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Climate-driven Spatiotemporal Dynamics of Dengue Transmission in Southern Brazil: Integrating Entomological Surveillance and Random Forest Prediction

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Abstract

Climatic variability is closely linked to dengue transmission; however, its integration with entomological surveillance and machine-learning models remains poorly explored in subtropical regions of South America. This study evaluated the predictive performance of Random Forest models combining meteorological variables, entomological surveillance data , and lagged epidemiological series to predict dengue transmission across four distinct subtropical municipalities in Santa Catarina, southern Brazil, during 2014–2023.

Entomo-epidemiological data were obtained from the Diretoria de Vigilância Epidemiológica de Santa Catarina (DIVE/SC), while climate data (temperature and precipitation) were obtained from the Instituto Nacional de Pesquisas Espaciais (INPE) and the National Centers for Environmental Prediction (NCEP). The Artificial Intelligence approach was implemented in Python 3, to predict dengue cases based on climatological elements, vector proliferation (breeding sites), and lagged epidemiological data. Spatiotemporal analysis revealed marked regional

heterogeneity: dengue transmission was concentrated in coastal and western zones within optimal vector thermal ranges (22°C–32°C), with epidemic peaks occurring earlier in the western region (weeks 12–16 in Chapecó) than on the coast (weeks 16–20). Therefore, predictive performance varied substantially across regions, achieving high accuracy in Chapecó (R^2 = 0.82) but lower efficacy in Florianópolis (R^2 = 0.38). Crucially, the models exhibited a systematic underestimation of extreme epidemic outbreaks when high-incidence historical data were absent from the training sets. These findings demonstrate that regional climatic heterogeneity strongly conditions dengue dynamics, highlighting that locally calibrated predictive models are essential to enhance early warning systems and guide One Health surveillance strategies in subtropical zones.

Keywords: Machine Learning; Early Warning Systems; Subtropical Climate; Epidemiological Surveillance; One Health.

Resumo

Este estudo investiga a relação entre variáveis climáticas, a proliferação de vetores biológicos (*Aedes aegypti* e *Aedes albopictus*) e a ocorrência de dengue em Santa Catarina (2014-2023). O objetivo central foi modelar a dinâmica epidemiológica espaço-temporal em quatro municípios catarinenses (Florianópolis, Itajaí, Joinville e Chapecó) para melhor compreensão e a previsibilidade da transmissão da dengue no Estado. Foram utilizados dados entomológicos e epidemiológicos da Diretoria de Vigilância Epidemiológica de Santa Catarina (DIVE/SC) e dados climáticos (temperatura e precipitação) do Instituto Nacional de Pesquisas Espaciais (INPE) e do Centro Nacional para Previsões Ambientais (tradução livre, *NCEP, National Centers for Environmental Prediction*). Utilizou-se uma abordagem de modelagem baseada em Inteligência Artificial com o algoritmo *Random Forest Regressor*, processado em *Python 3*, para prever casos de dengue com base em elementos climatológicos, proliferação de vetores biológicos e defasagem de casos anteriores. Identificou-se que a transmissão é heterogênea, com concentrações nas regiões oeste e litorânea, onde as temperaturas médias situam-se na faixa térmica ótima para o vetor biológico (22°C a 32°C). Os picos de casos ocorrem predominantemente entre as semanas epidemiológicas nº 16 e 20, embora em Chapecó o pico ocorra precocemente (semanas epidemiológicas nº 12 a 16). Os modelos de *Random Forest Regressor* demonstraram viabilidade preditiva, com o maior desempenho em Chapecó (R^2 = 0.82) e o menor em Florianópolis (R^2 = 0.38), revelando uma tendência de subestimação em picos epidêmicos não registrados anteriormente nos dados de treino. As variações climáticas regionais são determinantes na epidemiologia da dengue em Santa Catarina. Embora o modelo *Random Forest Regressor* seja uma ferramenta eficaz para predição, a precisão em anos epidêmicos extremos depende da inclusão de históricos de alta ocorrência para evitar subestimação, ressaltando a necessidade de estratégias de Saúde Única para a mitigação de arboviroses.

Palavras-chave: Aprendizado de Máquina; Sistemas de Alerta Precoce; Clima Subtropical; Vigilância Epidemiológica; Saúde Única.

Introduction

Dengue is one of the most significant public health concerns worldwide, with the disease endemic in more than 100 countries, predominantly across tropical and subtropical regions (WHO, 2025). According to Barth (2010), this arboviral infection is caused by an enveloped, positive-sense single-stranded RNA virus (ssRNA+) of the *Flaviviridae* family and genus *Flavivirus*. Like several other arboviruses, including Zika and chikungunya, dengue is primarily transmitted by mosquitoes of the genus *Aedes* (Meigen, 1818). In Brazil, urban dengue transmission has historically been maintained predominantly by *Aedes aegypti* (Linnaeus, 1762). Dengue has been considered a neglected and reemerging tropical disease in Brazil, with transmission reported in the early twentieth century, followed by several decades of interruption associated with vector eradication efforts, and a subsequent resurgence of endemic and epidemic transmission from the 1980s onward.. More recently, 2023-2024 epidemic season marked a pivotal moment for public health in the Americas, with the region experiencing an unprecedented surge in dengue cases (Rodriguez-Morales *et al.*, 2024). In 2023, Santa Catarina State, southern Brazil, reported 118.922 confirmed dengue cases, with DENV1 identified as the predominant circulating serotype. This represented a 42.38% increase compared with the number of cases reported in 2022. During the same period, the number of *Aedes* spp. breeding sites increased by 9.10%, reaching a total of 73,415 sites in 2023 (Santa Catarina, 2023).

Stolerman, Maia and Kutz (2019) demonstrated associations between dengue outbreaks and climate variables, particularly mean temperature and precipitation, across several Brazilian state capitals including Manaus, São Luís, Aracaju, Salvador, Belo Horizonte and Rio de Janeiro. In addition, their analysis identified mean temperature and precipitation as key predictors for dengue forecasting during winter in selected Brazilian capitals, including Aracajú, Belo Horizonte, Manaus e Rio de Janeiro. Temperature is particularly important for the reproduction and development of *Aedes* spp. mosquitoes, including in subtropical regions such as Santa Catarina (Matiola and Ribeiro, 2020).

In Santa Catarina State, seasonal patterns of *Aedes* spp. proliferation corresponds to temperature fluctuations, with increased activity in warmer months and reductions in colder periods (Matiola and Ribeiro, 2020), even noted in short periods as weekly frequency (Busato e Lutinski 2020, Souza, 2024). In Santa Catarina, the highest occurrence of dengue has been reported in the western region and along the Itajaí River basin, particularly in highly urbanized areas (Silva, 2020). More recently, increased dengue incidence has also been reported around the mouth of the Itajaí River and the metropolitan area of Florianópolis (Menezes, 2024). More recently, increased dengue incidence has also been reported around the mouth of the Itajaí River and in the metropolitan area of Florianópolis (Menezes, 2024). These spatial patterns should be considered in the context of the broader expansion of dengue transmission across the Americas. Rodriguez-Morales et al. (2024) described 2024 as a turning point in the epidemiological situation of dengue in the Americas, with an unprecedented surge in cases and the simultaneous circulation of the four dengue

virus serotypes (DENV-1, DENV-2, DENV-3, and DENV-4). The magnitude of this epidemic was further reflected in Latin America, where nearly two million suspected cases and 656 deaths were reported during the first eleven epidemiological weeks of 2024 (Sansone, Boschiero, and Marson, 2024). Santa Catarina followed this broader regional pattern, experiencing its most significant dengue epidemic during the 2024 season, with 336,986 probable cases, representing a 145.85% increase compared with 2023 (Santa Catarina, 2024).

The high burden of dengue persisted in Santa Catarina in 2025, when nearly 210 probable cases per 100,000 inhabitants were reported and 18 municipalities were classified as being at epidemic level (Azeredo et al., 2025). These recurrent epidemic patterns reflect the complex nature of dengue transmission and dissemination, which are influenced by a convergence of climatic, environmental, and social determinants. The interaction among these factors, together with insufficient or ineffective mosquito control, can contribute to the emergence and persistence of epidemic scenarios (Moreti, 2023).

According to Rodriguez-Morales *et al.* (2024), advancements in biological vector management — *Wolbachia*-carrying mosquitoes and the next-generation insecticides — show great potential for suppressing mosquito populations and curbing the spread of the dengue virus (DENV). However, these technological efforts face significant challenges, as Groskopf (2021) notes, the increase in mosquitoes breeding sites is primarily due to the expansion of urban areas, accompanied by a rise in population density and, consequently, an increase in the availability of breeding grounds for the mosquitoes.

In recent years, the integration of Machine Learning (ML) into public health surveillance has provided new avenues for disease forecasting and the development of Early Warning Systems (EWS) for vector-borne diseases. Initiatives such as Infodengue have advanced climate-based arbovirus nowcasting in tropical Brazil (Lowe et al., 2014; Codeço et al., 2018). However, important gaps remain in understanding how ML algorithms perform when meteorological data are combined with routine entomological surveillance, including indicators of *Aedes* spp. breeding sites activity, particularly in subtropical regions. These regions are characterized by pronounced climatic variability and distinct seasonal patterns of disease transmission, which may limit the transferability of models developed under more homogeneous climatic conditions.

So far, modeling results from Lowe *et al.* (2011) indicate that climatic variables are significantly associated with dengue transmission; although climate covariates alone explain only a limited proportion of the overall variation in dengue cases in Brazil.Additionally, Lowe *et al.* (2014) identified optimum trigger alert thresholds for dengue scenarios of medium-risk (Rio de Janeiro, Belo Horizonte, Salvado and Manaus) and high-risk (Recife, Fortaleza and Natal) by assessing past performance of forecasting system using observed dengue incidence. In this context, Codeço et al. (2018) developed an operational warning system, implemented in 2015, that classifies

environmental and epidemiological conditions according to their potential to support periods of high dengue transmission.

Although climate is recognized as an important determinant of dengue transmission, relatively few studies have integrated climatic variability, entomological surveillance and machine learning approaches to model dengue dynamics in subtropical regions of southern Brazil. To address this gap, we hypothesized that integrating meteorological variables and entomological surveillance data into Random Forest models would provide useful predictive information for dengue transmission in subtropical municipalities. Accordingly, the objective of this study was to evaluate the predictive performance of Random Forest models incorporating meteorological indicators, entomological surveillance data, and lagged epidemiological series to predict dengue transmission in four municipalities of southern Brazil.

Materials and Methods

Study Area

The study area includes four municipalities of Santa Catarina State, southern Brazil: Florianópolis, Itajaí, Joinville and Chapecó. The state is located south of the Tropic of Capricorn, between approximately 25°S - 30°S latitude, and 48°W - 54°W longitude. The state has experienced substantial demographic and urban changes over recent decades. Since the 1980s, its fertility rate has remained below the national average, while population growth has exceeded the national rate, largely driven by sustained migration. Santa Catarina has become an important regional, national, and international destination for migrants (Santa Catarina, 2019). Over the same period, the degree of urbanization nearly doubled, reaching 83.7% in 2015, with the most pronounced population and urban growth occurring in the northern region, the Itajaí Valley, and the area surrounding the state capital, Florianópolis (Santa Catarina, 2019).

The four municipalities were selected to capture contrasting geographic, climatic, meteorological, demographic, and epidemiological characteristics within the state. Chapecó represents the continental western region, whereas Joinville, Itajaí, and Florianópolis are located along the Atlantic coast and represent distinct coastal settings. Georeferenced municipal data for Santa Catarina were obtained from the Instituto Brasileiro de Geografia e Estatística (IBGE), using municipal boundaries updated in 2022 (IBGE, 2022, 2023, 2024).

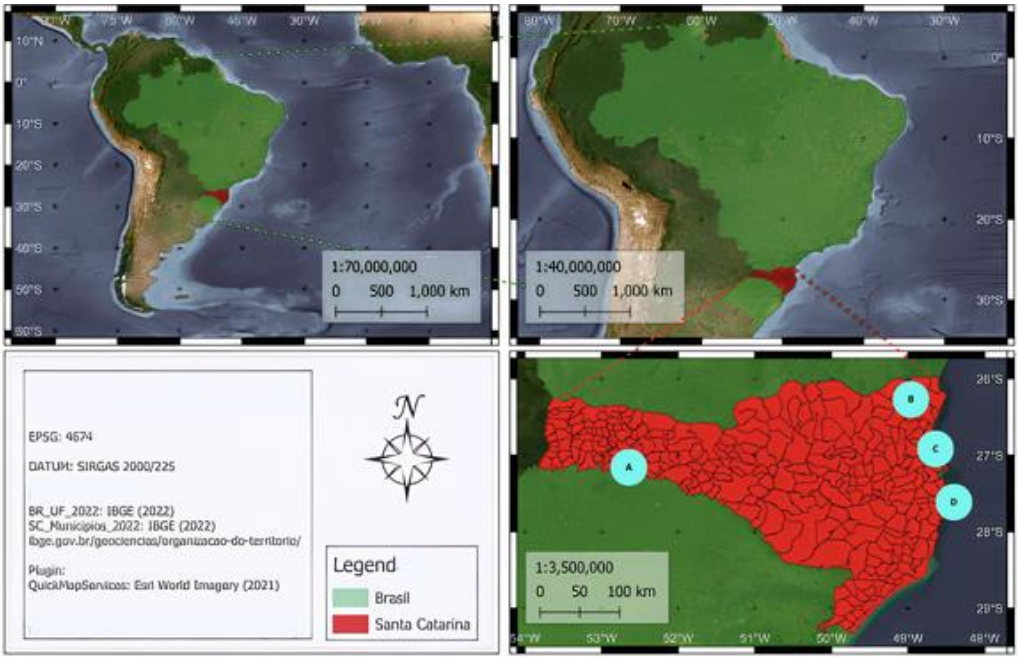
Geographically, the state is bordered by the Atlantic Ocean to the east and the Republic of Argentina to the west. Santa Catarina occupies approximately 1% of Brazil's territory and accounts for about 16% of the total area of the country's southern region (Santa Catarina, 2016b).

The municipalities were selected to represent distinct geographic and climatic settings, as well as meteorological and demographic characteristics, thereby capturing the regional heterogeneity of Santa Catarina in terms of entomological dynamics and dengue epidemiology. Chapecó represents the continental western region of Santa Catarina, characterized by a subtropical climate with earlier spring warming patterns (Figure 1 - A). In contrast, the remaining three municipalities are situated along the Atlantic coastline, capturing different coastal dynamics: Joinville represents the highly urbanized northern coast (Figure 1 - B), Itajaí accounts for the central-northern port and river valley zone (Figure 1 - C), and Florianópolis represents the central coastal metropolitan area subject to intense seasonal population mobility (Figure 1 - D).

Furthermore, these municipalities exhibit contrasting temporal patterns of dengue transmission, with epidemic peaks occurring earlier in the western region (epidemiological weeks 12–16) than in the coastal municipalities (weeks 16–20). Their selection was intended to capture geographic, climatic, and epidemiological

heterogeneity, enabling the assessment of climate-dengue relationships and predictive model performance across contrasting ecological settings of southern Brazil.

Figure 1 - Geographic location of Santa Catarina State (highlighted in red) at three map scales: South America (1:70,000,000), Brazil and state level (1:3,500,000), with the municipalities of Chapecó (A), Joinville (B), Itajaí (C), and Florianópolis (D) highlighted.



Climatic characterization

Santa Catarina, in southern Brazil, has a humid subtropical climate, with substantial spatial and seasonal variability in precipitation and temperature. Mean annual temperatures range approximately from 10°C to 22°C, while mean annual precipitation ranges from approximately 1,100 to 2,900 mm, reflecting differences in elevation, topography and coastal influence (Pereima et al, 2022; Oliveira and Quadro, 2024). Santa Catarina is often classified as temperate or mesothermal, with no distinct dry season and warm summer. Annual precipitation varies across the state, with the highest levels recorded in the eastern region, particularly around the state capital, Florianópolis, and along the northern coast. However, the southern coast area between Araranguá and Laguna, receives the lowest annual precipitation totals (Santa Catarina, 2016a).

Entomological and epidemiological Data

Data on *Aedes* spp. breeding sites through entomological surveillance and confirmed dengue cases were sourced from the Diretoria de Vigilância Epidemiológica de Santa Catarina (Dive/SC) and aggregated by epidemiologic weeks for each municipality.

The number of *Aedes* spp. breeding sites included sites associated with both *Aedes aegypti* and *Aedes albopictus*, as identified through routine. Surveillance activities included weekly check larvae traps, strategic points of vectorial control and others. For better understanding, it was assumed in this paper as *Aedes* spp., including the two species that occur in Santa Catarina, *A. aegypti* and *A. albopictus*. For entomological series obtained start in 2012 and end in 2023, for this analysis.

For epidemiological data, the temporal series obtained start in 2014 and finish in 2023 as well. dengue cases were confirmed by laboratory or clinic-epidemiologic diagnosis and grouped in epidemiologic weeks.

Not all the cities of Santa Catarina have registered cases of dengue and/or occurrence of *Aedes spp.* between this temporal frame, 2014-2023.

Climate-meteorological Data

The climatological elements, including precipitation (mm) and temperatures (ºC) – minimum, mean, and maximum – were obtained from the Instituto Nacional de Pesquisas Espaciais (INPE). Precipitation data were obtained from the MERGE (Merging Technique) reanalysis product, with a spatial resolution of 0.1° and hourly and daily temporal resolutions (ROZANTE et al., 2010; 2020), and are made available operationally (available at http://ftp.cptec.inpe.br/modelos/tempo/MERGE/). Temperatures were obtained from the South American Mapping of Temperature (SAMeT) dataset, which integrates model estimates and observations from weather stations at a height of 2 meters (ROZANTE; RAMIREZ; FERNANDES, 2021) (available online: http://ftp.cptec.inpe.br/modelos/tempo/SAMeT/).

The meteorological prediction variables were obtained from the Global Forecast System (GFS), by the National Centers of Environmental Prediction (NCEP), as reanalysis regression. According to the National Oceanic and Atmospheric Administration (NOAA, 2024), the GFS is the weather forecast model that generates data for meteorological variables. This modeling regression is from Modern-Era Retrospective analysis for Research and Applications, version 2 (MERRA2); and updated to version 16.0 (GFSv16) in march of 2020, which is used by the operational forecasters who predict weather out to 16 days in the future: hourly data for the first five days (0.25º) and three-hourly data until 16 days (0.5º). Its update frequency is four times a day, every six hours, starting at midnight UTC (00, 06, 12 e 18 UTC).

Climatological variables (precipitation, minimum, mean, and maximum temperatures) were extracted for each municipality using the geographic centroids of Florianópolis, Itajaí, Joinville, and Chapecó for the 2000–2023 period. Furthermore,

given the spatial resolution of the climatological datasets (MERGE and SAMeT), the centroid extraction provides a robust proxy for regional meteorological conditions directly influencing the urban disease transmission environment.

The study was carried out following the annual distribution of epidemiologic weeks, as usual for health data, which are routinely reported and aggregated by DIVE/SC.

Analysis and Modeling

The annual mean was derived from the annual distribution of averages of climatological, entomological, and epidemiological variables, returning the averages of the temporal series. Then, from these averages were composed the spatial distribution of each municipality and, from these results, the annual mean was georeferenced on the shapefile of Santa Catarina State (Figure 2).

The annual distribution was derived from the epidemiological week averages of climatological, entomological, and epidemiological variables, returning these averages of each epidemiological week. Then, from these averages were composed the annual distribution of each municipality and, from these results, the annual distribution was referenced on the epidemiological weeks (Figure 3).

Further analysis focused on four cities, these municipalities were eligible to the visualization of the distribution of these variables on this seasonal pattern (Figure 3) and their data were used to synthesized Random Forest predictive models, splitting the training dataset from the beginning to 2022, while the test dataset was reserved from 2023 up to the final (Figure 4).

A strict chronological train-test split was implemented, using the 2014–2022 historical series for model training and reserving the entire year of 2023 as an out-of-sample test set. This temporal separation was specifically selected to prevent data leakage inherent to standard random cross-validation in time-series data and to closely simulate real-world operational forecasting within public health Early Warning Systems (EWS). Evaluating model performance on 2023 provided a robust out-of-time validation under non-stationary conditions, reflecting the capacity of historical models to predict transmission during a period of escalating epidemic intensity.

To model the epidemiological pattern of each municipality were used the number of cases of dengue, as target or dependent variable, and, as features or explanatory variables, climatological elements, proliferation number of *Aedes* spp. and lagged number of dengue cases.

The models' predictive performances were evaluated using Mean Absolute Error (MAE) to measure average prediction accuracy in actual case units, Mean Squared Error (MSE) and Root Mean Squared Error (RMSE) to penalize larger forecasting errors during epidemic peaks, and the Coefficient of Determination (R^2) to quantify the overall proportion of variance explained across differing municipal transmission dynamics.

The Python scripts used in this study are available upon request.

Results

All the variable annual means were shown off in maps (Figure 2). The annual dengue cases revealed some hotspots (Figure 2A), such as the western Santa Catarina (nearby Chapecó) and the Santa Catarina coastal region (near Florianópolis, Joinville and the Itajaí). For the *Aedes* spp. proliferation, the annual mean showed a widespread distribution across the State, even in colder regions (Figure 2B). The annual precipitation was relatively uniform (Figure 2C), while temperatures (minimum, mean and maximum) gradients highlighted colder central regions and warmer areas, such as the coastal, western, and Itajaí river valley (Figures 2D, 2E and 2F).

In Florianópolis, Itajaí and Joinville, dengue cases peaked in austral autumn, between 16th and 20th epidemiological weeks (Figure 3), whereas Chapecó reached its highest point some weeks earlier, between 12th and 16th epidemiological weeks (Figure 3D). All these cities have the development of *Aedes* spp. on intraseasonal cycles, yet the highest values appear after the warmer period of the austral summer. The precipitation in these cities remained consistent year-round.

The Random Forest models demonstrated predictive viability and efficacy (Figure 4). When the greatest number of dengue cases is used on the training dataset, the prediction may reach this outbreak, as shown in Chapecó (Figure 4G). However, the models simulated the highest values trained, as the epidemiological behavior in Florianópolis, Itajaí and Joinville, where the greatest value appeared only in 2023 (Figures 4A, 4C and 4E, respectively). So, underestimation occurred during extreme outbreaks.

In the four municipalities, the Random Forest models for dengue cases concentrated the distribution of errors close to zero (Figure 4). Particularly for Florianópolis and Joinville, there is a rightward shift of the mean relative to the median, indicating outliers in the errors on the positive side (Figures 4B and 4F, respectively). Consequently, the models are underestimating the predictions, failing to capture the highest observed values, which is consistent with the low coefficient of determination (R^2).

Table 1: Statistical metrics for Random Forest prediction of the four municipalities modeling.

Florianópolis	27.01	190.14	[10.59; 43.44]	32.29	36,813.19	191.87	0.38
Itajaí	1.01	29.22	[-1.52; 3.53]	7.35	853.03	29.21	0.78
Joinville	7.97	282.15	[-16.41; 35.35]	72.58	79,519.87	281.99	0.76
Chapecó	3.35	38.3	[0.04; 6.66]	6.7	1,475.53	38.41	0.82

The statistical metrics for the four municipalities reveal the varying performance of the Random Forest models used to predict dengue transmission based on climate variables, mosquito proliferation, and lagged cases (Table 1). Chapecó exhibited the highest predictive efficacy with a R^2 of 0.82. In contrast, Florianópolis showed the lowest R^2 (0.38) and significant error values (MAE of 32.29). Joinville also demonstrated high absolute error metrics (MAE of 72.58 and RMSE of 281.99) and showed predictive viability ($R^2 = 0.76$), as Itajaí ($R^2 = 0.78$).

Figure 2 - Annual mean of dengue cases (A), Aedes spp. proliferation (B), and the climatological elements (precipitation (mm) (C), minimum temperature (D), mean temperature (E), and maximum temperature (F) in Santa Catarina State.

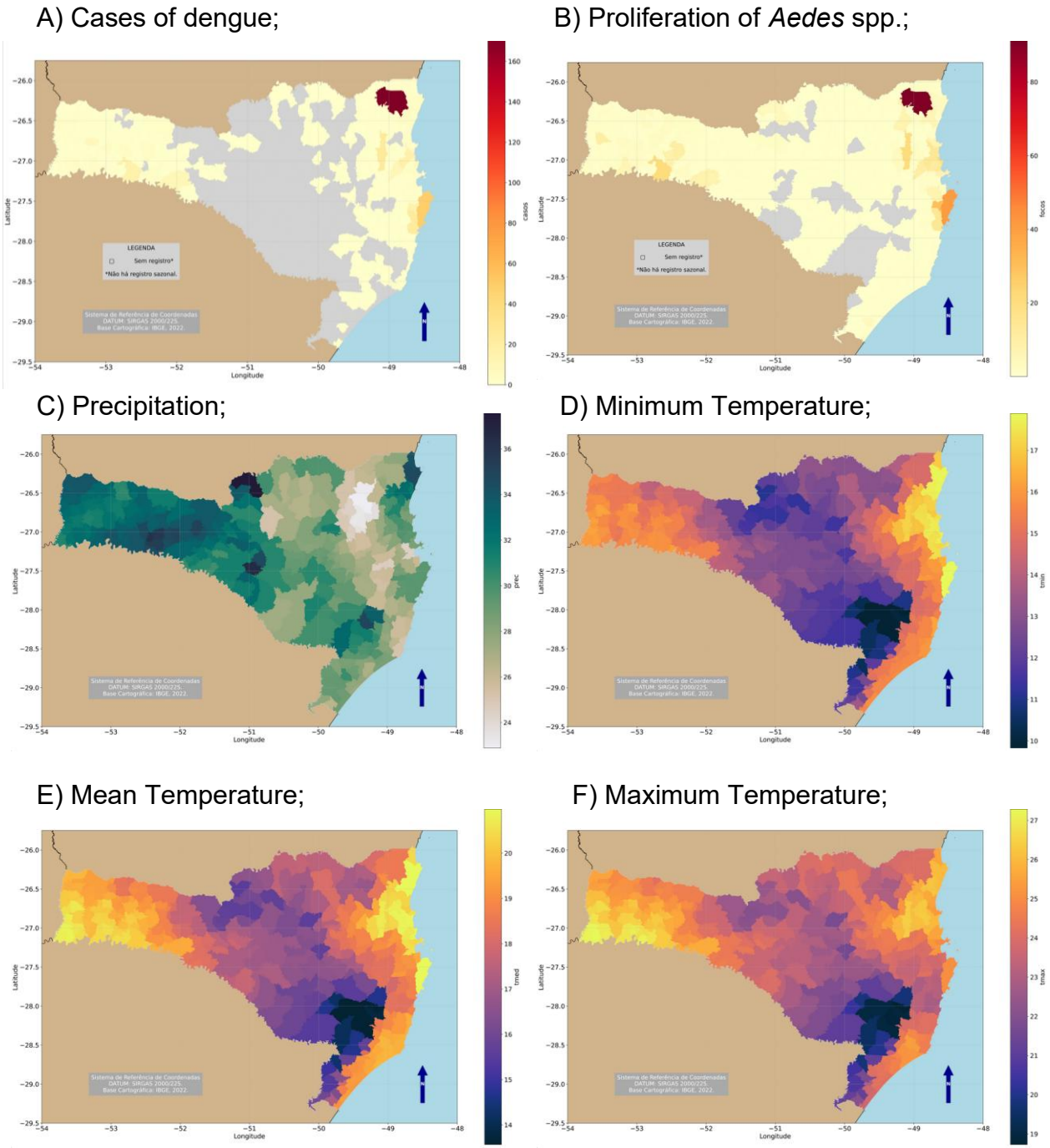
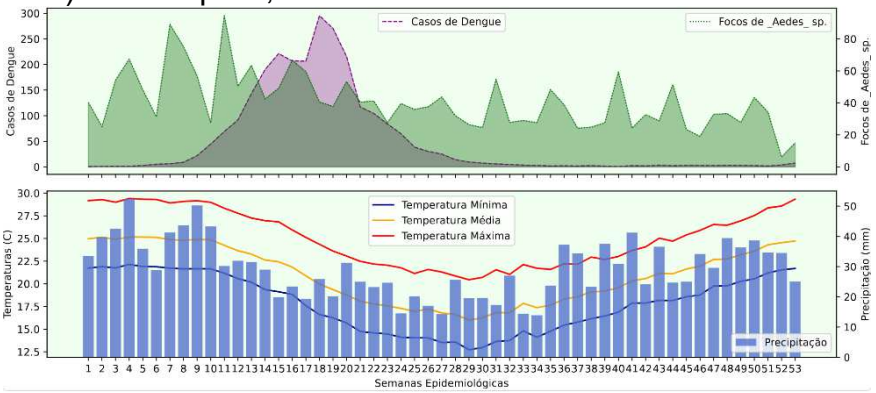
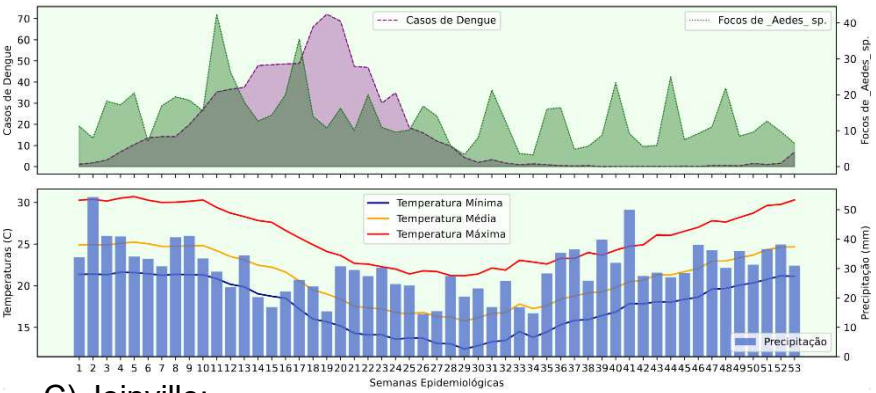


Figure 3 - Annual distribution (in epidemiological weeks) of climatological elements (precipitation (mm) and temperatures (°C) - min., mean and max.), proliferation number of *Aedes* spp. and number of cases of dengue for Florianópolis (A), Itajaí (B), Joinville (C), and Chapecó (D).

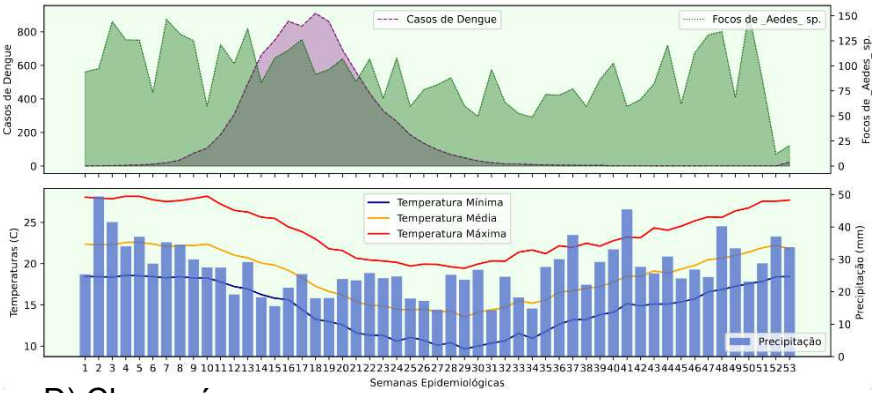
A) Florianópolis;



B) Itajaí;



C) Joinville;



D) Chapecó;

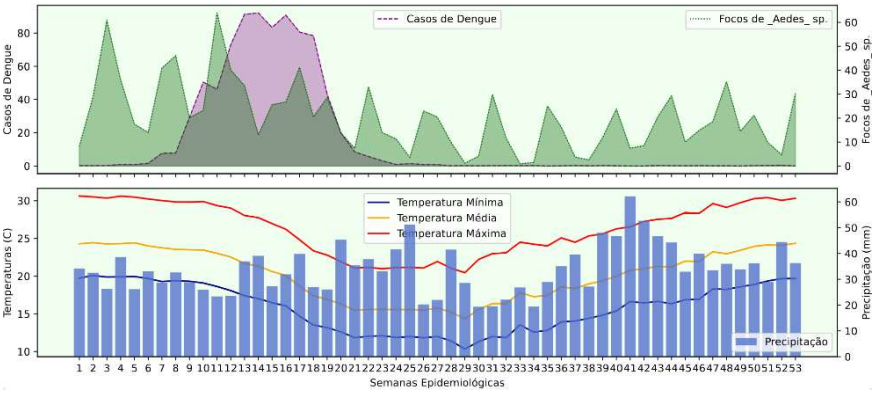
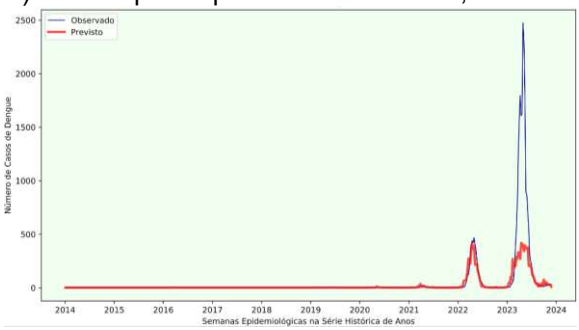
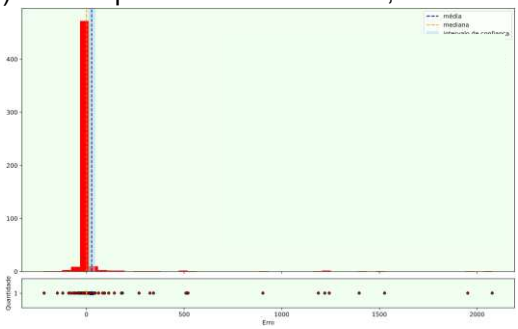


Figure 4 - Modeling dengue in epidemiological weeks from Random Forest Models. Graphical representations of forecast versus observed values in the left column and error distributions in the right column for the four cities in the Santa Catarina state.

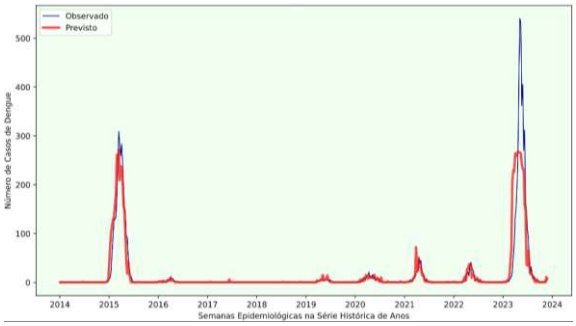
A) Florianópolis - predicted x observed;



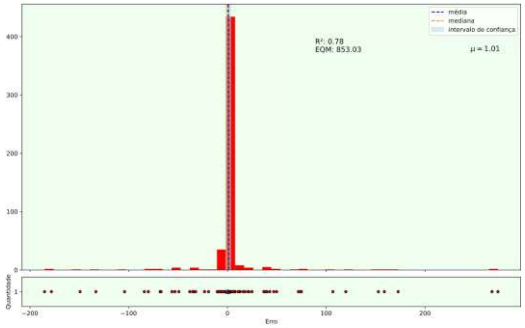
B) Florianópolis - error distribution;



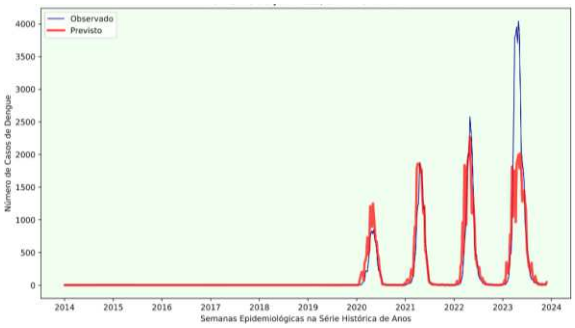
C) Itajaí - predicted x observed;



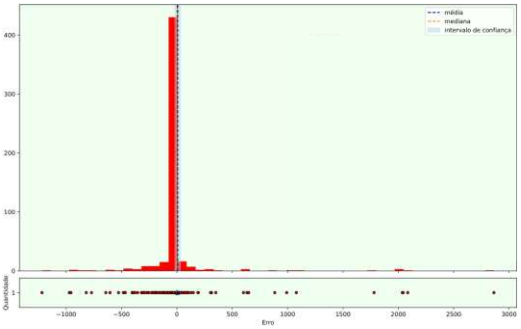
D) Itajaí - error distribution;



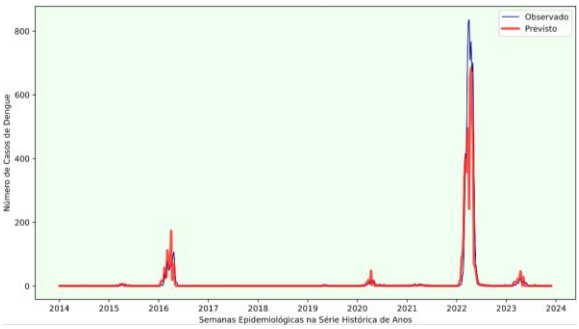
E) Joinville - predicted x observed;



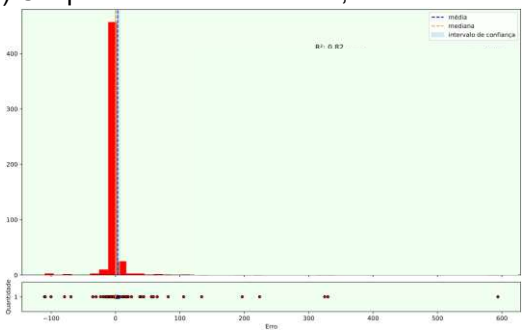
F) Joinville - error distribution;



G) Chapecó - predicted x observed;



H) Chapecó - error distribution;



Discussion

As Valle, Pimenta e Cunha (2015) observed, the extrinsic incubation period and the development of dengue virus are temperature-dependent. This temperature dependence shows regions of greater values of dengue cases, such as western and coastal regions of Santa Catarina State, and regions that poorly register cases, such as highlands and mountain ranges.

About the higher temperatures, Oliveira (2023) reported, the Santa Catarina coast presents extreme values of temperature near 40 °C degrees during the austral summer. As well as, the western region of Santa Catarina presents extreme temperatures, above 35 °C, earlier, in the austral spring. The anticipated behavior of increasing outbreaks of dengue in the west can be attributed to this early temperature pattern (Souza, 2024). Conversely, the highlands of Santa Catarina presents minimum temperatures outliers below -5 °C during the austral winter (Oliveira, 2023).

Referring to the development of *Aedes* spp. in the State of Santa Catarina, the distribution of the mosquitoes is similar to the occurrence of dengue cases, where the higher numbers are observed in the coastal and western regions. In fact, Beserra *et al*. (2009) confirmed the optimal temperature for the development of the mosquitoes of genus *Aedes* between 22 and 32 °C. These same authors (2009) discussed that temperatures below 18 °C and above 34 °C negatively affect mosquito development, restricting proliferation. Climatic shifts, specifically rising temperatures and modified precipitation distributions, have significantly optimized the environment for mosquito reproduction (Rodriguez-Morales *et al.*, 2024).

The four (4) municipalities in this study are located in the western region of Santa Catarina, Chapecó, or in coastal regions, such as Florianópolis, Itajaí and Joinville, where the temperatures fit the mosquitoes' optimal range of temperature. As cited by Moreti (2024), his synergy between temperature and disease spread is biologically driven: higher temperatures shorten the larval development cycle, resulting in rapid generational turnover and increased hatching success.

Data from 2022 and 2023 demonstrate a consistent seasonal trend, with peak incidence occurring between March and May, consistent with both patterns of Santa Catarina and Brazil (Moreti, 2024). Mosquito foci are most prevalent between January and May, a period that spans the height of summer through the start of the Austral autumn; the preceding summer's heat provides the necessary biological momentum for peak breeding (Souza, 2024).

Emphasis should be placed on integrating the One Health approach to better comprehend the mechanisms behind dengue emergencies and re-emergences; this multidisciplinary strategy is vital for addressing the threat of worldwide epidemics (Rodriguez-Morales et al., 2024).

The Random Forest models, as described by Breiman (2001), "are an effective tool in prediction. Because of the Law of Large Numbers they do not overfit. [...] makes them accurate classifiers and regressors". The prediction behavior of the models of these four (4) municipalities follows the observations, with some underestimated values on the highest outbreaks.

The highest coefficient of determination observed in Chapecó ($R^2 = 0.82$) can be attributed to the training dataset including historical outbreaks that allowed the model to better simulate high-incidence peaks. Even with a predictive viability, as in Joinville ($R^2 = 0.76$) and Itajaí ($R^2 = 0.78$), the models failed to capture the extreme outbreaks occurring during the 2023 testing period. They consistently struggle to capture the highest observed values when those specific epidemiological behaviors were not present in the training data. The lowest coefficient of determination observed in Florianópolis ($R^2 = 0.38$), consequently, the historical-based model failed to adequately capture the extreme values observed during the year of 2023, with underestimation and positive outliers in the error distribution (Figure 3A); the R^2 metric is sensitive to outliers.

Furthermore, integrating spatio-temporal modeling with Artificial Intelligence (AI) offers powerful predictive capabilities that can significantly enhance strategic efforts in the global fight against the disease (Rodriguez-Morales *et al.*, 2024).

Conclusion

Understanding regional climate variations aids in predicting dengue epidemiology and entomological distribution of *Aedes* spp. The best temperatures to the development of the mosquitoes are between 22 ºC and 32 ºC degrees, consequently the optimum to the transmission of dengue; where can be observed in Santa Catarina in coastal and western regions. Highlands and mountain ranges act as natural barriers to control the development of *Aedes* spp. and extrinsic incubation period of dengue virus.

Mosquito foci are most prevalent between 04th and 16th epidemiological weeks, coinciding with the transition from Austral mid-summer into the Austral autumn, when high temperatures historically accelerate the mosquito life cycle. Therefore, dengue cases peak in Austral autumn, between 16th and 20th epidemiological weeks, whereas the western region reaches its highest point some weeks earlier, between 12th and 16th epidemiological weeks.

About modeling epidemiological behavior, Random Forest models provide reliable predictions, warranting further studies to enhance their utility. The models underestimate the highest values, as evident with a rightward shift of the mean relative to the median, indicating outliers in the errors on the positive side, principally on municipalities that present the greatest number of dengue cases only on the testing dataset.

By treating suspected notifications as probable cases until their final disposition (confirmed, suspected, and inconclusive reports), the system provides a more precise real-time assessment and compensates for reporting lags, so it can be used to modeling epidemiological data with a clearer view of the current situation

The limitations of this research are tied to the nature of secondary datasets, specifically regarding underreporting and data gaps in dengue notifications.

Statements and Declarations

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Competing Interests
The authors have no relevant financial or non-financial interests to disclose.

Author Contributions
All authors contributed to the study conception and design. Material preparation, data collection, and analysis were performed by MFS and EWG. The first draft of the manuscript was written by MFS, and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

Data Availability
The epidemiological and entomological datasets analyzed during the current study were obtained from the Diretoria de Vigilância Epidemiológica de Santa Catarina (DIVE/SC) and are subject to public health surveillance reporting guidelines. Climate datasets are publicly available from the Instituto Nacional de Pesquisas Espaciais (INPE; MERGE and SAMeT products) and the National Centers for Environmental Prediction (NCEP/NOAA). Derived spatial and time-series data processed for this study are available from the corresponding author upon reasonable request.

Code Availability
The custom Python 3 scripts developed for data pre-processing, Random Forest modeling, and figure generation are available from the corresponding author upon reasonable request.

Ethics Approval and Consent to Participate
Not applicable. This study utilized secondary, fully anonymized, and aggregated public health surveillance data provided by official government health authorities (DIVE/SC) and open-access meteorological repositories. No individual-level patient data or direct human/animal interventions were involved.

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