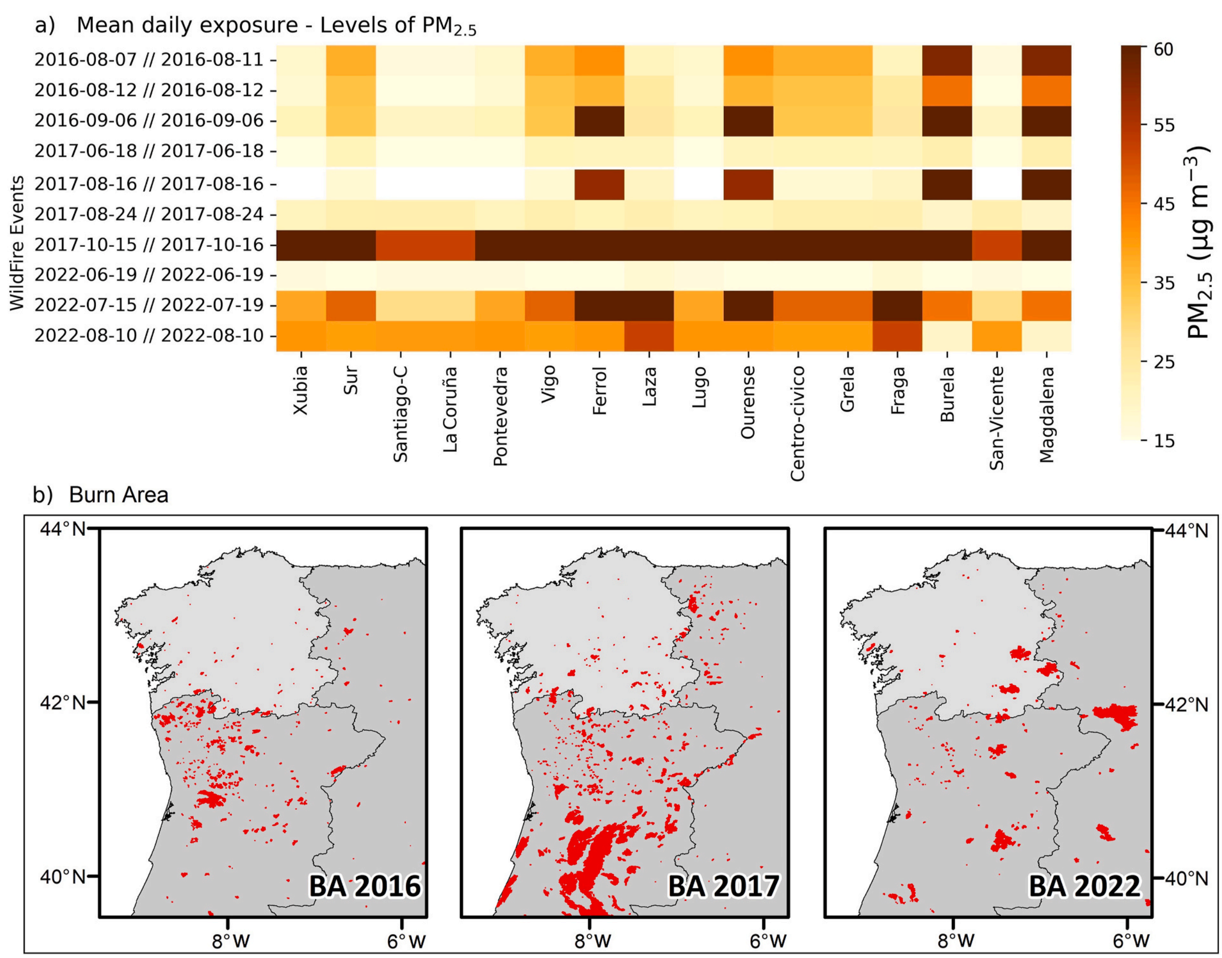

Fig. 6. NIP wildfire events (wildfires larger than 100 VIIRS active fires per pixel) that strongly exceed the WHO's daily limit of 15 μg/m^3. (a) Average pollution levels higher than 15 μg/m^3 for the selected days. (b) Burn area in the NIP detected for the season of JJA and SON for 2016–2017 and JJA in 2022.

At the monitoring stations located in Sur, Vigo, Ferrol, Ourense, Centro Cívico, Grela, Burela, and Magdalena, pollution levels exceeded 25 μg/m^3 per day for at least nine days in August and three in September, accumulating more than 11 days of high pollution levels in 2016 (Fig. 6a). We found a similar case in the summer (JJA) of 2017, which accumulated more than nine days of pollution levels ranging between 15 and 25 μg/m^3. Furthermore, in JJA of 2022, pollution levels exceeding WHO recommended values were recorded for at least 13 days at all stations in Galicia, demonstrating that the JJA season generally presents the highest accumulated number of high pollution levels in Galicia. The average data reported in July and August 2022 affected all monitoring stations in Galicia, with levels surpassing 35 μg/m^3 for at least eight days in July and three days in August. The event that occurred in October 2017 exhibited exceptionally high air pollution levels. During this period, levels exceeding 60 μg/m^3 were recorded for more than five consecutive days, prompting Portugal and Galicia to declare air pollution alerts (Ramos et al., 2023).

When analyzing the dates of these high pollution events, we found that they predominantly occurred during the boreal summer of 2016, 2017, and 2022, as well as during the boreal autumn of 2016 and 2017. These dates align with the burned areas and active fire detections reported during those seasons and days in the NIP (Fig. 6b), and are consistent with previous research (Parente et al., 2018; Alexander et al., 2018; Chas-Amil et al., 2020; Liz-López et al., 2024). From the mapped burned area, we quantified that during the 2016 JJA and SON seasons, approximately 99,000 ha were burned in the NIP, with 18% in Galicia and the remaining 82% in Portugal and Asturias. During the 2017 JJA and SON seasons, around 540,000 ha were burned, with around 37% occurring between October 15 and 20. Several conditions converged, causing those fires to become extreme fire events. The meteorological conditions associated with the passage of Hurricane Ophelia off the coast of Portugal caused exceptionally high temperatures due to warm air advection from Africa, highly influencing fire behavior (Ramos et al., 2023). The meteorological conditions added to a prolonged drought that contributed to accumulated water stress of vegetation and negligent ignitions by the population (Turco et al., 2019; Ramos et al., 2023) favored the occurrence of one of the largest fires the region has experienced.

Furthermore, in the boreal summer of 2022, approximately 125,000 ha were ravaged by fire in the NIP, with 45% concentrated in Portugal

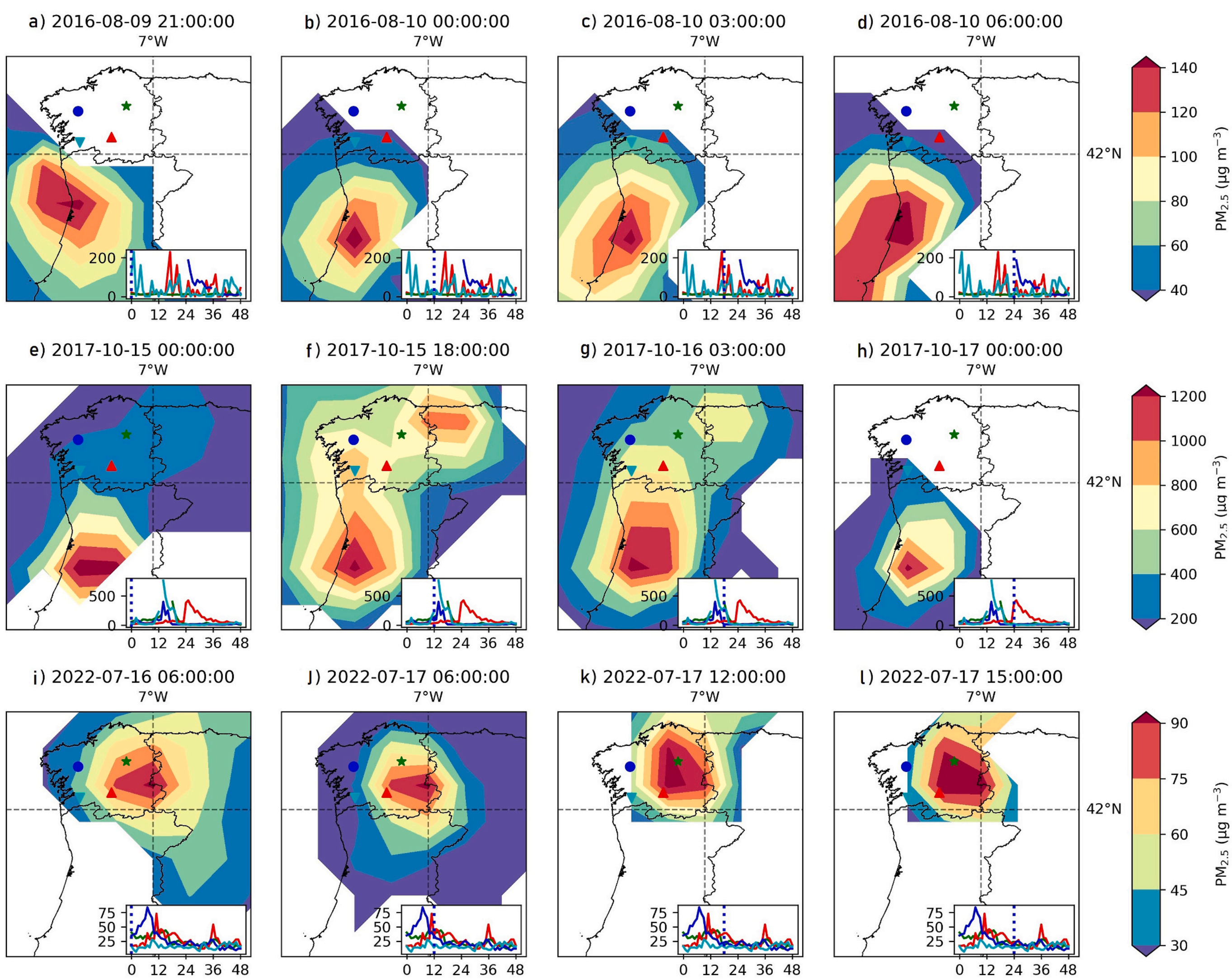

Fig. 7. Evolution of three wildfire events analyzed. $PM_{2.5}$ concentration values for an event in 2016 (a–d),2017 (e–h), 2022 (i–l). Time progresses from left to right (date and time in UTC). Four main cities are displayed: Vigo, cyan color (inverted triangle), Ourense, red color (triangle), Santiago-C in blue (circle), and Lugo in green color (star). The bottom box of each panel contains the evolution of the pollutant measurements from the ground station. On the x-axis, the time initiates when the event starts (first column) and is marked as zero, and the y-axis depicts the pollutant concentration (units of μg/m^3). The dotted vertical line in the box represents the time and date of the snapshot. The map panels were made using the Cartopy Python package (Met Office, 2010).

and the remaining 55% in Spain, while in Galicia alone, different wildfires each exceeding 500 ha were reported (Gili et al., 2024). The high frequency of wildfires in the region is evident, highlighting the need for preventive management measures to mitigate their devastating impacts. On the other hand, the concentration of burned areas in the NIP during the boreal summers and autumns of the years analyzed emphasizes the importance of a more detailed analysis of the conditions that contribute to the spread and magnitude of large-scale wildfires that have a significant impact on regional air pollution due to the LRT of contaminants.

The temporal and spatial progression of smoke plumes generated by wildfires within the NIP is illustrated in Fig. 7, where we focused on three high-pollution incidents. The wildfire events that occurred in 2016, 2017, and 2022 significantly increased $PM_{2.5}$ pollution in Galicia due to their intensity and spread of smoke plumes originating from northwest Portugal (Fig. 7). In the 2016 fire analysis, the plume initially moved southward, reaching monitoring stations in the cities of Vigo and Ourense within approximately 3 h. Over the next 6 h, the smoke plumes entered Galician territory, albeit with a weakening trend observed in the subsequent 3 h. This weakening is reflected in $PM_{2.5}$ measurements, showing a decreasing intensity southward. This dynamic is also evident in the temporal series of monitoring stations operated by Meteogalicia in Vigo, Ourense, and Santiago-C (Fig. 7a-b-c-d), confirming the tracker's accuracy in identifying smoke plume advancement. Despite pollution decreasing after an additional 6 h, it persisted for at least four more days due to other biomass burning sources present during that season, consistent with what is shown in the pollution events and burned area of Fig. 6.

In the 2017 events (Fig. 7e-f-g-h), we observed an exceptionally high pollution level on October 15th, surpassing 1000 μg/m^3. This spike coincided with multiple fire incidents recorded on that date, one originating in the central-northern region of Portugal (Fig. 7e), and another detected in northeastern Galicia, consistent with the burned areas identified in 2017 (Fig. 6b). The smoke plume rapidly moved northward, reaching the entirety of Galicia within just 3 h, with pollution levels ranging between 400 and almost 1000 μg/m^3 in Vigo, and 800 μg/m^3 in Santiago-C, Lugo, and Ourense. These exceedingly high pollution levels persisted for at least a day, with the most heavily affected area consistently located in northern Portugal, while in Galicia, the smoke plume gradually dissipated.

Regarding the 2022 event, depicted in Fig. 7i-j-k-l, the smoke plume predominantly developed within Galicia due to fires occurring on those dates, as shown in Fig. 6b. This smoke plume persisted for over two days, with pollution levels exceeding 75 μg/m^3, affecting nearly the entire region of Galicia. These wildfire events within Galicia showed that, due to fire and atmospheric dynamics, the pollution levels persist for longer periods, representing an increased risk for the population near these pollution sources (Gili et al., 2024).

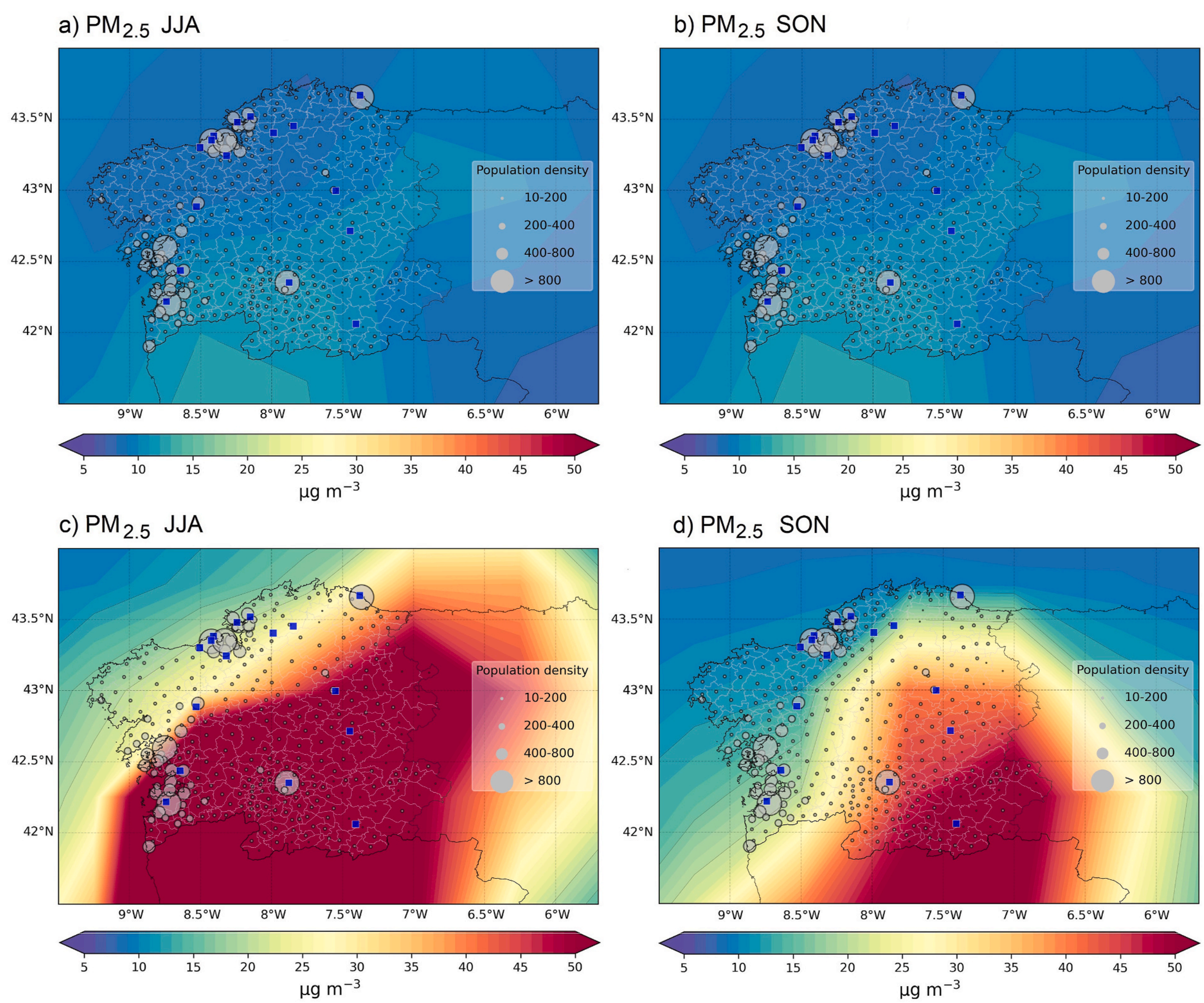

Fig. 8. Seasonal multi-annual average of $PM_{2.5}$ concentrations for the JJA and SON seasons from 2013 to 2022 when wildfire events are absent (a and b) and when wildfire events occur (c and d). The gray circles show the population density by municipality (units of inhabitants/km^2). The map panels were made using the Cartopy Python package (Met Office, 2010).

3.5. Potential exposure to $PM_{2.5}$ in galicia

From 2013 to 2022, $PM_{2.5}$ pollution from forest fires experienced notable variations in Galicia, especially during the boreal summer and autumn seasons when fires are most frequent. During periods of low wildfire activity, $PM_{2.5}$ levels remained within the annual average limits established by the WHO. However, during months with forest fire activity, a significant increase in $PM_{2.5}$ levels occurs (see Fig. 8a–d). In the northwest, between Ferrol and La Coruña (see Fig. 1 for city locations), and in the southwest area between Vigo and Pontevedra, there is a higher population density, exceeding 800 inhabitants/km^2 (Fig. 8). Although the municipalities of Santiago-C and Ourense have a slightly lower population density, they show values between 400 and 800 inhabitants/km^2.

We estimated that during JJA approximately 2,300,000 inhabitants, equivalent to ~85% of Galicia's total population, were exposed to high levels of pollution exceeding 45 μg/m^3 of $PM_{2.5}$ due to forest fires. Cities like Ourense, Lugo, Vigo, Pontevedra, and Santiago-C show significant pollution levels during JJA and SON seasons, posing health risks to the residents. Although pollution levels decrease during SON, the occurrence of large forest fire events may increase those levels, as happened in 2017. During the SON season, southeast Galicia is affected by hazardous pollution levels of $PM_{2.5}$ (>25 μg/m^3), where approximately 22% of Galicia's population resides. These findings underscore the profound impact of forest fires in Galicia, coinciding with the results of Barros et al. (2023) which reported that $PM_{2.5}$ levels could yield more than 1000 annual premature deaths.

Following the previous discussion on health hazards, it is important to highlight that exposure to high levels of $PM_{2.5}$ pollution in the population of Galicia represents both immediate and long-term risks, manifesting in both acute and chronic effects. Acute effects can occur over a short period of time. For example, during the events of October 2017 (see Fig. 6a), $PM_{2.5}$ levels exceeded the threshold and remained elevated intensely for a brief period, amplifying health concerns documented in Portugal (Augusto et al., 2020; de Souza Fernandes Duarte et al., 2023). On the other hand, the chronic effects of continuous or recurrent exposure to high levels of $PM_{2.5}$ are equally concerning. During the summer of 2022, at least 13 severe wildfire events were reported in the NIP (Tarín-Carrasco et al., 2021; Neves de Oliveira et al., 2023; Gili et al., 2024). During these events, pollution levels persisted at dangerous levels for several consecutive days. These chronic effects can lead to the development and worsening of chronic respiratory diseases such as COPD and emphysema, an increased risk of lung cancer, cardiovascular diseases such as hypertension and coronary artery disease, and higher premature mortality (WHO et al., 2013). These health effects could be particularly pronounced in densely populated regions, such as the municipalities located in southwestern Galicia (Vigo, Pontevedra), where greater exposure is observed during the JJA and SON seasons.

The findings underscore the potential public health risks posed by exposure to $PM_{2.5}$ due to wildfires in the Galicia region. Therefore, there is a critical need for targeted research initiatives to correlate air quality data, public health records, and epidemiological studies to assess the effects of exposures accurately. Such data is essential for informing fire management policy guidelines, air quality regulations, and public health measures to safeguard vulnerable populations. Additionally, concerted efforts should be directed toward modeling wildfires to develop early alert systems. These models can build upon historical meteorological variables, population data, geographical indicators, and temporal factors to estimate wildfire emissions, air quality levels, the health burden of wildfire smoke, and even consider different climate change scenarios.

4. Conclusions

Wildfire intensity and severity have been increasing in the Iberian Peninsula in recent years due to favorable conditions for extreme fire events, such as rising temperatures and accumulating drier fuels. One significant consequence of forest fires is their potential to impact air pollution since they can produce dense smoke plumes and strongly reduce air quality. This research analyzes $PM_{2.5}$ data over a decade (2013–2022) in the northwest of the Iberian Peninsula using statistical methods and Lagrangian tracking to monitor the evolution of smoke plumes. The findings reveal a significant rise in $PM_{2.5}$ concentrations during wildfire seasons, often exceeding health guidelines and posing serious health risks to the population.

We proved that the CAMS reanalysis dataset evaluation is a reliable tool for assessing $PM_{2.5}$ concentration in Galicia, demonstrating consistency in representing its magnitude and evolution and in identifying extreme events. Using the CAMS dataset, distinct regional variations in pollution levels are observed, with southern Galicia experiencing greater susceptibility to wildfires and consequently higher concentrations, contrasting with relatively lower pollution levels in the north. This discrepancy underscores the necessity for tailored strategies to address air quality concerns.

The reanalysis data also served as input for the Lagrangian tracker, which unveils insights into pollution events' spatial and temporal progression. First, the tracker showed a strong correlation between wildfire activity and heightened pollution levels, particularly during boreal summer and autumn. Consequently, boreal summer and autumn are subject to more frequent wildfires and extreme pollution events related to fires than the winter and spring seasons, emphasizing the need for comprehensive pollution management strategies.

To comprehensively address acute exposure to severe air pollution, we analyzed events surpassing WHO thresholds, particularly notable in 2016, 2017, and 2022. Most of these events originated in Portugal and eastern Spain, and the smoke was transported to Galician cities, triggering concentration peaks that can exceed WHO-recommended $PM_{2.5}$ levels by 200%, increasing the potential of human respiratory diseases related to $PM_{2.5}$. The meteorological conditions driving these compound events require in-depth study, and to be accurately modeled, advanced forecasting is necessary. Besides, international cooperation is imperative, given the potential for cross-border impacts, underscoring the need for collaborative efforts to address transboundary air pollution challenges.

Examination of population exposure to $PM_{2.5}$ pollution during wildfire events and non-fire periods reveals very high concentration values when wildfires occur, posing substantial health risks. Wildfires exacerbated the impacts, especially in southern and eastern Galicia urban areas. The consistently high $PM_{2.5}$ concentration values highlight the urgency for targeted interventions to protect public health during wildfire seasons. Effective air quality management in Galicia is paramount, necessitating policies and actions that prioritize public health protection and bolster preparedness for extreme pollution events, encompassing early warning systems and enhanced wildfire management practices.

CRediT authorship contribution statement

César Quishpe-Vásquez: Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Patricia Oliva:** Writing – review & editing, Visualization, Validation, Supervision, Methodology. **Ellie Anne López-Barrera:** Writing – review & editing, Visualization, Supervision, Formal analysis. **Alejandro Casallas:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Cesar Quishpe-Vasquez reports financial support was provided by University of Alcala. Patricia Oliva reports financial support was provided by Community of Madrid. Alejandro Casallas reports financial support was provided by European Union. Ellie Anne Lopez-Barrera reports financial support was provided by Sergio Arboleda University. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.jenvman.2024.122093.

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