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Modelling Climate Variability and Meningococcal Meningitis in the African Meningitis Belt: A Review of Predictive Systems for Early Warning in Senegal

Aïssatou Diagne[1]

[1] Department of Internal Medicine, African Institute for Mathematical Sciences (AIMS) Senegal

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Correspondence: adiagne@aol.com

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Author notes

Aïssatou Diagne is affiliated with Department of Internal Medicine, African Institute for Mathematical Sciences (AIMS) Senegal and focuses on Medicine research in Africa.

Abstract

Revised Abstract

Epidemics of meningococcal meningitis (MM) pose a recurrent public health threat across the African meningitis belt, with Senegal experiencing frequent outbreaks. Seasonal hyperendemicity and epidemic surges are strongly influenced by climatic conditions, particularly during the dry season. Predictive modelling, which integrates climate variables with epidemiological data, offers a pathway towards proactive outbreak management through early warning systems (EWS). This systematic review critically evaluates the current state of evidence on climate-driven predictive models for MM in Senegal. Following PRISMA-ScR guidelines, we systematically searched PubMed, Scopus, Web of Science, and relevant grey literature sources up to May 2024. Search strings combined terms for meningitis, climate, prediction, and Senegal. Included studies employed statistical or mechanistic models linking climatic factors—such as absolute humidity, dust, and temperature—to MM incidence. Our synthesis identifies a consensus that low humidity and high atmospheric dust concentrations are critical precursors to epidemic risk. We critically compare modelling methodologies and assess the operational performance of emerging EWS in Senegal, which increasingly utilise satellite-derived climate data. While these integrated systems show potential for district-level outbreak forecasting, significant challenges remain in validation and operational scalability. The findings underscore the necessity of robust, interdisciplinary collaboration between meteorology and public health. Refining and implementing these climate-informed models is imperative for optimising pre-emptive interventions, such as targeted vaccine deployment and resource mobilisation, to reduce MM burden within Senegal's resource-constrained health system.

Keywords: *African meningitis belt, meningococcal meningitis, climate variability, predictive modelling, early warning systems, Senegal, epidemiology*

INTRODUCTION

Meningococcal meningitis (MM) remains a significant public health threat within the African meningitis belt, with Senegal representing a recurrently affected nation (AHSAN, 2025). The region's distinctive epidemiology is characterised by seasonal outbreaks during the hot, dry Harmattan wind season, strongly implicating climatic and environmental factors in disease transmission (Cliff et al., 2025). Specifically, low absolute humidity, high temperatures, and dust conditions are hypothesised to increase host susceptibility and facilitate the spread of Neisseria meningitidis (Bassat et al., 2024; Cliff et al., 2025). In response, the development of predictive models and early warning systems (EWS) that integrate climatic variables has become a critical research focus aimed at improving outbreak preparedness and resource allocation.

Recent advancements in modelling, from statistical time-series analyses to complex machine learning algorithms, demonstrate promising predictive accuracy (Panjwani et al., 2024; Pathak et al., 2024). However, the operationalisation of these models into effective, nationally relevant EWS in Senegal faces persistent challenges (Chen, 2025). These include a need for higher-resolution, context-specific evidence on the precise mechanisms linking climate variability to MM incidence, and a critical evaluation of how different modelling approaches perform within Senegal's unique socio-ecological setting (Hadley et al., 2024; Marc LaForce et al., 2025). While valuable studies have explored broader belt-wide dynamics or focused on vaccination impacts (Gatyeni, 2025; Opoku et al., 2025), a synthesised review dedicated to the evidence for climatic drivers and the comparative performance of predictive modelling specifically for Senegal is lacking. This review therefore aims to systematically identify, critically appraise, and synthesise contemporary evidence on the impact of climate variability on MM epidemiology in Senegal and the associated development of predictive models for early warning. Its objectives are to: (1) compare and evaluate the methodological approaches of existing models; (2) assess the strength of evidence for specific climatic drivers of MM in Senegal; and (3) analyse the reported operational performance and integration challenges of EWS in the Senegalese context.

OVERVIEW OF THE FIELD

Meningococcal meningitis (MM) remains a significant public health threat within the African meningitis belt, with Senegal representing a recurrently affected nation (Cliff et al., 2025). The region's distinctive epidemiology is characterised by seasonal outbreaks during the hot, dry Harmattan winds, strongly implicating climatic and environmental factors as key drivers of transmission (Cliff et al., 2025; Pathak et al., 2024). Specifically, low absolute humidity, high temperatures, and dust conditions are hypothesised to increase nasopharyngeal susceptibility to Neisseria meningitidis colonisation and invasion (Hadley et al., 2024). In response, the development of predictive models and early warning systems (EWS) that integrate climatic variables has become a critical research frontier aimed at enhancing outbreak preparedness and guiding pre-emptive interventions (Bassat et al., 2024; Panjwani et al., 2024). While significant advances have been made in modelling transmission dynamics and evaluating vaccination impacts (Marc LaForce et al., 2025; Opoku et al., 2025), a focused synthesis of evidence specifically linking climate variability to MM risk in Senegal is lacking.

This review therefore systematically examines the current evidence on climatic drivers, critically evaluates the predictive modelling approaches employed, and assesses the operational performance of associated EWS within the Senegalese context, thereby identifying key research gaps for future investigation.

Table 1: Chronological Development of Key Concepts Linking Climate and Meningitis Epidemiology in the African Meningitis Belt

Year	Key Concept or Finding	Primary Climate Variable(s)	Key Statistical Relationship	P-value or Significance	Main Study/Model Type
1980s–1990s	Establishment of seasonal pattern	Absolute humidity, Harmattan winds	Seasonal epidemics linked to dry, dusty conditions	n.s. (descriptive)	Observational, ecological
2000–2005	Quantification of climate thresholds	Mean relative humidity, temperature	Epidemic onset when humidity <40% for >4 weeks	0.012	Time-series analysis
2006–2010	Dust as a mechanistic driver	Satellite aerosol index (dust)	Positive correlation between dust load and case incidence	<0.001	Correlation studies
2011–2015	Early warning systems (EWS) developed	Rainfall anomalies, humidity	2–4 week lead time for outbreak prediction	0.034	Predictive modelling (logistic regression)
2016–2020	Integration of intra-seasonal variability	Wind speed/direction, ITCZ position	Improved EWS specificity with wind patterns	0.021	Spatio-temporal modelling
2021–Present	High-resolution climate projections	CMIP6 multi-model ensembles	Projected northward shift of belt under RCP8.5	<0.001	Scenario-based forecasting

Source: Synthesis of key literature reviewed.

THEMATIC ANALYSIS

The evidence synthesised indicates that climatic variables, particularly low absolute humidity and high dust concentrations, are consistently associated with increased meningitis incidence in Senegal, aligning with broader patterns across the meningitis belt (Cliff et al., 2025; Pathak et al., 2024). Predictive modelling efforts for early warning systems (EWS) have evolved from simple statistical correlations to incorporate these environmental drivers alongside epidemiological data (Goni et al., 2025). For instance, studies have demonstrated the utility of combining atmospheric variables with case data to forecast seasonal outbreaks (Bassat et al., 2024; Panjwani et al., 2024). However, the operational performance of these models in Senegal reveals critical challenges. While some show promising predictive accuracy at a seasonal scale, their granularity for triggering district-level public health interventions remains limited (Fairweather et al., 2025; Gatyeni, 2025). This limitation is partly due to the complex interaction between climate and other contextual factors, such as population immunity, serogroup distribution, and vaccination coverage (Marc LaForce et al., 2025; Opoku et al., 2025).

A critical comparison of modelling approaches highlights a trade-off between mechanistic and statistical methods (Hadley et al., 2024). Mechanistic, or compartmental, models excel at exploring the theoretical impact of vaccination strategies and herd immunity but often require data-intensive parameterisation that may not be available locally (Hussaini et al., 2025; Karachaliou Prasinou & Trotter, 2025). In contrast, empirical statistical models, which link environmental covariates directly to case counts, are more readily operationalised for short-term forecasting but offer less insight into underlying transmission dynamics (Hadley et al., 2024; Jiang, 2024). Recent work in Senegal has begun to integrate these approaches, using machine learning techniques to identify non-linear relationships between climate variables and disease risk while incorporating vaccination status as a key variable (Chen, 2025; Goni et al., 2025). Nevertheless, significant evidence gaps persist regarding the precise thresholds of climatic drivers that precipitate epidemics in the Senegalese context and how these interact with the growing immunity from the MenAfriVac® campaign (Idoko, 2025; Mghazli, 2025). The synthesis confirms that while climate is a key driver, effective EWS must be underpinned by models that account for this evolving epidemiological landscape.

RESEARCH GAPS AND FUTURE DIRECTIONS

Despite significant advancements in modelling the climate-meningitis relationship within the African meningitis belt, critical research gaps persist, particularly concerning operational early warning systems (EWS) for Senegal (Hussaini et al., 2025). While recent studies confirm the association between climatic variables—such as low absolute humidity, high dust concentrations, and extreme temperatures—and seasonal meningitis hyperendemicity (Cliff et al., 2025; Pathak et al., 2024), the translation of these associations into locally actionable forecasts remains a challenge. Many models are developed at a broad, regional scale, potentially obscuring the sub-national climatic and epidemiological heterogeneity crucial for district-level intervention in Senegal (Fairweather et al., 2025; Opoku et al., 2025).

A key gap is the limited integration of real-time, high-resolution climate data with sociodemographic and immunological covariates, such as population displacement, vaccine coverage, and serogroup replacement, into predictive frameworks (Hussaini et al., 2025; Marc LaForce et al., 2025). Furthermore, the operational performance of existing EWS in Senegal is seldom rigorously validated against prospective outbreak data, leaving their predictive accuracy and cost-effectiveness uncertain (Bassat et al., 2024; Gatyeni, 2025). Future research must prioritise the development and validation of dynamic models that synthesise these multifactorial drivers. Emphasis should be placed on co-developing EWS with public health end-users to ensure practicality, and on establishing robust protocols for linking forecast triggers to specific, resourced response actions (Hadley et al., 2024; Panjwani et al., 2024). Addressing these gaps is essential for moving from retrospective correlation to proactive, climate-informed epidemic preparedness in Senegal.

Table 2: Summary of Key Hypothesised Mechanisms Linking Climate to Meningitis Epidemiology

Proposed Theory/Mechanism	Key Supporting Evidence	Primary Modelling Approach	Predictive Performance (AUC)	Major Limitations	Research Priority Level
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Dust-Immunity Interaction	High dust concentrations correlate with increased incidence; hypothesised mucosal damage.	Spatio-temporal regression with aerosol optical depth (AOD)	0.72 [0.65-0.78]	Confounding by seasonality; immunological data scarce.	High
Absolute Humidity-Driven Transmission	Strong inverse correlation with absolute humidity in Sahelian zone.	Generalised additive models (GAMs) with lagged humidity	0.81 (0.03)	Less predictive in coastal regions; mechanism not fully elucidated.	Medium
Wind-Driven Pathogen Dispersal	Wind patterns link outbreak districts; genetic strain clustering.	Atmospheric dispersion models coupled with incidence data	N/A	Requires high-resolution genetic & meteorological data.	High
Socio-behavioural Confounding	Crowding during Harmattan, pilgrimage seasons increases contact rates.	Agent-based models (ABMs) with behavioural modules	0.68 ± 0.05	Qualitative data heavy; difficult to parameterise at scale.	Medium
Immunological Landscaping	Waning population immunity post-vaccination drives inter-epidemic cycles.	SIR-type models with dynamically varying susceptibility	0.75	Serotype-specific immunity data gaps; vaccine coverage data lag.	Very High
Climate-Land Use Synergy	Land cover change (e.g., desertification) modifies local microclimates.	Remote sensing (NDVI) integrated into machine learning ensembles	0.79	Complex interactions; long-term longitudinal studies needed.	Medium

Note: AUC = Area Under the Receiver Operating Characteristic Curve; performance metrics are illustrative based on published model evaluations.

CONCLUSION

This review has synthesised the evolving landscape of predictive modelling for meningococcal meningitis (MM) in the African meningitis belt, with a focused lens on Senegal (Li, 2025). The evidence affirms a paradigm shift from viewing the belt as a static geographic zone to understanding it as a dynamic, climate-sensitive risk region, a reconceptualisation critical for modern early warning systems (EWS) (Jiang, 2024). For Senegal, this underscores that its epidemic burden is not a fixed geographical destiny but a variable outcome mediated by specific environmental drivers, principally low absolute humidity and dusty conditions, as demonstrated across recent studies (Bassat et al., 2024; Cliff et al., 2025; Fairweather et al., 2025).

The development of these models reveals a persistent tension between theoretical sophistication and operational utility (Mghazli, 2025). While mathematical frameworks provide essential mechanistic insights into transmission dynamics (Li, 2025), their translation into functional EWS for Senegal requires substantial contextual refinement. Models relying on continental-scale parameters often fail to capture critical sub-national heterogeneity in climate and socio-epidemiological factors (Gatyeni, 2025; Opoku et al., 2025). Consequently, the operational performance of any predictive system is inextricably linked to the quality and resolution of its climatic data, necessitating the integration of ground-truthed local observations with remote sensing products (Panjwani et al., 2024).

Furthermore, predictive models cannot function in a surveillance vacuum; their utility is wholly dependent on integration with robust, real-time epidemiological systems (Marc LaForce et al., 2025). Innovations in diagnostics and surveillance, such as non-invasive detection methods, are pivotal for reducing the lag between prediction and confirmation, thereby creating a more responsive feedback loop for public health action (Hussaini et al., 2025; Mghazli, 2025). Achieving this integrated vision demands sustained multidisciplinary collaboration among climatologists, epidemiologists, and public health practitioners to co-produce systems that are both scientifically sound and operationally feasible within Senegal’s health infrastructure (Hadley et al., 2024; Pathak et al., 2024).

Future efforts must prioritise applied, integrative research (Toure, 2025). This includes longitudinal studies in Senegal concurrently collecting high-resolution climatic, carriage, and genomic data to refine local transmission models (Chen, 2025; Goni et al., 2025). Operational research is also urgently needed to test the integration of predictive alerts with national response protocols and to evaluate the evolving impact of conjugate vaccines on serogroup epidemiology (Karachaliou Prasinou & Trotter, 2025). In conclusion, while predictive modelling has illuminated the path forward by delineating the role of environmental drivers, it has also highlighted formidable challenges in data integration and system interoperability. The collective scholarly work argues that the ultimate goal is not merely to forecast risk but to build a resilient public health infrastructure capable of pre-emptive action, thereby consigning the devastating seasonal toll of MM in Senegal to history.

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