Characterisation of the respiratory syncytial virus seasonality and its environmental factors in the Americas—a multi-country observational study using routine surveillance networks

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Summary

Background Respiratory Syncytial Virus (RSV) is an important cause of bronchiolitis and pneumonia in young children. Circulation patterns represent challenges for immunoprophylaxis, requiring tailored interventions to address RSV activity linked to climate. We assessed RSV seasonality across the Americas and its relation to environmental factors and influenza circulation.

Methods RSV seasonality was assessed using data reported in 2010–2019 to a multi-country respiratory surveillance network. Time-series analysis identified temporal patterns and trends. Negative binomial, Moving Epidemics Method, and WHO Moving Averages Models were compared to assess seasonality. Correlation and regression were used for associations of RSV with environmental and influenza predictors.

Findings During 2010–2019, 32 countries in the Americas reported 14,308,503 respiratory samples, with 446,648 RSV-positive (3.12%) samples. RSV seasonal epidemics progressed from south to north. In South America, RSV seasons began in early May, peaking in August. RSV seasonality was less distinct in Caribbean; RSV started in September and peaked in October–November. Central Americas' RSV season lagged behind influenza, whereas in the Andes, it peaked earlier. At higher latitudes, RSV epidemics occurred earlier with shorter durations. RSV circulation negatively correlated with lower temperatures (–0.43; $p < 0.0001$), and precipitation (–0.04; $p = 0.0035$); and was positively correlated with decreased longitude (0.12; $p < 0.0001$) and barometric pressure (0.15; $p < 0.0001$), and was associated with lower elevation (0.02; $p = 0.10$), and westerly locations (0.12; $p < 0.0001$).

Interpretation Subregional and interannual variations in RSV seasonality were influenced by environmental factors, underscoring the importance of ongoing surveillance. Collaborative efforts improve surveillance, shaping evidence-based strategies for preventive product introductions and effective RSV control.

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Keywords: Respiratory syncytial virus; RSV vaccines; Seasonality; Climate drivers

Introduction

Respiratory Syncytial Virus (RSV) is a leading cause of bronchiolitis and pneumonia in young children aged below 5 years, with higher morbidity and mortality risk in infants during the first year of age. Children under six months account for 1.4 million (1.0–2.0 million) or

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Disclaimer: This summary is available in Spanish and Portuguese in the Supplementary Material.

Research in context

Evidence before this study

Respiratory Syncytial Virus (RSV) is a leading cause of bronchiolitis and pneumonia in young children. Its variable seasonality poses challenges for planning effective RSV preventive strategies. Tailored interventions are needed to address the regional patterns of RSV activity, which are influenced by climate and geography. Two immunisation strategies —maternal vaccination and monoclonal antibodies— have recently been recommended in the Americas. However, their limited duration of protection underscores the need for a clearer understanding of RSV circulation's timing and geographic variability to inform optimal timing and duration of immunoprophylaxis.

To assess the existing evidence, we conducted a literature search in PubMed, Scopus and Medline in December 2024. The search terms included all studies published up to November 2024, with no language restriction, and also considered studies in revision during November and December 2024. Search terms included combinations and synonyms of: ("RSV" AND "seasonality"), ("RSV" AND ("climate" OR "environment")), ("RSV" AND "Latin America") OR ("RSV" AND "Caribbean").

The search yielded 3754 publications, nearly half (49.9%; n = 1873) of which were published between 2019 and 2024. Of these, 167 studies investigated the seasonal trends of RSV in the Americas, most of which were conducted in high-income North American countries, with approximately 50% (n = 92) focusing on that region. In contrast, only 38 studies originated from Latin America and the Caribbean, including six from Central America, three from the Caribbean, and fifteen from South America.

A broader review identified 452 studies examining RSV in relation to influenza, and 35 studies on RSV and environmental factors, with eight from North America and only seven from Latin America and the Caribbean. Most studies in Latin America and the Caribbean relied on short-term observational data, primarily from hospitalised patients. While previous research has documented substantial subregional and subnational variability in RSV circulation, mainly attributed to geographical and climate factors, significant gaps remain. In particular, greater understanding is needed of how environmental conditions influence the seasonal dynamics of RSV, especially within the context of existing influenza surveillance systems, that could be leveraged for RSV monitoring. Improving understanding of RSV transmission patterns—specifically in tropical and subtropical regions— is imperative to inform effective RSV prevention and control measures.

Added value of this study

This study depicted RSV seasonal patterns in relation to environmental factors and influenza seasons, by analysing a decade of virological surveillance data across multiple countries in the Americas. It characterised the association between patterns of RSV circulation, environmental variables and influenza seasons, providing insights on timing to inform evidence-based RSV control and prevention strategies. A key strength of this study lies in leveraging sustainable routine respiratory surveillance data from the SARINet Plus Network countries, supporting operational research and evidence-based policymaking in the region.

Implications of all the available evidence

This comprehensive analysis of RSV and influenza seasonality across the Americas enhances our understanding of the transmission dynamics of these respiratory viruses. The study provides critical insights to inform evidence-based policymaking and strategies for RSV control and prevention by leveraging and strengthening routine sustainable respiratory surveillance networks. These findings can guide regional technical advisory groups, ministries of health, and scientific societies in optimising the timing of RSV-related public health interventions.

39% of RSV-associated lower respiratory tract infections (LRTI) hospital admissions and more than 50% of in-hospital deaths,[1] necessitating comprehensive strategies for control and prevention. Apart from young children, RSV is also considered an important cause of morbidity and mortality comparable to influenza in adults aged 65 years and above and high-risk individuals.[2]

Complexities in RSV seasonality, marked by variable onset and duration, pose challenges to planning preventive strategies.[3,4] Until 2023, Palivizumab was the only available monoclonal antibody.[5] Currently, two immunisation strategies against RSV are also available and recommended for use in the Americas. These include the maternal RSV prefusion F protein-based vaccine (RSV-PreF) and the long-acting monoclonal antibody Nirsevimab for protection of infants; and protein sub-unit vaccines (RSV-PreF and RSV-PreF3) for use in older adults. The recently approved Nirsemivab[6] was introduced for newborns entering their first RSV season from October to March–April in the United States and Canada,[6,7] and from April to September in Chile.[8] In 2024, Argentina, Canada, the United States, and Uruguay incorporated the maternal RSV vaccine to prevent infant severe disease at the start of the RSV season: from September to January in the northern countries and from March to September in the Southern countries[6,8,9] In November 2023, the Pan American Health Organization's (PAHO) Technical Advisory Group (TAG) recommended RSV vaccination among

pregnant individuals at 32–36 weeks of gestation to prevent disease in infants across the region.[10]

Implementing immunoprophylaxis with a limited duration of protection requires understanding of a patient's risk status and the optimal timing and duration of immunoprophylaxis, considering the variability in RSV outbreaks and seasons.[11,12] Previous studies highlight the diverse regional and local RSV activity across the Americas, attributed to geographical and climate variations, posing a challenge for the seasonal administration of monoclonal antibodies and vaccines against RSV.[3,13,14] With substantial variability observed even within provinces and climatically disparate countries like Argentina, Brazil, Chile, and the USA, a better understanding of RSV epidemiology is imperative. The potential mismatch between fixed-schedule prophylaxis on seasonal basis and changing RSV seasons emphasises the need to characterise and monitor RSV activity for effective preventive and control measures and the success of RSV vaccines.

The Americas region benefits from established and integrated respiratory virus surveillance equipped with laboratory diagnostics, including immunofluorescence, RT-PCR, and genomic surveillance as part of the WHO Global Influenza Surveillance and Response System (GISRS) and the PAHO Severe Acute Respiratory Infections Plus multi-country regional network, SARI*net* Plus.[15,16] The diagnostic capacity for RSV is part of the viral triad of influenza, SARS-CoV-2 and RSV in the Americas, with multiple-pathogen testing performed for years. Respiratory surveillance data are reported by Member States to global platforms for weekly epidemiological assessments following WHO mandates.[17] Collaborative efforts with Argentina, Brazil, Canada, and Chile within the WHO RSV Global Project, a global initiative that integrated RSV surveillance into the Global Influenza Surveillance and Response System (GISRS) since 2016[18] have augmented RSV surveillance for vaccine development.

Current gaps in the understanding of the timing of RSV activity in low-and middle-income countries in tropical or subtropical regions include understanding of the relationship between RSV activity and climate factors require assimilation of epidemiological information, focusing on seasonality patterns, within the existing influenza surveillance systems in the regional and global networks.[19]

This study's objective is to depict RSV seasonal patterns and their relation to environmental factors and influenza seasons to contribute to evidence-based RSV control and prevention strategies in the region by leveraging virological data from surveillance.

Methods

We described the RSV seasonality by country for the American region by including a time series decomposition and focussed on assessing seasonality metrics using three independent methods. Regression models explored factors associated with RSV seasonal patterns, including seasonal influenza activity and environmental factors.

Data sources and surveillance case definitions

This study utilised data on RSV and influenza from national integrated respiratory surveillance systems for the period 2010–2019 from the American Region. Countries report case counts for each of the respiratory viruses as weekly aggregates to FluNet PAHO/WHO.[19] We included virologic, epidemiologic, and population denominator data by week and year. Data from other respiratory viruses and prior years were excluded. Age-disaggregated data were not available, limiting the ability to assess RSV trends in specific at-risk populations.

Environmental variables, including publicly available data for mean temperature (maximum, average and minimum), mean pressure at sea level, mean dew point, wind speed, elevation, latitude, and longitude were sourced from the nearest national weather stations using the GSODR R package. For Brazil and Bolivia, data from weather stations was grouped by subregions covered by each National Influenza Centre's subnational data. Brazil included three subregions, and in Bolivia, weather data were divided into La Paz and Santa Cruz subregions.

The study utilised specific standardised WHO case definitions from respiratory surveillance, including Severe Acute Respiratory Infection (SARI), Influenza-like Illness (ILI), and Acute Respiratory Infection (ARI) (Table 1; Supplementary Table S1)[20](18). Data collection involved a dataset with total specimens tested and test positives for influenza and RSV reported by laboratories weekly. The dataset was stratified by settings (ambulatory and in-hospital), surveillance types (SARI, ILI, ARI), or diagnostic tests (immunofluorescence, PCR) where possible.

We included de-identified datasets from routine surveillance evaluation and reporting to global platforms. The research protocol was reviewed for the University of Edinburgh Sponsorship and approved by ACCORD sponsor number AC19121 and ethics approval was obtained from the Pan American Health Organization Ethics Review Committee (PAHOERC).

Time series and seasonality analysis

Exploration of time series and missing data

Descriptive and time-series analysis characterised RSV activity through STL decomposition for trend and seasonal subtractions, test for trends (Spearman's rank correlation rho) and seasonality using Stata IC15[21] and R. Tableau and Excel were used for data visualisation. The analysis of missing data were determined with ImputeTS CRAN R package. Low

Country	Surveillance strategy	Case definitions used	Testing approach	Setting	RSV/ Influenza surveillance	RSV study years	Influenza Study years	Years of RSV data	Years of influenza data
Argentina	Sentinel national	SARI, ILI, ARI	Mol/IF	A, H	Yes	2010–2019	2010–2019	10	10
Aruba	Sentinel	SARI, ARI	Mol/IF	A, H	Yes	2015–2019	2015–2019	5	5
Barbados	Sentinel	SARI, ARI	Mol/IF	A, H	Yes	2012–2019	2012–2019	8	8
Belize	National	SARI, ILI, ARI	Mol/IF	A, H	Yes	2018–2019	2018–2019	2	2
Bolivia	Sentinel National	SARI ARI	Mol/IF	A, H	Yes	2010–2019	2010–2019	10	10
Brazil	National Sentinel	SARI ILI	Mol/IF	A, H	Yes	2010–2019	2010–2019	10	10
Canada	Sentinel National	SARI, ILI ARI	Mol/IF	A, H	Yes	2013–2019	2010–2019	7	10
Chile	Sentinel	SARI, ILI	Mol/IF	A, H	Yes	2011–2019	2010–2019	9	10
Colombia	Sentinel National	SARI, ILI ARI	Mol/IF	A, H	Yes	2010–2019	2010–2019	10	10
Costa Rica	Sentinel	SARI, ILI, ARI	Mol/IF	A, H	Yes	2010–2019	2010–2019	10	10
Cuba	National	SARI, ILI, ARI	Mol/IF	A, H	Yes	2010–2019	2010–2019	10	10
Dominican Republic	Sentinel National	SARI, ILI ARI	Mol/IF	A, H	Yes	2010–2019	2010–2019	10	10
Ecuador	Sentinel	SARI	Mol/IF	H	Yes	2010–2019	2010–2019	10	10
El Salvador	Sentinel National	SARI, ILI ARI	Mol/IF	A, H	Yes	2010–2019	2010–2019	10	10
Guatemala	Sentinel National	SARI, ILI ARI	Mol/IF	A, H	Yes	2010–2019	2010–2019	10	10
Haiti	Sentinel National	SARI, ILI ARI	Mol/IF	A, H	Yes	2015–2019	2013–2019	5	7
Honduras	Sentinel National	SARI, ILI ARI	Mol/IF	A, H	Yes	2010–2019	2010–2019	10	10
Jamaica	Sentinel	SARI, ILI	Mol/IF	A, H	Yes	2018–2019	2018–2019	2	2
Mexico	Sentinel	SARI, ILI, ARI	Mol/IF	A, H	Yes	2010–2019	2010–2019	10	10
Nicaragua	Sentinel National	SARI, ILI, ARI	Mol/IF	A, H	Yes	2010–2019	2010–2019	10	10
Panama	Sentinel National	SARI, ILI, ARI	Mol/IF	A, H	Yes	2010–2019	2010–2019	10	10
Paraguay	Sentinel National	SARI, ILI, ARI	Mol/IF	A, H	Yes	2010–2019	2010–2019	10	10
Peru	Sentinel National	SARI, ILI, ARI	Mol/IF	A, H	Yes	2010–2019	2010–2019	10	10
Saint Lucia	Sentinel	SARI, ILI, ARI	Mol	A, H	Yes	2015–2019	2015–2019	5	5
Suriname	Sentinel	SARI, ILI, ARI	Mol/IF	A, H	Yes	2013–2019	2012–2019	7	8
Trinidad and Tobago	Sentinel National	SARI ILI, ARI	Mol	A, H	Yes	2015–2019	2015–2019	5	5
United States of America	Sentinel National	ILI SARI	Mol/IF	A, H	Yes	2013–2019	2011–2019	7	9
Uruguay	Sentinel	SARI, ILI	Mol/IF	A, H	Yes	2010–2019	2010–2019	10	10
Venezuela	National	SARI	Mol/IF	H	Yes	2010, 2011, 2015–2019	2010, 2011, 2015–2019	7	7

References: Severe Acute Respiratory Infection (SARI); Acute Respiratory Infection (ARI) Influenza-like Illness (ILI); A (Ambulatory) and (B) Hospitalised; (Mol) Molecular and (IF) Immunofluorescence. (Source: Own elaboration based on data reported to FluID, Flunet and the SARINet Plus Network in PAHO, 2022[19]).

Table 1: **Description of the respiratory surveillance systems by country in the Region of the Americas.**

data quality criteria included: missing more than 4% of the annual data (e.g., missing case counts in >2 out of 52 weeks); reporting fewer than three years of data; and >50% of the weeks with no positive samples. Local smoothing regression was available to impute missing values with an optimal window parameter through the ImputeTS R package, but no imputation was necessary. Low quality datasets were excluded from modelling (Supplementary Methods).

Stationarity and seasonal stability testing

Each country's analysis involved stationarity testing and interannual variability assessment of the time series using R script.[22,23] A stationarity assessment of the time series was performed using the Augmented Dickey–Fuller test. To ascertain the stability of seasonal patterns, the Canova and Hansen test (Uroot R CRAN Package) was employed. The Augmented Dickey–Fuller test for stationarity corroborated stationary behaviour ($p < 0.05$), while the Webel and Ollech test (seastests R CRAN Package) assessed whether seasonality existed. The coefficient of variation, calculated as the ratio of standard deviation to its mean, expressed the annual percentage of variability or instability annually and between years. The consecutive disparity index (CValternatives R CRAN Package) compared consecutive values (ranging from 0 for uniform distributions -or little variability-to 1 for high instability between consecutive values) and explored whether RSV seasons were evenly distributed over time.[24]

Seasonality methods

While several methods of variable complexity exist to assess respiratory viruses' seasonality and establish activity thresholds, there is no gold standard, each with different limitations. Three known methods typically applied and recommended in influenza global surveillance were run and compared for viral activity by country. RSV and influenza seasonality were modelled using the WHO Average Curves Method (Moving Average Method), the Negative Binomial Method, and the Moving Epidemics Method (MEM) in parallel to evaluate consistency in timing results. The choice of case counts or proportions depended on country-specific suitability; for the final models and comparison, viral proportions were used rather than case counts to account for differences in testing volume across countries A shared testing algorithm integrated influenza and RSV surveillance data into the analysis. Each country was analysed individually, without cross-country aggregation. Subregions and countries' patterns were compared using these methods. We used Wilcoxon ran-sum tests to assess differences in RSV and influenza seasonality among the three methods by comparing onset, offset, duration of epidemics, and peak values, all represented by epidemiological weeks. One method was selected based on which may represent a country's activity better and surveillance data availability.

The methods -negative binomial regression model,[25,26] MEM,[27] and WHO average curves[28,29] are described in Supplementary Table S2 and available through scripts and online applications. Methods were compared based on appropriateness, with results tabulated and Wilcoxon rank-sum tests applied. Key metrics were calculated, including epidemic period length, onset and offset weeks, peak timing, and coverage, were calculated. These methods' average epidemic curves determined specific weeks above the seasonal threshold, aiding in assessing timing and duration. Additionally, the onset, offset, peak, and duration of RSV and influenza activity were calculated by country. Both negative binomial method and WHO methods allowed for exploring two-wave patterns in countries with more than one peak, while MEM is limited to capturing multiple peaks in a year since it overlaps the peaks regardless of their timing, to analyse epidemics. The timing of the onset, peaks and the epidemic length (in weeks) for RSV proportion and counts obtained by the three methods were plotted and compared through Wilcoxon Signed-Rank test, correlations were assessed between latitude and RSV seasonal onset, offset or duration by method.

Factors associated with RSV seasonality: influenza patterns and environmental variables

Exploratory analysis of simple correlations and regression models assessed environmental relationships between RSV seasonality (represented by the case counts and the proportion of positives) and environmental factors, including mean average, maximum and minimum temperature, mean pressure at sea level, mean dew point, wind speed, elevation, latitude, longitude, and seasonality component. Meteorological data source from the nearest weather station using the GSODR R package. Eighteen countries out of thirty-one with modelled RSV season reported environmental variables for 2010–2019. Countries and years without data were excluded. Figures and statistics were summarised for temperature, elevation, average pressure at sea level, average dew point (included to replace humidity), wind speed, and total precipitation (in mm). To avoid introducing bias in the regression models by using sentinel and national datasets in the same country, we excluded the following datasets from uni- and multivariate analyses: SARI or ILI sentinel surveillance datasets from Bolivia–La Paz, Chile, Cuba, Paraguay, Ecuador, Uruguay. Relationships between RSV seasonality with environmental predictors were examined by combining weighted least squares (WLS) stepwise models and quantile models.[30] Homoscedasticity was checked using the Breusch–Pagan test and non-multicollinearity through a variance inflation factor. Variance distribution among final predictors was also assessed. Based on a WLS fit model, a quantile regression model explored trends across all data ranges for quantiles 50, 75, and 95 and accounted for heteroscedasticity in environmental predictors.[31,32] This approach provided more detailed insights for climate analysis than traditional regression, which only focuses on the average trend using the weighted least-squares method.[31] The WLS model predictors included influenza-positive case counts, precipitation, pressure at sea level, average temperature, longitude, elevation and a seasonality component. To

address the heteroscedasticity, a final quantile regression model based on the WLS results further explored the same predictors against RSV activity for a wider outcome distribution and its coefficients at Q50, Q75 and Q95. This final model aimed to clarify RSV-influenza interactions and variation:

$$\text{Count of samples RSV positives} = \alpha + \beta_1\ \text{mean temperature} + \beta_2\ \text{precipitation} + \beta_3\ \text{longitude} + \beta_4\ \text{elevation} + \beta_5\ \text{sin}_{\text{week}} + \beta_5\ \text{Pressure at sea level} + \beta_6\ \text{Count of samples Influenza positive}$$

The final dataset and k = 20-fold quantile regression model were used for cross-validation. The quantile regression plots were compared with the weighted least squares (WLS).

All data analyses were done using R software (version 4.0.5). The R codes for the analysis are available online, and the methods described in "Supplementary Methods".

Role of the funding source

No role in the study, publication costs only were supported.

Results

Descriptive analysis of respiratory surveillance data

Comprehensive virological surveillance data for RSV and influenza exist in the Americas. Data from 51 national laboratories across 32 countries (including all subregions) spanning 2010 to 2019, were included in the analysis based on sample sufficiency for modelling seasonality (Table 1, Figs. 1 and 2). From epidemiological week (EW) 1, 2010 to EW 52, 2019, countries and territories reported 14,308,503 respiratory samples tested for RSV, influenza and other respiratory viruses to Flunet/PAHO. A cumulative total of 1,812,295 samples tested positive for influenza (12.67%), and 446,648 were RSV-positive (3.12%).

The North American region contributed significantly, reporting 12,013,434 samples (83.96% of the total), predominantly from the U.S.A. and Canada. Brazil and the Southern Cone accounted for 1,645,463 samples (11.5%). These subregions documented 129,750 (29.05%) and 262,569 (58.79%) RSV-positive samples, respectively. The Southern Cone reported the highest RSV percentage of positivity (58.79%), followed by the Andean subregion (5.76%) and Central America (4.77%). The Caribbean subregion (1.63%) reported the lowest percentage and cumulative number of RSV-positive samples from respiratory cases (7263 cases). Argentina, Chile and Canada reported the highest cumulative RSV counts (164,393, 68,523 and 94,040, respectively) (Supplementary Table S3).

The distribution of respiratory cases from surveillance included 778,919 confirmed cases of influenza A non-subtyped (42.98% of influenza-positive samples) and 391,622 cumulative samples positive for influenza B of undetermined lineage (21.61%). 340,143 cases of influenza A (H3N2) (57.27%) and 253,718 cases of A (H1N1)pdm09 (42.7%) predominated among the subtyped samples. Influenza B Yamagata predominated among samples where lineage was determined. The influenza positivity percentages varied by country, with

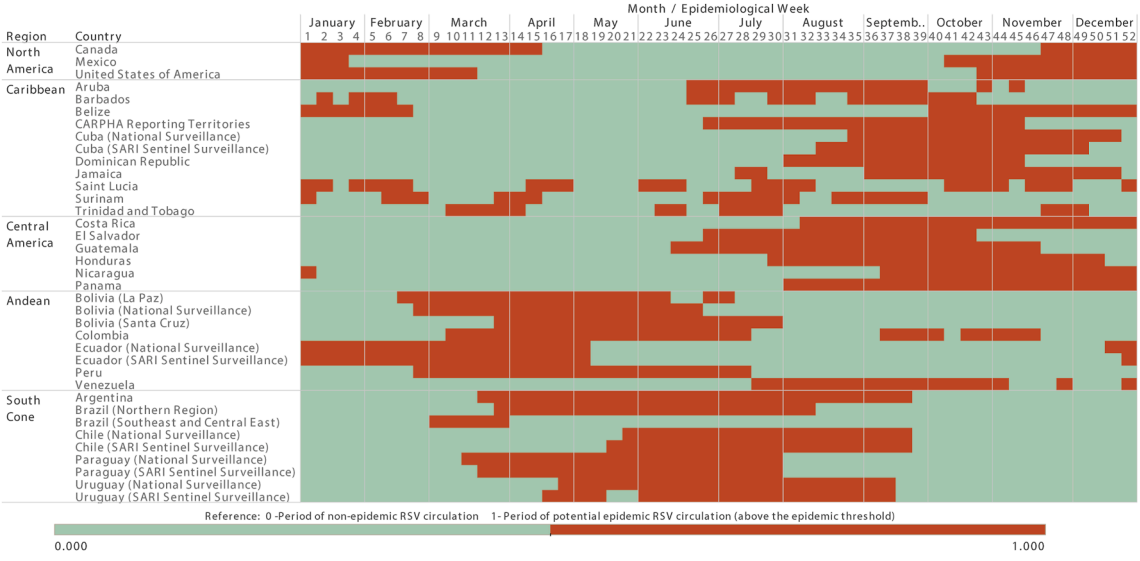

Fig. 1: Timing of RSV season by median start and median length in epidemiological weeks, based on the WHO Average curve method resulted from the 2010–2019 period, by country and subregion. (Source: Own elaboration based on seasonality results from WHO/PAHO data).

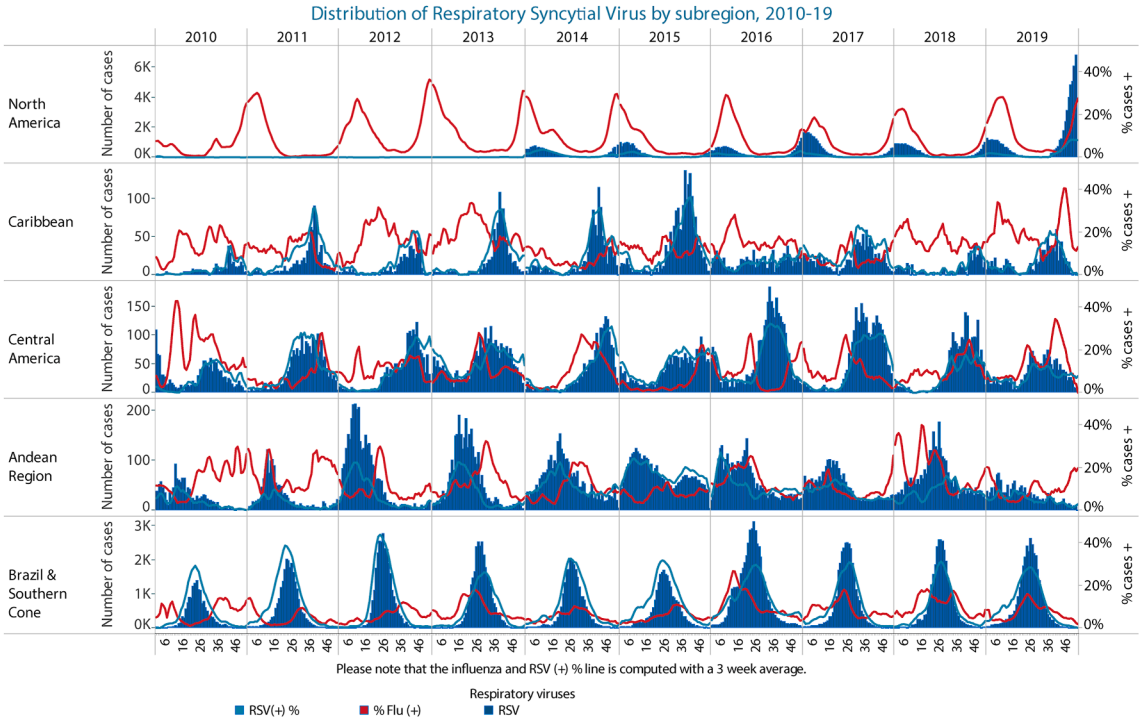

Fig. 2: Distribution and percentage of positivity for Respiratory Syncytial virus by subregion, 2010–2019. (Source: Own elaboration based on data reported to FluID, FluNet).

differences ranging from 5.7% in Argentina to 29.9–36.3% in Caribbean countries, linked to their surveillance system robustness (Fig. 2, Supplementary Table S3, Supplementary Fig. S1).

Time series and seasonality

Exploration of time series and missing data

Time series analysis was undertaken across 46 countries and territories. The non-parametric Spearman test revealed non-significant results ($p > 0.05$) for linear trends in each series. A linear trend test was conducted on mean RSV against day/week/month numbers to ascertain the need for detrending due to significant linear trends within the dataset. Supplementary Table S4 and Fig. 3 detail the time series decomposition of RSV activity by country. Seasonal RSV patterns varied from 1.2 to 15.5 across 29 countries, with no significant changes during stability tests, supporting stable seasonal patterns throughout the study period. The Augmented Dickey–Fuller test indicated that RSV activity is stationary, with an average test statistic of −5.2 and all p-values below 0.01. Trend analysis revealed a statistically significant positive monotonic trend in most countries, while negative trends were noted in Barbados, Brazil, Chile, Colombia, and Guatemala. The annual coefficient of variation averaged over 60%, indicating considerable annual RSV variability. The mean consecutive disparity index was 0.5, reflecting instability in RSV activity between consecutive years. No significant temporal correlation was in year-to-year activity.

Missing data were higher in the Caribbean and specific surveillance datasets (e.g., Uruguay ILI and SARI surveillance) due to fewer tested cases and reported seasons. No imputation was applied. Low-quality national or subnational RSV or influenza data were excluded from seasonal modelling. Thirty-eight time-series datasets (national and subnational) were included, while thirteen of 51 datasets (25%) were excluded for low quality: eight datasets with <3 years of data; five with >50% weeks lacking RSV-positive samples; and six with >4% missing annual data (Supplementary Table S3). The Supplementary Results detailed the flowchart and data selection process.

RSV seasonality analysis by subregion

In North America, the average onset of RSV seasons across different years surpassed the epidemic threshold in late September-early October (around week 40), spanning 15–22 weeks across the years and peaking in early December to early January. Peaks occurred between weeks 49 (Mexico) and 1 (Canada and the USA). On average, Central America exhibited RSV onset in mid-July (week 29), lasting 4–6 months (from 16 to 24 weeks). Peaks occurred between mid-August and late November, around weeks 33

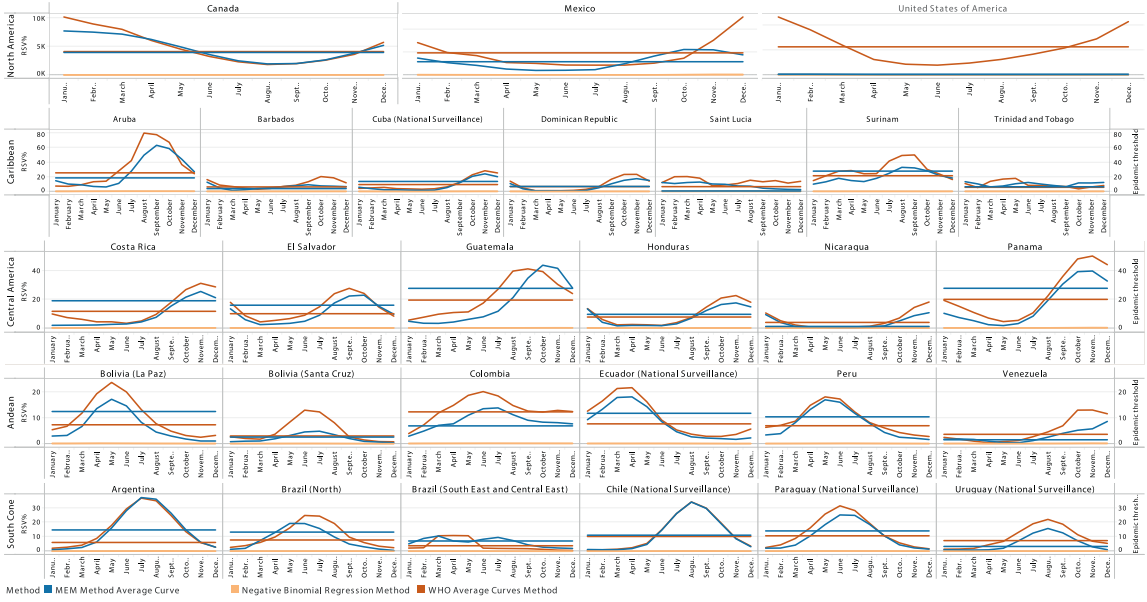

Fig. 3: RSV seasonality—Estimated average epidemic curves by methods (MEM, WHO Average Curve, Negative binomial) by country.

(El Salvador) and 47 (Nicaragua). The Caribbean experienced an overall late-June RSV onset (weeks 22–25), with 4–5 months (17–21 weeks) span and average peaks in late July and early August. RSV began earlier in Saint Lucia (week 3) and spiked from week 29 in Surinam to week 5 for Saint Lucia). On average, across the years, Caribbean RSV seasonality was less defined and spread more throughout most of the year than in the rest of the region. The Andean subregion displayed an average RSV onset in mid-to-late January (weeks 52–8), lasting 4–5 months (18–21 weeks) and peaking from early-March (week 8) to late June. Ecuador presented the earliest onset (week 52), while Venezuela exhibited the latest (week 29). In Brazil and the Southern Cone, RSV seasons began in early-March (week 9) to late June (week 23), spanning 16 weeks on average with a late peak in July–August. Southeast and Central-Eastern Brazil showed earlier activity in late February–March with longer duration (Figs. 1–3, Supplementary Figs. S4 and S5).

When comparing the timing of RSV onset, peaks and the epidemic length (in weeks) obtained by the three methods, significant negative correlations were observed between RSV onset and latitude (–0.361; CI: –0.610, –0.047) or RSV season duration and latitude (–0.501; CI: –0.705, –0.220) (Supplementary Figs. S6 and S7).

Factors associated with RSV seasonality: influenza patterns and environmental variables

Analysis of RSV seasonality compared with influenza patterns

On average, across different years, RSV and influenza had distinct seasonal patterns and durations across subregions. In North America, influenza activity commenced around week 46, lagging behind RSV (weeks 19–42) and lasting 5–8 months. Influenza peaked in week 3 (Canada) to 7 (USA). Central America initiated around week 23, spanning from 8 up to 29 weeks and peaking at week 31. Nicaragua's analysis of influenza data exhibited late activity (week 35), while Guatemala's was the earliest (week 6), considered integrated surveillance systems while accounting for simultaneous influenza and RSV testing. The Caribbean exhibited average influenza onset at week 19 (weeks 1–37), spanning 15 weeks and peaking at week 26. Trinidad and Tobago exhibited late activity (week 49). Overall, RSV seasons in the Caribbean lagged behind influenza, while in the Andean countries, RSV peaks preceded influenza. The Andean subregion displayed influenza onset at week 22, lasting 17 and up to 22 weeks, with peaks around week 29. Colombia showed early activity (week 16). Brazil and the Southern Cone commenced around week 21, lasting 21 weeks, with peak activity at week 26. Uruguay displayed late activity (week 28), and Brazil's Northern region presented early activity (week 9) (Figs. 1–4, Supplementary Figs. S4 and S5, Supplementary Results).

Association between the RSV seasonality and environmental variables

Eleven countries with latitude $\leq|23.5°|$ mostly represented tropical data (including Costa Rica, Guatemala, Honduras, Panama, Bolivia, Colombia, Ecuador, Brazil, and Peru), followed by temperate and subtropical climate countries (with latitude $>|30°|$ and $|23.6°|$, respectively). Plotted environmental variables over time

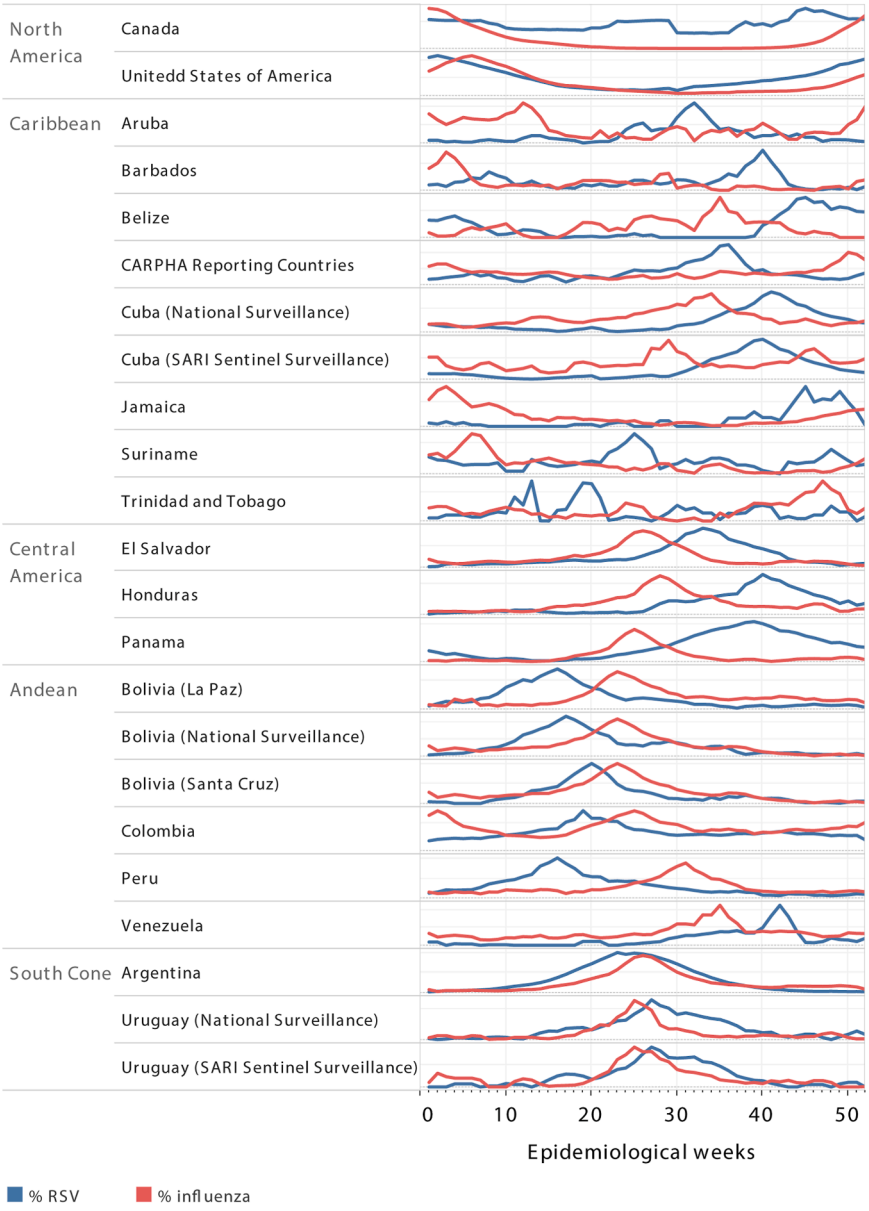

Fig. 4: RSV and influenza seasonality by country: Estimated average epidemiological curves for percentages of positivity using the WHO Average Curves Methods. Note: Further analysis of RSV and influenza seasonality and interactions are in the Supplementary Results. (Source: Own elaboration based on data reported to FluNet and FluID, PAHO/WHO).

by subregion are in the Supplementary Results. RSV counts negatively correlated with average temperature (–0.43; 95% CI: –0.45, –0.41; $p < 0.0001$), total precipitation (–0.04; 95% CI: –0.07, –0.01; $p = 0.0035$), average dew point (–0.36; 95% CI: –0.38, –0.33; $p < 0.0001$), latitude (–0.09; 95% CI: –0.12, –0.06; $p < 0.0001$), and influenza activity (–0.004; 95% CI: –0.034, 0.026; $p < 0.0001$). RSV activity positively correlated with average pressure at sea level (0.15; 95% CI: 0.12, 0.18; $p < 0.0001$), longitude (0.12; 95% CI: 0.09, 0.15; $p < 0.0001$), wind speed (0.04; 95% CI: 0.006, 0.066; $p = 0.018$), and seasonal component (0.06; 95% CI: 0.03, 0.09; $p < 0.0001$) (Supplementary Table S13). While latitude was not included in the model below, it was negatively related to RSV counts, indicating heightened activity in lower latitudes characterised by tropical and subtropical climates.

Quantile regression model results showed several climate variables influenced RSV activity: Lower mean temperatures and higher cumulative precipitation are

associated with increased RSV activity at all quantiles except Q95, where higher precipitation is associated with a decreased RSV activity ($p = 0.011$). All these effects were modest but statistically significant except for precipitation at Q75. Overall, all predictors were either negatively (average temperature, seasonal component, influenza counts and altitude) or positively (pressure at sea level, wind speed and atmospheric pressure) associated with increased RSV activity ($p < 0.01$), including influenza seasonality (counts) at all quantiles. The final quantile regression showed the full spectrum of the relationship between predictors at different or extreme RSV outcomes (Supplementary Table S14; Supplementary Figs. S10 and S11). Lastly, increased atmospheric pressure was associated with increased RSV activity at Q75 and 95 ($p \geq 0.05$) (Supplementary Results).

Discussion

Our study revealed that both Southern and Northern American countries exhibited clear RSV seasonal epidemics, with an average seasonal duration of 4–5 months. Tropical Caribbean countries displayed more year-round spread patterns, with most exhibiting durations of 3–4 months, while others revealed multiple shorter outbreaks. RSV epidemics tended to occur earlier and lasted for shorter durations at higher latitudes, suggesting a potential influence of latitude on the timing of viral activity. In addition, local environmental factors and influenza activity potentially influenced RSV seasonality. Across nineteen countries, RSV circulation positively correlated with lower average temperatures, greater precipitation, higher pressure at sea level and atmospheric pressure. RSV activity also correlated with decreased influenza circulation, increased longitude, decreased elevation, and locations further west. By employing established seasonality methodologies, this study offers a comprehensive view of the seasonal dynamics of these respiratory viruses across the region. The results, with non-statistically significant differences in seasonality characteristics, underscore the overall suitability of all these methods in periodically monitoring RSV and influenza seasonality through surveillance data.

Comparing these findings with those from published peer-reviewed analyses of RSV and influenza seasonality in the Americas highlights the consistency of the patterns observed. During the cold months, RSV cases occur in places with high rainfall, such as Chile.[33] In tropical and subtropical countries with seasonal rainfall, higher RSV activity was described during the hot and rainy rather than the cold seasons.[34] Previous studies by Obando-Pacheco (2018) analysing the RSV seasonality demonstrated similar patterns to the current analysis, where RSV seasons started in the south and moved to the north. The season's onset in the Southern Hemisphere began between March and June, while in countries in the Northern Hemisphere, it began between September and December. Similarly, the duration of the activity in both hemispheres was 5–6 months. In contrast, countries with rainy seasons presented more extended RSV activity, up to 10 months, reinforcing the validity of these findings.[3]

Our results are similar to several published studies exploring the onset of RSV seasons in relation to geographic location and altitude, where seasonal epidemics tend to appear in clusters.[13,34,35] A global review of geographical variations in RSV seasonality showed that it typically peaked in winter months in temperate countries, with variable patterns in the tropics. The timing of seasonal epidemics presented latitudinal gradients, with peak timing occurring later with increasing latitude. 80% of tropical locations experienced a 6-month or less RSV season. While data on seasonal patterns may be limited in under-sampled tropical areas, respiratory virus surveillance quality and reporting among SARINet Plus network countries during recent years has increased, predominantly in Central America and the Caribbean. In temperate climates, higher RSV activity during cold months was related to increased indoor crowding, enhancing viral transmission and increasing viral stability and host susceptibility.[13,34,35]

Recently, Li and colleagues developed a prediction tool to assess the onset month of local influenza and RSV epidemics to supplement surveillance data. Based on this predictive model, global and regional patterns of viral activity showed that influenza and RSV patterns differ in timing and duration of the epidemics and between hemispheres. RSV activity presented a latitudinal gradient in the timing of epidemics and initiated later with increasing latitude. Likewise, for countries with a range of climate patterns, the study showed that epidemics varied within those countries.[14] Our findings in the subregion and within countries such as Brazil and Bolivia, which have heterogeneous climate patterns, are closely aligned with those reported by Li et al. In temperate climates, RSV regularly causes community outbreaks in the Northern and Southern hemispheres in the fall, winter, and spring months. Nevertheless, a substantial variability is present in the timing and duration of outbreaks.[36] The seasonal trends of RSV in the tropics still requires further study, though there is a clear seasonal pattern. Despite the absence of a winter season, there were consistent seasons of RSV infection. These seasons are less defined than in temperate areas. Like data from other countries in the Caribbean subregion analysed in this study, data from Suriname (3.9° N) exhibited RSV activity all year round, with no distinct evidence of seasonal peaks. Our analysis identified seasonal patterns of RSV and influenza for tropical regions with more than eight years of reported data. Strengthening integrated surveillance

systems in those countries allows for a better understanding of seasonality in the tropics and the possibility of presenting multiple annual peaks of RSV and influenza activity.

One significant aspect of this study is its reliance on sustainable routine respiratory surveillance in the SARI*Net* Plus Network countries, which can play a pivotal role in operational research and evidence-based policymaking. The use of standardised integrated surveillance testing laboratory protocols and case definitions following WHO recommendations for respiratory surveillance allowed for comparability across the region.[37] This approach enhances the study's credibility and utility in guiding public health decisions and interventions. It provides guidance on the timing for RSV vaccines and monoclonals and monitoring of effectiveness through existing routine surveillance.

Despite the strengths of this study, it was not without limitations. The use of aggregated data without individual identifiers may have limited the granularity of analysis and reduced the precision of timing estimates, such as epidemic onset and duration. A convenience sampling approach inherent in routine surveillance could introduce biases in generalising findings while ensuring annual monitoring among national teams.

Additionally, the reliance on available data sources might have resulted in incomplete or skewed representations of RSV and influenza activity due to missing seasons or underreporting in certain years. This could introduce regional imbalance or limit the generalisability of our findings to countries with weaker surveillance systems. To mitigate these issues and preserve reliability of seasonal patterns, we applied inclusion criteria for data quality. While residual data quality differences may still introduce some uncertainty, they are unlikely to substantially alter the identified seasonality patterns. Similar limitations were highlighted by Li et al. (2019), emphasising the need for careful interpretation and contextualisation of the findings within the limitations of the surveillance data sources. According to a study by Suryadevara et al. (2021), reports from tropical countries in South America that describe results from RSV surveillance studies performed for more than one season are scarce. Where available, such studies have shown that RSV seasonality varies by country and geographic regions of the same country. Since most reports included small numbers collected over a year, comparisons of trends or patterns across different countries or regions may need multi-year data to be collected from larger-sized cohorts or established surveillance systems.[38] Future research could address these limitations with individual patient data or through comprehensive sampling strategies to target specific age-groups and explore the impact of other factors, such as demographic or socioeconomic variables, on RSV and influenza dynamics in at-risk populations. A recently study analysing the association between socioeconomic factors and RSV season timing provides valuable context for future research.[39] Comparative studies, including different regions and the Americas in similar latitudes, could provide insights into the variability of RSV seasonality and inform more targeted interventions.

Furthermore, the methods used for seasonality assessment have a number of potential limitations. These approaches (MEM in particular) may not fully capture the complex two-wave patterns observed in certain countries, such as Brazil, or Caribbean territories with tropical climates. Although all three methods provided valuable insights, they could potentially overlook nuanced variations in the timing and shape of seasonality patterns. In countries with multiple peaks, MEM often merged or overlapped peaks, regardless of when they occurred, limiting its utility to assess timing across distinct epidemic waves—though it remained suitable for evaluating overall epidemic thresholds. To compare the performance across, we performed Wilcoxon-rank-sum tests. To minimise risk of oversimplification, we selected the most representative method for each country and considered the results from the WHO average curves method better captured seasonal complexity.

Quantile regression offered a more suitable approach for exploring the association between RSV and environmental predictors, under conditions of heteroscedasticity. Unlike other regression analyses, namely WLS, it revealed non-uniform effects across different levels of RSV activity. For instance, precipitation showed a positive association with RSV activity at lower and mid quantiles and a negative association at the Q95. These findings suggest uneven effects of predictors across different RSV levels. Such variability likely reflects additional, unmeasured factors not included in this study—such as changes in healthcare-seeking behaviour, indoor crowding, affected reporting practices or the implementation of public health interventions triggered public health interventions—that merit further investigation.

Diverse RSV patterns across subregions, influenced by latitude and climate, highlighted the need for tailored interventions and future vaccination strategies. This study provides essential evidence for health policy decisions by integrating surveillance data and environmental factors. The findings may foster collaborations, enhance regional surveillance networks and optimise the timing for evidence-based strategies to mitigate the impact of RSV infections in vulnerable populations, ultimately contributing to effective disease management.

In conclusion, this study's comprehensive analysis of RSV and influenza seasonality within the Americas significantly contributes to our understanding of these respiratory viruses' transmission dynamics. By leveraging and strengthening routine sustainable

respiratory surveillance networks, the study provided insights for evidence-based policymaking and set the framework for future RSV control and prevention strategies. A comprehensive understanding of the regional variability in RSV seasonality is essential for monitoring preventive, control and response strategies. These findings from sustainable RSV surveillance are pivotal in informing decisions within the Region's technical advisory groups, Ministries of Health, and scientific societies.

Contributors

PC had full access to all the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis.

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All authors have reviewed and approved the final version of the manuscript.

PC and HN were responsible for the decision to submit the manuscript for publication.

Members of the *Sarinet Plus Network contributed to data provision, data verification and interpretation, and reviewed the final version of the manuscript.*

Data sharing statement

All relevant data are provided in the paper and its supporting information files. Country data is only available by request.

Declaration of interests

All authors have submitted an ICMJE COI form and signed a completed Author Statement Form. PC, MR, JL, AR, AV report no conflicts of interest. HN reports no support for the present manuscript, grants or contracts to institution from NIHR, IMI, MSD, AstraZeneca, Pfizer, and WHO Geneva outside the submitted work, consulting fees to institution from AstraZeneca, Pfizer, GSK, Sanofi outside the submitted work, honoraria for lectures and presentations to institution from Pfizer outside the submitted work. HC reports support from the University of Edinburgh as the main employer, grants or contracts to institution from NIHR Global Health Research Unit funding, and MRC Mental Health Hub funding outside the submitted work, consulting fees from WHO paid via the main employer outside the submitted work. YL reports no support for the present manuscript, institutional grants from GSK, MSD and WHO outside the submitted work, consulting fees from WHO, Pfizer and GSK outside the submitted work, honoraria from Pfizer and MSD outside the submitted work, and support from Sanofi, MSD, and Pfizer for attending meetings or travel outside the submitted work.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.lana.2025.101166.

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