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Meteorological conditions and sporadic Legionnaires' disease in Spain

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ABSTRACT

Background: The incidence of legionellosis has increased in Spain in recent years, potentially influenced by climate-related changes that favour *Legionella pneumophila* proliferation.
Aim: The main aim of this study was to evaluate whether extreme meteorological events are associated with increased sporadic legionellosis incidence. Additional objectives included examining the short-term association across increasing percentiles of each meteorological variable and describing the spatiotemporal distribution of sporadic cases in Spain from 2011 to 2023.
Methods: Sporadic Legionnaires' disease (LD) cases reported to the National Epidemiological Surveillance Network (RENAVE) between 2011 and 2023 were included. Meteorological data on daily mean temperature, cumulative precipitation, mean relative humidity and maximum wind speed from the Spanish State Meteorological Agency (AEMET) stations were aggregated by meteorological warning areas. A generalised linear mixed-effects model was applied in a sensitivity analysis to examine associations between exceeding percentile thresholds (p5–p95) for each variable and incidence 2–14 days later. A second model evaluated the association between days with extreme events (p95) and subsequent incidence.
Results: A significant increase in sporadic LD was observed ($p < 0.05$), with the highest rates in northeastern Spain. Incidence increased progressively with higher percentiles of temperature, precipitation and humidity, while wind percentiles showed an inverse pattern. Days exceeding the 95th percentile of temperature, precipitation and humidity were associated with higher incidence; extreme wind showed no significant effect.
Conclusions: Extreme temperature, precipitation and humidity are associated with short-term increases in sporadic LD. Incorporating meteorological indicators into surveillance could improve early warning and support public health interventions under changing climatic conditions.

Introduction

Legionellosis is an infectious disease caused by the inhalation of aerosols containing water contaminated with the bacterium *Legionella pneumophila*. The distribution of these microorganisms is global, with soil and water serving as the primary reservoirs (Cooke and Slack, 2017). The capacity of *L. pneumophila* to replicate within free-living amoebae and water temperatures between 20 and 45 °C favours its proliferation (National Academies of Sciences, Engineering, and Medicine, 2019). Surveillance and control measures are therefore needed in structures such as showers, cooling towers, ornamental fountains and other water reservoirs, which are the locations associated the most with the transmission of this disease (Centers for Disease Control and Prevention, 2025a). However, in most cases, the source cannot be identified (Orkis et al., 2018).

The disease may either manifest as a mild and self-limited febrile illness known as Pontiac fever, with an incubation period of 24–48 h, or as an atypical pneumonia called Legionnaires' disease (LD), with an

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incubation period of 2–10 days (Pergam and Hawn, 2022). The fatality rate averages 10% (Centers for Disease Control and Prevention (CDC), 2025b).

The World Health Organization (WHO) estimates an incidence of between 1.0 and 1.5 cases per 100,000 persons per year. The most affected population groups are men, people over 50 years old and those presenting risk factors such as recent travel, immunosuppression or smoking (World Health Organization, 2025). According to the latest data reported by the European Centre for Disease Prevention and Control (ECDC), corresponding to the year 2024, the incidence of legionellosis in Europe was 3.37 cases per 100,000 inhabitants, which represents the highest value observed in the historical annual series (European Centre for Disease Prevention and Control, 2025). Spain reported a notification rate of 4.46 cases per 100,000 inhabitants, ranking seventh in terms of age-standardised incidence and representing a slight decrease compared with the previous year (4.66 cases per 100,000) (Cano Portero et al., 2024).

The precise causes of this rising incidence of legionellosis in our environment remain uncertain, although environmental and climatic factors might be involved (Moffa et al., 2023). Climate change may be a contributing factor, since it prolongs the time in which climate conditions are favourable for the growth of this bacterium in water, with increasingly longer periods with high temperatures and more intense rainfall events (Robinson et al., 2021). In fact, the Mediterranean region, which encompasses Spain, is particularly vulnerable to climate change (Cos et al., 2022). In recent decades, the number and intensity of heat waves in mainland Spain have increased, bringing temperature records to beat unprecedented values in at least the last millennium (Tejedor et al., 2024). These changes in the environmental conditions are proved to be related with changes in the incidence of LD (Fischer et al., 2023; Pampaka et al., 2022; Wade and Herbert, 2024).

This study aims to better characterise the relationship between meteorological conditions and the incidence of sporadic LD in Spain, with a particular focus on the response of incidence to extreme events. To this end, a spatiotemporal analysis of disease incidence across the country in 2011–2023 is provided. We further evaluate the behaviour of incidence following meteorological extreme events of temperature, precipitation, humidity, and wind.

Methods

LD and meteorological data sources

The information on confirmed sporadic LD cases was obtained from the National Epidemiological Surveillance Network in Spain (*Red Nacional de Vigilancia Epidemiológica*, RENAVE).

Population data were obtained from the Spanish National Institute of Statistics (*Instituto Nacional de Estadística*, INE) (Instituto Nacional de Estadística (INE), 2025a). Meteorological data were collected from the Spanish State Meteorological Agency (*Agencia Estatal de Meteorología*, AEMET), which includes data from 928 meteorological stations distributed throughout Spain, providing broad coverage of the country's main climatic regions. Geospatial data were obtained from AEMET, based on the division used to partition Spain into 182 isoclimatic zones known as meteorological warning areas (Agencia Estatal de Meteorología (AEMET), 2017).

Descriptive spatiotemporal analysis of LD

For this study, sporadic LD was defined as confirmed community-acquired Legionnaires' disease in which the likely exposure occurred in a setting unrelated to travel or healthcare. Accordingly, all confirmed LD cases notified to RENAVE between 2011 and 2023 were initially considered, and cases were excluded if they corresponded to Pontiac fever or were travel-related (domestic or abroad), hospital-acquired, or outbreak-associated. The analysed variables were age, sex, date of symptom onset (or if unavailable, date of diagnosis), municipality of residence (or if unavailable, municipality of the case) and death. Annual incidence and mortality rates were calculated, globally, by sex and by age groups. The global case-fatality rate was also estimated (deaths per 100 cases). Incidence and mortality were calculated per 100,000 inhabitants and 1,000,000 inhabitants, respectively, using the total Spanish population as the denominator, extracted from the INE for each year, and by areas using as spatial unit the 182 meteorological warning areas, aggregating the data of the municipalities within each area. Incidence rates shown in maps were age-standardised using the direct method, with the following age groups: <15, 15–24, 25–44, 45–64, 65–84, and ≥ 85 years.

A time-series analysis was conducted to assess trends and seasonality. Linear regression was performed on the annual incidence, mortality, and case-fatality rates. Analyses were also stratified by sex, age group and area. Time-series graphs, tables, and maps were produced to visualise the results.

Statistical analysis on the relation between LD and meteorology

The meteorological variables analysed were daily mean temperature, cumulative precipitation, mean relative humidity and maximum wind speed. Daily data from 2011 to 2023 were aggregated by meteorological warning area (averaging all stations within each area). Binary variables were created to indicate whether each meteorological variable exceeded percentiles from 5th to 95th in intervals of 5 of its distribution. Percentiles were calculated using the pooled distribution of daily observations from all meteorological warning areas across the entire study period. Therefore, the same absolute threshold was applied to all areas and years for each meteorological variable.

A generalised linear mixed-effects model (GLMM) assuming a negative-binomial distribution with a log link function was fitted for each meteorological variable to assess the association between meteorological conditions and subsequent sporadic LD incidence. The unit of analysis was the meteorological warning area-day. For each area-day, the dependent variable was the sporadic LD incidence rate in the subsequent lag window, calculated as the number of cases occurring in the corresponding meteorological warning area during the following 2–14 days divided by the population of that area. A population offset was not included because population size was already incorporated in the incidence-rate outcome. The 2–14-day lag interval was selected to reflect the typical incubation period of LD and potential environmental delays between meteorological exposure, bacterial proliferation, aerosol formation, human exposure and clinical onset. The fixed effects included the percentile-based meteorological indicators, as well as trend and seasonality variables. The long-term temporal trend was defined as the number of days elapsed since the beginning of the study period, and seasonality was modelled using sine and cosine functions of calendar month: $\sin(2\pi \times \text{month}/12)$ and $\cos(2\pi \times \text{month}/12)$. Meteorological warning area was included as a random intercept to account for baseline differences between areas. Collinearity was assessed prior to model fitting. Results were plotted for each meteorological variable.

Overdispersion was assessed by fitting an initial Poisson model and examining the Pearson chi-square goodness-of-fit statistic relative to the residual degrees of freedom. Since this ratio was clearly greater than 1, indicating overdispersion, negative-binomial models were used. The likelihood-ratio test for the negative-binomial overdispersion parameter alpha against zero also supported the use of the negative-binomial specification.

Extreme meteorological events were defined using the 95th percentile (p95) of each meteorological variable. This threshold was selected to ensure an adequate number of observations for robust statistical analysis, to capture meteorological conditions likely to affect the population, and to minimize the influence of very rare or outlier values.

To assess the impact of these extreme meteorological events, separate generalised linear mixed models were fitted for each meteorological variable, with the dichotomized variable included as a fixed-effect term. Each model was further refined by adjusting for potential confounding factors or interactions with the other meteorological variables. Collinearity was also assessed prior to model fitting. Additionally, the associations were examined separately for the 2–7-day and 8–14-day periods following exposure.

To evaluate the robustness of the P95 threshold, we conducted a supplementary sensitivity analysis by repeating the extreme-event models using P90 and P99 thresholds and comparing the results with the main P95 models. To ensure comparability across thresholds, these sensitivity models were adjusted for long-term trend, seasonality and meteorological warning area as a random effect, but were not additionally adjusted for other meteorological variables or interaction terms.

The threshold for statistical significance was set at a p-value of 0.05. Analyses and visualization were conducted using Microsoft Excel, Stata 18.5 and QGIS 3.44 software.

Results

Descriptive spatiotemporal analysis of LD

From 1st January 2011 to 31st December 2023, a total of 18,564 confirmed cases of legionellosis (LD and Pontiac fever) were notified in Spain, of which 13,037 (70.2%) met the inclusion criteria for this study.

The average annual rate of sporadic LD was 2.17 cases per 100,000 inhabitants in Spain. Most cases (71.93%) occurred in men (9572), with the average annual incidence rate in men being almost three times higher than in women (3.16 versus 1.19 cases per 100,000). The median age of LD cases was 64 years (p25-p75: 54–77). The mean annual incidence rate varied across age groups, demonstrating an increasing trend in both sexes from 0.02 cases per 100,000 inhabitants in the under-15 age group to 8.22 cases per 100,000 inhabitants in the over-85 age group (Table 1).

The incidence of LD showed an increasing trend, with an increase of 0.19 cases per 100,000 inhabitants annually (95% CI: 0.15–0.23, $p < 0.001$) (Fig. 1A). The year with the lowest incidence was 2013, with 1.32 cases per 100,000 inhabitants, while 2022 had the highest incidence with 3.46 cases per 100,000 inhabitants (Fig. 1A). The temporal distribution of cases exhibited a clear annual cycle, with most cases occurring between June and November, peaking in September with an average of 160 cases per month. In contrast, April showed the lowest incidence, with an average of 41 cases per month.

Regarding the spatial distribution by meteorological warning area of the age-standardised annual average incidence of LD over the 13-year study period, the zones with the highest incidence rates were in the northeastern part of the Iberian Peninsula and in the Balearic Islands, with some zones reaching incidence rates above 6 cases per 100,000 inhabitants (Fig. 2A).

Over the study period, 823 deaths due to LD were reported, which corresponds to an average annual mortality rate of 1.34 deaths per million inhabitants. The sex and age distribution of mortality mirrored that of incidence, with an average annual mortality rate in men that was almost three times higher than in women (1.95 deaths per million inhabitants in men vs. 0.74 in women).

Table 1
Average annual incidence of sporadic LD (cases per 100,000 inhabitants) and average annual mortality (cases per million inhabitants) by age group and sex in Spain (2011–2023).

Age groups	Incidence (per 100,000 inh.)			Mortality (per million inh.)		
	Men	Women	All	Men	Women	All
<15 years	0.02	0.02	0.02	0.04	0.02	0.03
15–24 years	0.15	0.05	0.10	0.07	0	0.03
25–44 years	1.02	0.28	0.66	0.16	0.04	0.10
45–64 years	5.02	1.54	3.26	1.55	0.44	1.00
65–84 years	8.26	2.83	5.28	6.87	2.03	4.22
≥85 years	14.31	5.15	8.22	24.21	6.71	12.49
All	3.16	1.19	2.17	1.95	0.74	1.34

The average annual mortality rate increased with age, from 0.03 deaths per million inhabitants under 15 years of age to 12.49 deaths per million among those aged ≥85 (Table 1). The case-fatality rate of this disease was 6.30%.

Mortality showed an upward trend, with an annual increase in its rate ranging from 0.09 to 0.20 deaths per million population (95% CI, $p < 0.01$). The annual mortality rate reached its minimum in 2016 (0.64 deaths per million population), while 2023 recorded the highest mortality (2.83 deaths per million population) (Fig. 1B). In contrast, logistic regression analysis did not identify a significant temporal trend in case fatality rate ($p > 0.05$), which fluctuated between 3.94% in 2016 and 8.35% in 2023.

The annual average age-adjusted mortality by LD was more evenly distributed across the territory, without being as clustered in specific zones as incidence was (Fig. 2B). There were no declared deaths in 57 zones.

LD incidence and meteorological conditions

Results of the sensitivity analysis assessing the association between each meteorological variable exceeding its 5-percentile groups and the incidence of sporadic LD within the next 2–14 days are shown in Fig. 3. The percentile cut-off values for the meteorological variables are reported in Supplementary Table S1.

Regarding the temperature, the risk of sporadic LD in the subsequent days increased progressively as higher temperature percentiles were exceeded. This risk was significantly lower when temperatures surpassed the 5th to 30th percentiles. However, from the 50th percentile onward, the risk of LD at 2–14 days increased significantly, reaching a 4.3% higher risk at the 50th percentile and up to 33.9% at the 95th percentile.

For accumulated precipitation, an increased incidence of LD in the subsequent days was observed once any precipitation occurred. Percentiles from the 5th to the 55th corresponded to minimal rainfall (essentially exceeding 0 mm), so the observed increase in risk in this range reflects the contrast between dry days and days with any precipitation. From the 65th percentile onward, the risk rose progressively, reaching up to a 25.3% increase at the 95th percentile.

For maximum wind speed, the risk of LD in the subsequent days showed a generally decreasing trend as wind intensity increased. At the lowest percentiles (5–15), the risk was elevated, reaching up to 22.1% above baseline at the 5th percentile. From the 20th to the 85th percentiles, the risk gradually declined, with smaller increases ranging from approximately 10% to 5%. At the 95th percentile, corresponding to days with the strongest wind gusts, the risk approached baseline, but not reaching a statistical significance.

The results of the GLMM regarding the association of the extreme weather events (p95) and the incidence of sporadic LD are shown in Table 2.

Days with a mean temperature above the 95th percentile (26.5 °C) are associated with a 36% higher risk of cases of LD occurring within the next 2–14 days. This increased risk remained consistent throughout the 2–7 days (first week) and 8–14 days (second week) after the meteorological event.

Days with cumulative precipitation above the 95th percentile (10.3 mm) are associated with a 28% higher risk of LD cases occurring within the next 2–14 days, adjusted for interaction with maximum wind speed. The increase in risk is higher in the second week (49%) than in the first week (8%) after the exposure.

Days with relative humidity above the 95th percentile (90.3%) are associated with a 12% higher risk of LD cases occurring within the next 2–14 days. This increase is not statistically significant in the second week.

Days with maximum wind speeds above the 95th percentile (16.3

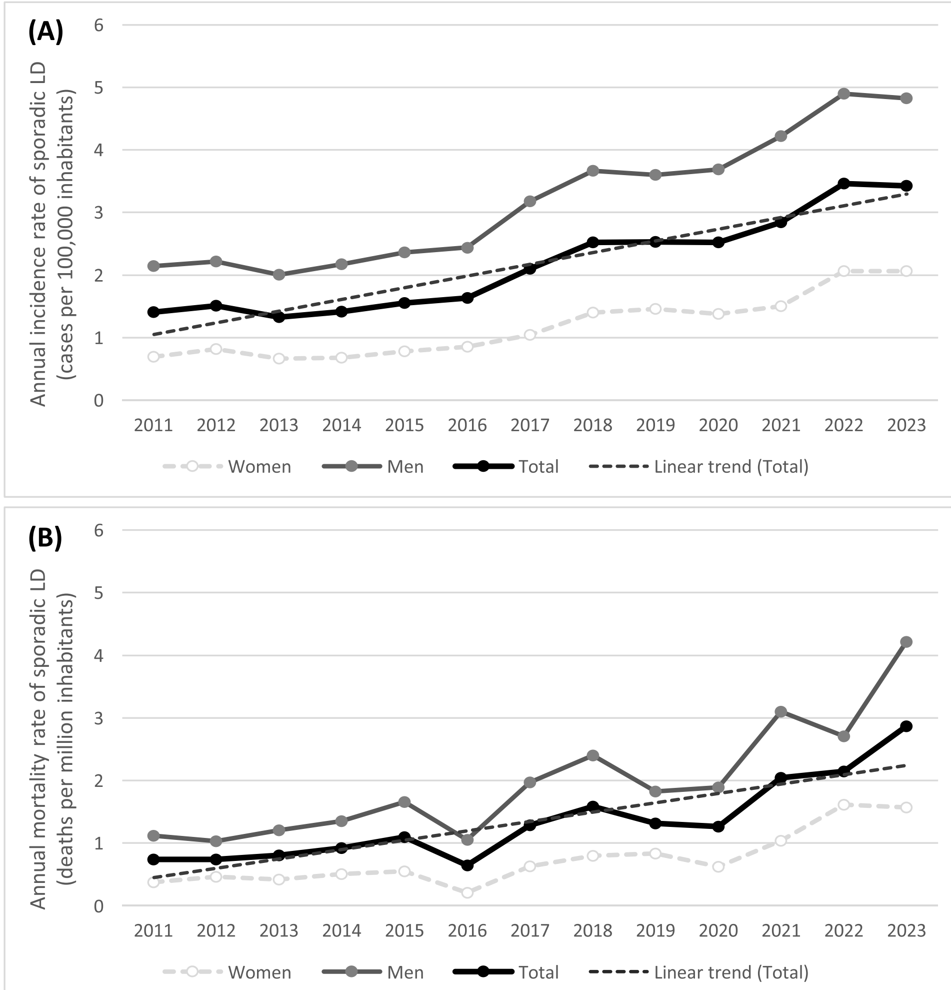

Fig. 1. Annual incidence rates of sporadic LD (cases per 100,000 inhabitants) (1A) and annual mortality rates of sporadic LD (deaths per million inhabitants) (1B) by sex in Spain (2011–2023).

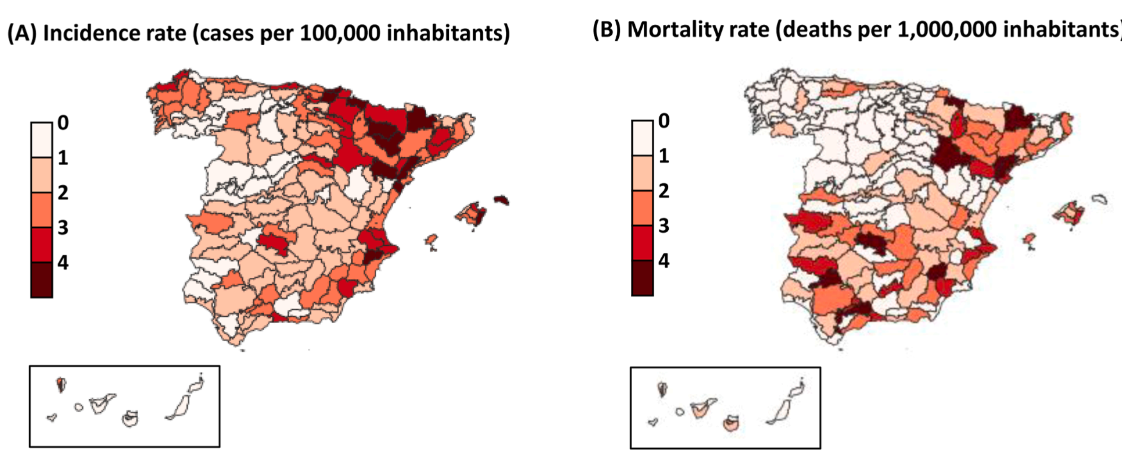

Fig. 2. Average annual incidence rate of sporadic LD (cases per 100,000 inhabitants) (2A) and average annual mortality rate of sporadic LD (deaths per million inhabitants) (2B) by meteorological warning area in Spain (2011–2023).

km/h) are not associated with a statistically significant effect on the risk of LD cases occurring within the next 2–14 days. However, they are associated with an increase in risk in the second week only (7%).

Sensitivity analyses using P90, P95 and P99 thresholds are shown in Supplementary Table S2.

Discussion

This is the first nationwide study conducted in Spain to examine the association between meteorological phenomena and legionellosis, including >13,000 cases that met the inclusion criteria.

The results of the spatiotemporal descriptive analysis of sporadic LD

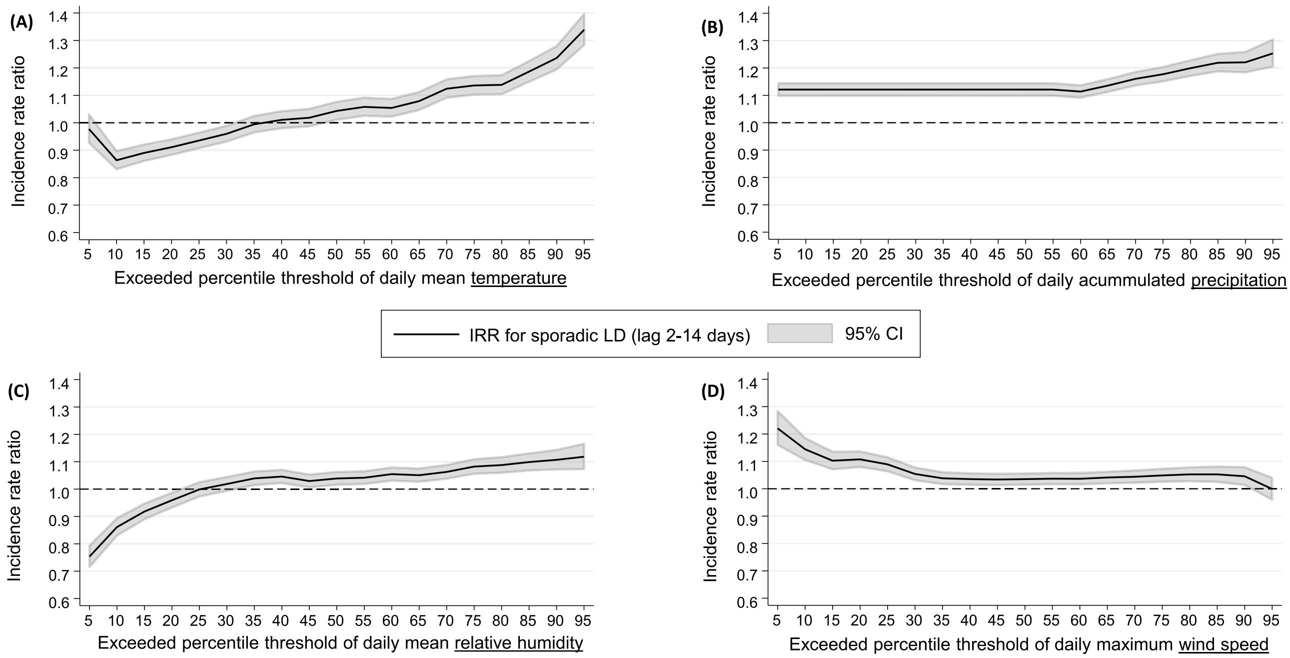

Fig. 3. GLMM results for LD incidence 2–14 days after exceeding the 5–95th percentile of mean temperature (3A), accumulated precipitation (3B), mean relative humidity (3C) and maximum wind speed (3D). (i)IRR: incidence rate ratio; 95%CI: 95% confidence interval.

Table 2
GLMM results for sporadic LD incidence 2-14 days, 2-7 days and 8-14 days after a meteorological extreme event (p95).

Meteorological extreme event (p95)	Sporadic LD incidence in subsequent 2-14 days			Sporadic LD incidence in subsequent 2-7 days			Sporadic LD incidence in subsequent 8-14 days		
	IRR	95%CI	p-value	IRR	95%CI	p-value	IRR	95%CI	p-value
Mean temperature ≥ 26.5 °C	1.36	1.30-1.42	<0.001	1.37	1.28-1.46	<0.001	1.37	1.29-1.45	<0.001
Cumulative precipitation ≥ 10.3 mm	1.28[a]	1.22-1.34	<0.001	1.08	1.02-1.15	0.012	1.49	1.41-1.57	<0.001
Mean relative humidity ≥ 90.3%	1.12	1.07-1.18	<0.001	1.12	1.06-1.19	<0.001	1.04[b]	0.98-1.10	0.240
Maximum wind speed ≥ 16.3 km/h	1.02[c]	0.97-1.07	0.424	1.04[d]	0.97-1.11	0.281	1.07	1.01-1.14	0.017

(i) IRR: incidence rate ratio; 95%CI: 95% confidence interval.
*Adjusted for
[a] Interaction with maximum wind speed.
[b] Confusion with cumulative precipitation.
[c] Interaction with cumulative precipitation.
[d] Interaction with relative humidity.

show an upward trend in the number of cases in Spain from 2011 to 2023, with an annual average of 2.17 cases per 100,000 inhabitants. The incidence of this disease is higher among men in older age groups. It follows a seasonal pattern, with most cases occurring during the warmer months. Mortality from LD shows a similar trend, also affecting the same population group, with a case fatality rate of 6.30%. The areas with the highest incidence are located in the northeastern part of the Iberian Peninsula and in the Balearic Islands.

As average temperature, accumulated precipitation, and mean relative humidity increase, a higher incidence of sporadic LD is observed in the following 2–14 days. This pattern does not apply to wind, for which an inverse association is observed. These findings are consistent with the systematic review by (Pampaka et al., 2022), which reported a positive correlation between LD incidence and temperature, precipitation, and humidity. Furthermore, they identified an inverse association, with limited evidence, between the incidence of this disease and other meteorological factors such as wind, atmospheric pressure, visibility, and solar radiation.

Days with temperatures above the 95th percentile (26.5 °C) were associated with a 37% higher incidence of sporadic LD within the following 2–14 days. This could be related to the proliferation of *L. pneumophila* in stagnant water, as temperatures would reach the range in which the bacteria grow optimally, between 20 and 45 °C (National Academies of Sciences, Engineering, and Medicine, 2019). A higher use of air conditioning systems and increased hotel occupancy during warmer months (Instituto Nacional de Estadística, 2025b) could also contribute, since these establishments often have facilities such as cooling towers or large plumbing systems, which are known risk factors for LD transmission (Centers for Disease Control and Prevention, 2025a). In this study, a potential bias from this effect was minimized by excluding imported and travel-related cases, many of which followed hotel stays, by removing outbreak-related cases, and by adjusting for seasonality in the model.

Exceeding the 95th percentile of rainfall (10.3 mm) was associated with an 8% increase in the incidence of sporadic LD in the 2–7 days following the event, and a 49% increase in the 8–14 days thereafter. This association may be related to the accumulation or renewal of stagnant water reservoirs after heavy rainfall, which can favour the growth of free-living amoebae and the subsequent intracellular replication of *L. pneumophila*. Rainfall may also increase environmental moisture and promote aerosol formation or dispersion from contaminated water or wet surfaces (Villanueva and Schepanski, 2019). The stronger association observed in the second week is biologically plausible, as it may reflect the time required for environmental amplification of Legionella, subsequent exposure, and the clinical incubation period before symptom onset. However, reporting delays, residual seasonality or temporal autocorrelation may also contribute to this lag pattern.

Days with a mean relative humidity above the 95th percentile (90.3%) were associated with a 12% increase in the incidence of LD within the following 2–14 days. This increase was 12% in the 2–7 days after the event but was no longer significant in the 8–14-day period. The shorter lag observed for relative humidity may indicate a more immediate role in aerosol persistence and transmission conditions. High humidity can favour the survival and transport of aerosols, potentially increasing the probability of inhalation shortly after exposure. Unlike rainfall, humidity may not require time for water accumulation or bacterial growth, which could explain why the association was concentrated in the first week.

On the other hand, days with maximum wind gusts above the 95th percentile (16.3 km/h) were only associated with a significant effect on the incidence of sporadic LD in the 8–14 days following the event, showing a modest 7% increase. Wind is not expected to directly favour the transmission of LD, as higher wind speeds may dilute or disperse contaminated aerosols, reducing exposure (Pampaka et al., 2022). However, the interpretation of wind speed is less straightforward. Higher wind speeds may disperse or dilute contaminated aerosols, potentially reducing local exposure, but they may also facilitate wider transport under certain conditions. In this study, the association with maximum wind speed was weak and inconsistent, and the delayed second-week signal should therefore be interpreted cautiously. It may reflect indirect mechanisms, residual confounding or correlation with other meteorological conditions rather than a direct causal effect. Future analyses could explore alternative indicators, such as mean wind speed, to better capture the potential influence of wind-related factors.

In Spain, the association between LD and meteorological factors was first examined in 2013, when a hospital-based study already identified rainfall as a risk factor for *L. pneumophila* pneumonia (Garcia-Vidal et al., 2013).

The present findings are broadly in line with the national-level study conducted in Switzerland by (Fischer et al., 2023), which, although using slightly different methodology and threshold definitions, analysed all legionellosis cases notified through the Swiss national surveillance system between 2017 and 2021. That study also found an association between these meteorological factors (temperature, precipitation, and humidity), as well as vapor pressure, and an increased incidence of autochthonous cases of legionellosis in the subsequent days. Similarly, a large nationwide study in the United States (Wade and Herbert, 2024) provides valuable evidence on the impact of weather and environmental factors on legionellosis, although it focuses specifically on hospitalizations recorded in administrative databases, which capture severe cases but not milder or non-hospitalized infections.

This study has several strengths. First, it is based on a large national surveillance dataset including >13,000 confirmed sporadic community-acquired LD cases over a 13-year period. Second, it combines epidemiological data from RENAVE with meteorological information from AEMET, allowing the analysis of short-term associations between weather conditions and LD incidence across Spain. Third, the lag-stratified analysis enabled us to explore whether associations differed between the first and second week after meteorological exposure. Finally, the use of meteorological warning areas as the spatial unit of analysis provides a refined spatial resolution and better captures local weather variability than broader administrative units such as provinces or national averages (Agencia Estatal de Meteorología (AEMET), 2018). Because these areas are also used for official meteorological warnings, they may support future studies on weather-based early-warning systems for sporadic LD.

This study has some limitations that should be considered. Underreporting or variability in diagnostic capacity across regions could have influenced the apparent spatial distribution of cases.

Exposure misclassification is another limitation of this study. Meteorological exposure was assigned according to the municipality of residence, or the municipality of the case when residence was unavailable, and then aggregated to meteorological warning areas. However, the actual place of exposure may have differed from the place of residence, as sporadic LD can be acquired in workplaces, public spaces, recreational facilities or other built-environment settings. This may have introduced spatial misclassification and could have biased the estimated associations, most likely towards the null. Nevertheless, the use of meteorological warning areas may partly reduce this limitation, as these zones cover broader areas with relatively homogeneous meteorological conditions and are more appropriate for capturing local weather exposure than individual municipalities or isolated weather stations.

The spatial distribution of sporadic LD should also be interpreted cautiously. Although higher incidence rates were observed in the northeastern Iberian Peninsula and the Balearic Islands, this study did not aim to formally identify spatial clusters or hot spots. Therefore, the spatial analysis should be considered descriptive. Further studies specifically designed for spatial epidemiological analysis would be needed to identify statistically significant clusters and potential local determinants of increased incidence.

Residual confounding by unmeasured regional and environmental factors cannot be ruled out. Socioeconomic characteristics, population density, tourism, diagnostic practices, air-conditioning use, urban infrastructure and the distribution of potential Legionella-related water systems may influence sporadic LD incidence and may also be correlated with meteorological conditions. Several of these variables are relatively stable over time and are more likely to contribute to baseline differences between areas than to short-term day-to-day variation in LD incidence. Meteorological warning area was therefore included as a random effect to partially account for stable differences between areas, although residual confounding by unmeasured or time-varying local determinants cannot be excluded.

An additional limitation of this study is the lack of air pollution indicators (e.g., PM2.5, PM10, NO2, SO2) among the explanatory variables. Epidemiological evidence indicates that air pollution can affect susceptibility to respiratory infections and may interact with meteorological factors in aerosol behaviour (Monoson et al., 2023); therefore, omitting these variables could leave residual confounding in some of the observed associations.

In the sensitivity analysis, several percentile thresholds were evaluated, which may increase the possibility of false-positive findings due to multiple testing. However, this analysis was exploratory and was intended to assess the consistency of the exposure–response pattern rather than to interpret each percentile-specific estimate as an independent result. In addition, adjacent thresholds are highly correlated and should not be considered independent tests.

The sensitivity analysis using P90, P95 and P99 thresholds supported the choice of P95 as the main definition of extreme meteorological events. Although P99 captured more extreme conditions and showed a stronger association for daily mean temperature, it involved substantially fewer exposed observations and generally wider confidence intervals, limiting its usefulness for routine public health surveillance. In contrast, P95 provided a better balance between identifying uncommon meteorological conditions, retaining sufficient observations for stable estimation, and preserving operational relevance for early-warning purposes.

The present results are consistent with the hypothesis that meteorological conditions contribute to short-term variation in sporadic LD incidence. The observed associations with extreme temperature, precipitation and humidity suggest that meteorological extremes may create environmental conditions favourable for the proliferation, aerosolization or transmission of *L. pneumophila*. In the context of climate change, such conditions may become more frequent or intense (van Daalen et al., 2024), potentially increasing the relevance of meteorological surveillance for LD prevention. However, causality cannot be established from this ecological study, and the observed long-term increase in LD incidence may also reflect changes in surveillance, diagnostic practices, population ageing, clinical awareness, infrastructure, travel patterns or reporting completeness.

These findings highlight the importance of integrating meteorological and environmental surveillance into public health strategies to anticipate increases in infectious diseases incidence under changing climatic conditions. In the case of sporadic LD, P95 thresholds for temperature, precipitation and relative humidity could be explored as components of early-warning tools to identify periods of increased risk during the following 2–14 days. Future studies should evaluate whether official warnings for adverse meteorological events can improve the short-term prediction of sporadic LD incidence and support operational early-warning systems.

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CRediT authorship contribution statement

Javier Chaves-Cordero: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **María Guerrero-Vadillo:** Writing – review & editing, Supervision, Data curation. **Carmen Varela-Martínez:** Writing – review & editing, Supervision, Data curation. **Félix García-Pereira:** Writing – review & editing, Visualization, Methodology, Conceptualization. **Ayelén Rojas-Benedicto:** Writing – review & editing, Data curation. **David Expósito-Singh:** Writing – review & editing, Project administration, Funding acquisition. **Diana Gómez-Barroso:** Writing – review & editing, Visualization, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.heha.2026.100191.

References

Agencia Estatal de Meteorología (AEMET), 2018. Plan Nacional de Predicción y Vigilancia De Fenómenos Meteorológicos Adversos (Meteoalerta). AEMET. Available from. https://www.aemet.es/documentos/es/eltiempo/prediccion/avisos/plan_meteoalerta/plan_meteoalerta.pdf.

Agencia Estatal de Meteorología (AEMET), 2017. Detalle de municipios por zonas meteorológicas. Plan Meteoalerta. Madrid: AEMET. https://www.aemet.es/documentos/es/eltiempo/prediccion/avisos/plan_meteoalerta/detalle_municipios_zonas_meteorologicas.pdf.

Cano Portero, R., Martín Mesonero, C., Amillategui Dos Santos, R., 2024. Estudio epidemiológico de la legionelosis en España. Año 2023. Bol. Epidemiológico Sem. 32, 94–104. Available from. https://revista.isciii.es/index.php/bes/article/view/1379.

Clinical Features of Legionnaires' Disease and Pontiac Fever, 2025a. Centers for Disease Control and Prevention (CDC) [Internet]. Available from https://www.cdc.gov/legionella/about/causes-transmission.html.

Clinical Features of Legionnaires' Disease and Pontiac Fever, 2025b. Centers for Disease Control and Prevention (CDC) [Internet]. Available from. https://www.cdc.gov/legionella/hcp/clinical-signs/index.html.

Cooke, F.J, Slack, M.P.E., 2017. Gram-negative coccobacilli. Infectious Diseases [Internet]. Elsevier, pp. 1611–1627.e1. https://doi.org/10.1016/B978-0-7020-6285-8.00183-0.

Cos, J., Doblas-Reyes, F., Jury, M., Marcos, R., Bretonnière, P.A., Samsó, M., 2022. The Mediterranean climate change hotspot in the CMIP5 and CMIP6 projections. Earth Syst. Dynam. 13, 321–340. https://doi.org/10.5194/esd-13-321-2022.

European Centre for Disease Prevention and Control (ECDC), 2025. Surveillance Atlas of Infectious Diseases. Stockholm: ECDC. https://atlas.ecdc.europa.eu/public/.

Fischer, F.B., Saucy, A., Vienneau, D., Hattendorf, J., Fanderl, J., de Hoogh, K., Mäusezahl, D., 2023. Impacts of weather and air pollution on Legionnaires' disease in Switzerland: a national case-crossover study. Environ. Res. 233, 116327. https://doi.org/10.1016/j.envres.2023.116327.

Garcia-Vidal, C., Labori, M., Viasus, D., Simonetti, A., Garcia-Somoza, D., Dorca, J., et al., 2013. Rainfall is a risk factor for sporadic cases of *Legionella pneumophila* pneumonia. PLoS One 8 (4), e61036. https://doi.org/10.1371/journal.pone.0061036.

Instituto Nacional de Estadística, (INE)., 2025a. Cifras De Población y Censos Demográficos. INE, Madrid. https://www.ine.es/dyngs/INEbase/categoria.htm?c=Estadistica_P&cid=1254735572981.

Encuesta De Ocupación Hotelera, 2025b. Instituto Nacional de Estadística [Internet].

Legionelosis, 2025. World Health Organization (WHO) [Internet]. Available from. https://www.who.int/es/news-room/fact-sheets/detail/legionellosis.

Moffa, M.A., Rock, C., Galiatsatos, P., Gamage, S.D., Schwab, K.J., Exum, N.G., 2023. Legionellosis on the rise: a scoping review of sporadic, community-acquired incidence in the United States. Epidemiol. Infect. 151, e133. https://doi.org/10.1017/S0950268823001206.

Monoson, A., Schott, E., Ard, K., Kilburg-Basnyat, B., Tighe, R.M., Pannu, S., Gowdy, K. M., 2023. Air pollution and respiratory infections: the past, present, and future. Toxicol. Sci. 192 (1), 3–14. https://doi.org/10.1093/toxsci/kfad003.

National Academies of Sciences, Engineering, and Medicine, 2019. Management of Legionella in water systems. Chapter 2, Diagnosis, Ecology, and Exposure Pathways. National Academies Press, Washington (DC). Available from. https://www.ncbi.nlm.nih.gov/books/NBK555116/.

Orkis, L.T., Harrison, L.H., Mertz, K.J., Brooks, M.M., Bibby, K.J., Stout, J.E., 2018. Environmental sources of community-acquired Legionnaires' disease: a review. Int. J. Hyg. Environ. Health 221 (5), 764–774. https://doi.org/10.1016/j.ijheh.2018.04.013.

Pampaka, D., Gómez-Barroso, D., López-Perea, N., Carmona, R., Portero, R.C., 2022. Meteorological conditions and Legionnaires' disease sporadic cases-a systematic review. Environ. Res. 214, 114080. https://doi.org/10.1016/j.envres.2022.114080.

Pergam, S.A., Hawn, T.R., 2022. Infecciones por Legionella. editores. In: En:Loscalzo, J., Fauci, A., Kasper, D., Hauser, S., Longo, D., Jame-son, J.L. (Eds.), Harrison Principios de Medicina Interna, 21e [Internet]. McGraw-Hill Education, New York, NY. Available from. https://www.accessmedicina.mhmedical.com/content.aspx?aid=1192786604.

Robinson, A., Lehmann, J., Barriopedro, D., et al., 2021. Increasing heat and rainfall extremes now far outside the historical climate. NPJ Clim. Atmos. Sci. 4, 45. https://doi.org/10.1038/s41612-021-00202-w.

Tejedor, E., Benito, G., Serrano-Notivoli, R., et al., 2024. Recent heatwaves as a prelude to climate extremes in the western Mediterranean region. NPJ Clim. Atmos. Sci. 7, 218. https://doi.org/10.1038/s41612-024-00771-6.

van Daalen, K.R., Tonne, C., Semenza, J.C., Rocklöv, J., Markandya, A., Dasandi, N., et al., 2024. The 2024 Europe report of the Lancet Countdown on health and climate change: unprecedented warming demands unprecedented action. Lancet Public Health 9 (7), e495–e522. https://doi.org/10.1016/S2468-2667(24)00055-0.

Villanueva, D., Schepanski, K., 2019. Investigation of atmospheric conditions fostering the spreading of legionnaires' disease in outbreaks related to cooling towers. Int. J. Biometeorol. 63 (10), 1347–1356. https://doi.org/10.1007/s00484-019-01751-9.

Wade, T.J., Herbert, C., 2024. Weather conditions and legionellosis: a nationwide case-crossover study among Medicare recipients. Epidemiol. Infect. 152, e125. https://doi.org/10.1017/S0950268824000979.