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Influence of Heat Wave and Precipitation on Chikungunya Transmission

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Key Points:

- Heat waves reduced mosquito survival, but accelerated viral replication rate and altered human behavior, increasing infections by 76.0%
- Effective precipitation increased mosquito abundance by 205.0% and amplifying chikungunya transmission by 10.5%
- Control measures remain the most effective way of limiting the transmission, without which the outbreak would increase by 611.73%

Supporting Information:

Supporting Information may be found in the online version of this article.

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Abstract Increasingly frequent extreme weather events are heightening the chances of mosquito-borne diseases outbreaks, posing a notable threat to human health. However, how extreme weather influences the transmission dynamics of mosquito-borne diseases remains poorly understood. Here, we integrate heat waves and effective precipitation as parameterization schemes into an SEI-SEIR dynamic model to quantify their driving effects on chikungunya transmission. Based on the 2025 chikungunya fever outbreak in Foshan, the model successfully reproduced the observed transmission dynamics. Attribution analysis revealed that heat waves exerted a dual effect on transmission. Mosquito suitability declined by 9.7%, yet accelerated viral replication and altered human behavior generated a positive forcing that drove a net 76% increase in infected cases. Effective precipitation regulated outbreak scale nonlinearly, dispersed rainfall increased mosquito abundance by 205% and amplified transmission by 10.5%. Our research offered new insights into the impact of extreme weather on mosquito-borne infectious diseases.

Plain Language Summary Extreme weather has multiple effects on mosquito-borne diseases. Heat waves act as a "dual driver," suppressing mosquito populations while accelerating the replication rate of viruses and modifying human behavior. The effective precipitation operates as a "risk amplifier," expanding mosquito breeding habitats and thereby widening the risk of the outbreak. Control measures serve as a "controllable brake," remaining the most effective way to respond to an outbreak. Our research provided a scientific basis for early warning and prediction of compound disasters involving extreme weather and mosquito-borne diseases, with the objective of reducing infection risks and economic losses.

1. Introduction

Arthropod-borne viruses (arboviruses) pose an important threat to human health (Weaver & Reisen, 2010), transmitted to humans primarily through mosquito bites, especially by *Aedes aegypti* and *Aedes albopictus* (Kraemer et al., 2019). Global warming has greatly expanded the regional distribution of vector organisms (Medlock et al., 2012; Wu et al., 2023), with 3.9 billion people in 120 countries at risk of dengue and chikungunya virus (CHIKV) infection (Brady et al., 2012). In China, CHIKV was first isolated from a patient in Yunnan in 1987 (Xia et al., 2018), and then chikungunya fever was long-term characterized by sporadic imported cases. The first community-based outbreak was reported in Dongguan, Guangdong Province, in 2010, with 253 cases. In July 2025, Foshan City experienced a large-scale chikungunya fever outbreak, with over 9,700 confirmed cases have been reported as of August 31 (Nama et al., 2025; Zhang et al., 2025). With the current global warming challenge, frequent human migration and rapid urbanization, the outbreaks of arbovirus infection might have a gradual northward progression in China (H. Liu et al., 2023). These trends underscore the urgent need to strengthen research on mitigating arbovirus transmission (Maneerattanasak et al., 2024).

Climate change is a critical driver of disease transmission (T. Li et al., 2023; Yan et al., 2025). CHIKV and its vector are sensitive to temperature and rainfall (C. Li et al., 2018; Yu et al., 2025), which affect the lifespan of mosquitoes and viral transmission probability. Rainfall amount and intensity constitute different level risk scenarios, with dispersed rainfall associated with higher infection risk (Wu et al., 2023). Temperature affects the characteristics of vectors, including the extrinsic incubation period and biting rate (Edillo et al., 2024; H. Liu et al., 2023; Mercier et al., 2022). Substantial studies have focused on the statistical model of meteorological factors and incidence, mathematical temperature-sensitive functions for vector transmission risk (Briere et al., 1999; Mordecai et al., 2017), potential risk under future climate scenarios (Feng et al., 2025; Zheng

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et al., 2019). In addition, some scholars also have developed dynamic transmission models, incorporating empirically parameterized traits for mosquitoes and viruses (Huber et al., 2018; Ni et al., 2024; Zhao et al., 2025). However, these approaches rely on conventional meteorological variables suited to capturing gradual climatic influences rather than the acute impacts of extreme events. Given the rapid expansion of mosquito vectors and the increasing frequency of extreme weather events (Harish et al., 2024), there remains a lack of process-based, quantitative understanding of how extreme weather influence transmission dynamics.

Extreme weather events exhibit significant nonlinear influences on the transmission of arboviruses (Carreto et al., 2022; Monaghan et al., 2018), altering mosquito geographic distributions and modulating human exposure risk (Abbasi, 2025; Huang, Lian, et al., 2025). Critically, conventional indicators, mean temperature and total precipitation, cannot adequately capture these nonlinearities. Mean temperature averages over short-duration extremes, obscuring the biological disparity between a week of steady warmth and a week punctuated by a heatwave. Total precipitation similarly conflates ecologically opposite rainfall patterns: dispersed, moderate rainfall sustains container-type breeding sites, whereas concentrated downpours of equivalent volume flush out eggs and larvae. These limitations motivate the use of heat waves and effective precipitation—indicators designed to recover the biologically salient dimensions of weather variability that conventional metrics erase. By isolating sustained thermal extremes from background conditions and resolving the temporal distribution of rainfall that governs breeding-site persistence, these indicators provide a more biologically grounded basis for attributing outbreak dynamics to extreme weather events.

To address these gaps, we constructed three parameterization schemes, including heat wave, precipitation, and control measures, and simulated the evolution of actual epidemic. We quantified their respective contributions to the 2025 chikungunya outbreak in Foshan. Specifically, this study aims to (a) incorporate extreme weather events into a dynamic model to simulate chikungunya fever, (b) quantify the contributions of heat waves, effective precipitation and control measures to outbreak via attribution analysis, and (c) elucidate the mechanisms by which heat waves and effective precipitation amplify chikungunya outbreak. This study provides a comprehensive understanding of the impact of heat waves and precipitation on mosquito-borne diseases, with direct implications for early warning and outbreak response.

2. Materials and Methods

2.1. Data Source

In this study, the chikungunya fever confirmed case data was collected from the report released by Guangdong Provincial Center for Disease Control and Prevention (GDCDC, 2025). The time range of daily reported cases was from July 8 to 31 August 2025.

The daily 2 m-temperature and precipitation for June–August 2025 were obtained from ERA5-Land at $0.1° \times 0.1°$ spatial resolution (Muñoz Sabater, 2019). The gridded data were aggregated to Foshan City. Attribution analysis were driven by daily precipitation from the corresponding 2024 period and by daily temperatures from the 1991–2020 climatological baseline.

2.2. Parameterization Schemes

Parameterization is a mathematical process that expresses the state quantities and transmission process as a function of independent variables. We have constructed three parameterization schemes to simulate the transmission process of CHIKV, including heat wave, effective precipitation and control measures. We have defined heat wave and precipitation concentration degree (PCD) in Text S1 in Supporting Information S1.

Heat wave affects the survival of mosquitoes and the virus extrinsic incubation rate. Heat wave has a dual effect on CHIKV. When heat wave events occur, the survival suitability of mosquitoes decreases and the mortality rate increases. Then, heat wave may exacerbate the virus replication rate and accelerate virus transmission. The parameterization scheme is constructed as follows:

$$\omega_M(t) = \omega_{M_{\text{base}}}(t) \cdot (1 + \alpha \cdot \text{heat}_{\text{excess}} \cdot \log(\text{heat}_{\text{duration}})) \quad (1)$$

$$\mu_M(t) = \mu_{M_{\text{base}}}(t) \cdot (1 + \delta \cdot \text{heat}_{\text{excess}}) \quad (2)$$

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where $\text{heat}_{\text{excess}}$ represents heat wave degree and $\text{heat}_{\text{duration}}$ is the duration of heat wave. α and δ are obtained through nonlinear fitting.

Precipitation mainly increases available breeding grounds (such as small water containers), directly improving the birth rate of mosquitoes. The parameterization scheme is constructed as follows:

$$a_M(t) = a_{M_{\text{base}}}(t) \cdot \left(1 + \theta \cdot \text{Prep}_{\text{eff}}\right) \tag{3}$$

where $a_{M_{\text{base}}}(t)$ represents base birth rate and Prep_{eff} is effective precipitation. θ is obtained through nonlinear fitting.

Control measures such as clean up accumulated water are still the most effective methods to prevent the development of CHIKV. We developed a parameterization scheme for control measures affecting mosquito mortality and survival rates. The parameterization scheme is expressed as follows:

$$\mu_M(t) = \mu_{M_{\text{base}}} \cdot (1 + l_{\text{control}}(t)) \tag{4}$$

$$k_M(t) = k_{M_{\text{base}}} \cdot (1 - l_{\text{control}}(t)) \tag{5}$$

where $\mu_{M_{\text{base}}}$ and $k_{M_{\text{base}}}$ are base mortality and survival rates. l_{control} represents the different level control measures.

3. Results

3.1. The 2025 Foshan Chikungunya Outbreak

On 8 July 2025, an imported chikungunya fever case was identified in Shunde District, Foshan City, during routine public health surveillance. The subsequent spread of the outbreak from Shunde District to other districts of Foshan City and other areas of Guangdong Province is of particular interest. As shown in Figure 1a, the number of confirmed cases (blue bars) rose sharply in July, with the cumulative case curve exhibiting an exponential growth pattern. Daily new cases peaked at approximately 400, reflecting delayed detection in the early stages of the outbreak and rapid transmission among susceptible populations. By August, the growth rate of cumulative cases had gradually slowed, reaching a total of 9,717 confirmed cases by 31 August. This plateauing trend was most likely driven primarily by control measures. A series of robust control measures were implemented to suppress mosquito survival and reduce biting rates. Consequently, the outbreak was effectively controlled by the end of August.

Climatic conditions in Foshan were conducive to mosquito breeding prior to the chikungunya outbreak. Starting in June, favorable temperatures (Figure 1b) and adequate rainfall (Figure 1c) likely facilitated optimal conditions for mosquito propagation, thereby elevating the probability of CHIKV outbreak (Liang et al., 2026). During July–August, Foshan experienced three heat waves, each of which was followed by a precipitation event with weekly rainfall exceeding 150 mm. This suggested that such compound events may have been a key factor driving the rapid spread of the chikungunya outbreak.

3.2. Nonlinear Effects of Temperature and Precipitation on Transmission

It was established that chikungunya outbreaks were associated with lower rainfall concentration (i.e., evenly distributed, dispersed rainfall). To investigate the effects of precipitation and PCD on chikungunya fever, a generalized additive model (GAM, described in Text S2 in Supporting Information S1) was employed (Figure 2b). It is hypothesized that more dispersed rainfall is more likely to increase the risk of chikungunya fever outbreaks, while highly concentrated rainfall reduces the risk of transmission. This is due to the fact that continuous rainfall accompanied by heavy precipitation causes runoff, which in turn inhibits the survival and growth of mosquitoes. The risk of CHIKV transmission is greatest in conditions of precipitation levels below 50 mm and moderate PCD (nearly 0.12). Concurrently, elevated levels of precipitation and PCD have been observed to heighten the risk of mosquito proliferation, attributable to the creation of extensive areas of standing water that provide optimal and protracted conditions for mosquito breeding.

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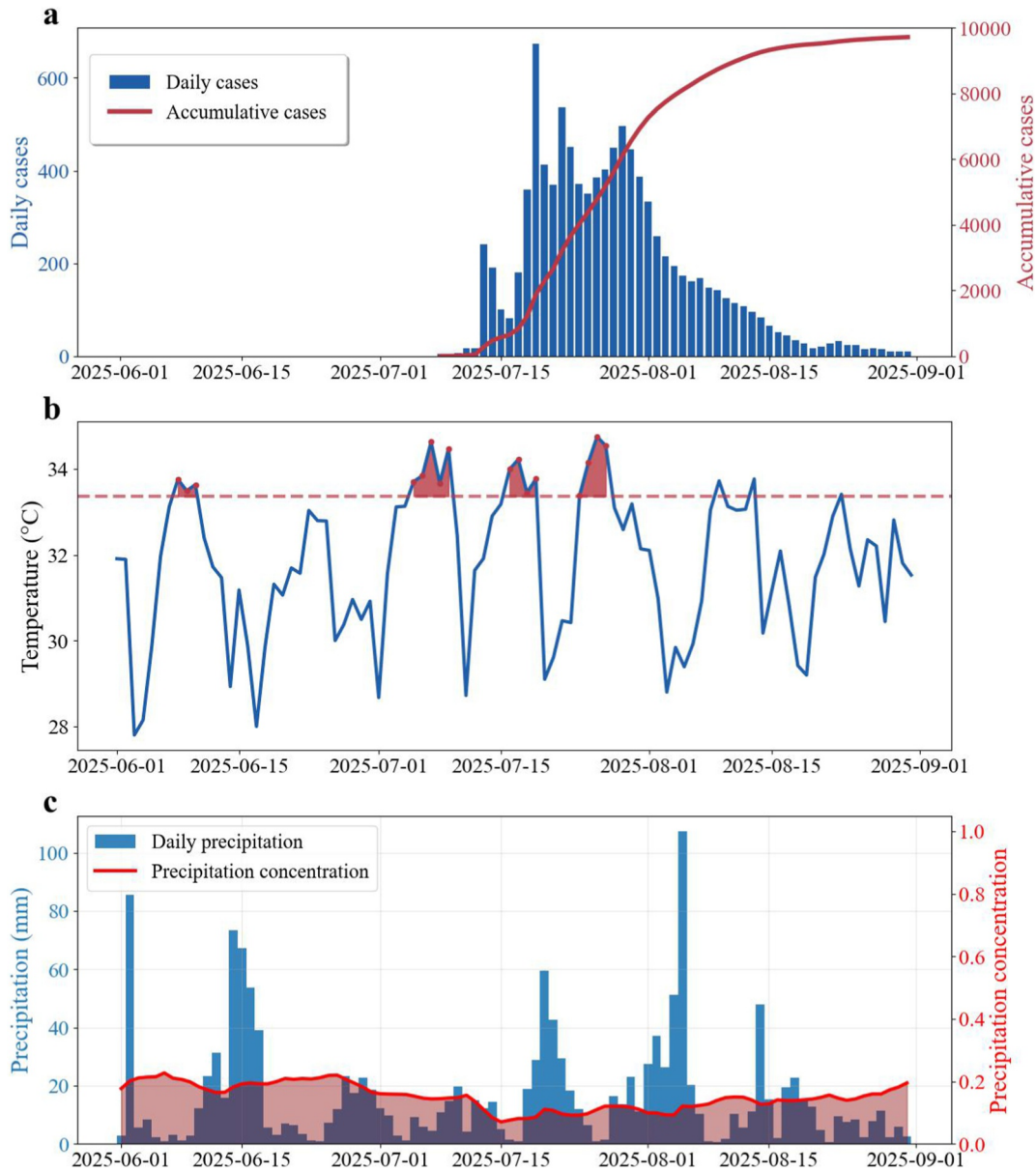


Figure 1. Chikungunya infected cases and temperature and precipitation conditions from June to August. (a) The number of Chikungunya cases (the bars represent daily new cases, and the red line represents the cumulative cases); (b) Daily temperatures and the red shading indicating heatwave events; (c) Precipitation conditions, with the bars representing daily precipitation and the red line indicating precipitation intensity.

At the same time, while moderate temperatures are conducive to the survival of mosquitoes, high temperatures can also increase the risk of transmission. The distributed lag nonlinear model (DLNM, described in Text S2 in Supporting Information S1) was utilized to analyze the impact of temperature on the risk of CHIKV transmission. It was determined found that temperatures between 28 and 30°C were optimal for mosquito-borne transmission. Above 30°C, temperature suitability decreased, and the risk of transmission was reduced. However, when temperatures exceeded 33°C, the risk of CHIKV infection actually rose. As shown in Figure 2a, it was determined that high temperatures (accompanied by a delay of more than 7 days) may enhance the proliferation of mosquito habitats when concomitant with precipitation, thereby promoting the emergence of chikungunya fever outbreaks.

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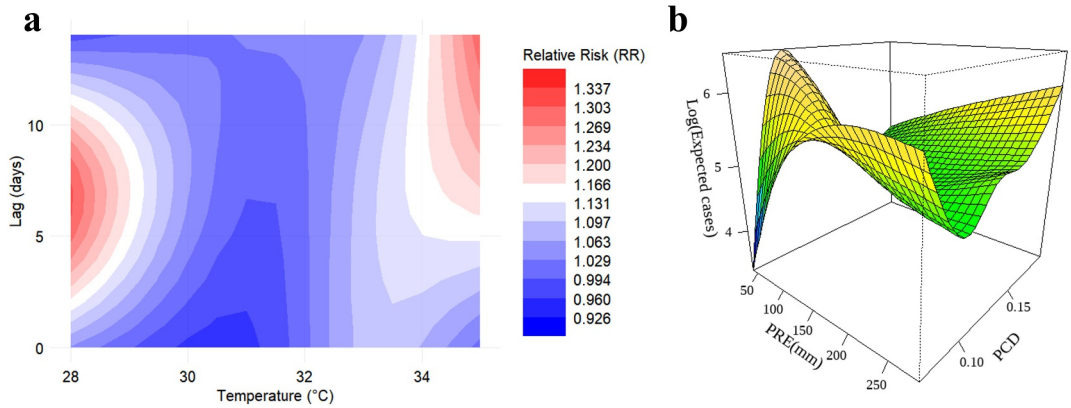


Figure 2. Statistical relationship between cases of Chikungunya and temperature and precipitation. (a) The relationship between temperature and reported cases relative risk (RR) over 14 lag days. (b) Exposure-response curves of the combined effect of precipitation (PRE) and precipitation concentration degree on Chikungunya incidence Foshan city.

3.3. Attribution of Extreme Weather Events and Control Measures to Infected Cases

We used an SEI-SEIR model (susceptible–exposed–infected–removed for humans, with corresponding mosquito compartments) with a multi-factor parameterization scheme to simulate the chikungunya outbreak in Foshan (Text S3 and Figure S1 in Supporting Information S1). The model incorporated three fundamental driving factors: heat wave, effective precipitation, and dynamic control measures and successfully reproduced the transmission process of the outbreak. As shown in Figure 3a, the simulated outbreak curve (orange) exhibits high degree of consistency with the actual reported cases (blue), particularly during the rising phase, indicating that the model accurately captured the dynamic changes in the actual development (Figure S2 in Supporting Information S1). The inclusion of heatwave parameterization significantly improved simulation accuracy. Meanwhile, effective precipitation events increased mosquito breeding sites and effectively sustained the epidemic at a high level (He et al., 2025). The model effectively characterized the driving roles of heat waves and precipitation on mosquito density and transmission rates, revealing a synergistic mechanism of "heat wave-driven and precipitation-sustained" transmission. To further elucidate the role of extreme weather events in transmission dynamics, we conducted an attribution analysis (Text S4 in Supporting Information S1).

Heat waves reduced mosquito populations but resulted increased infected cases. First, the heat wave parameterization was replaced with the average climate temperature. This alteration led to a decline in mosquito populations and an increase in infected cases (Figure 3b), suggesting that the effects of heat waves may be counterintuitive. While heat waves increased mosquito mortality and subsequent reduction in mosquito populations, they also accelerated viral replication and altered human behavior. Furthermore, the occurrence of heat

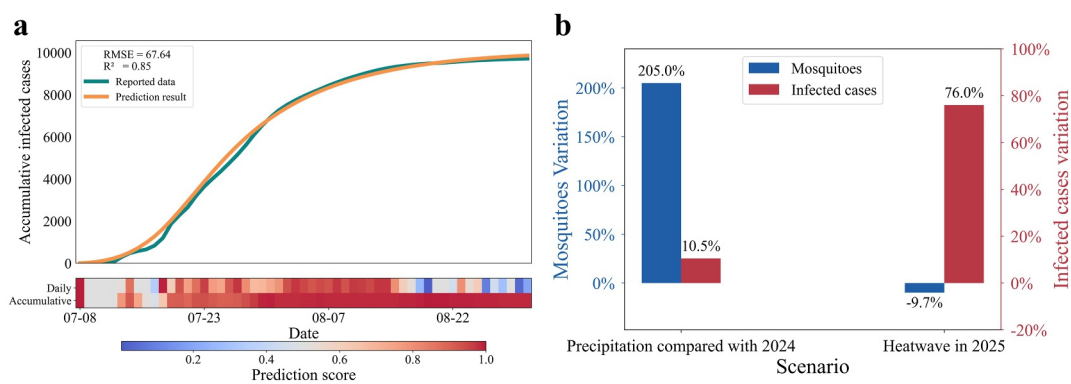


Figure 3. Prediction results and attribution analysis. (a) Comparison of prediction result and reported data of cumulative infected cases in Foshan City. (b) Attribution analysis of the contribution of heatwaves and precipitation to cases of Chikungunya fever in 2025.

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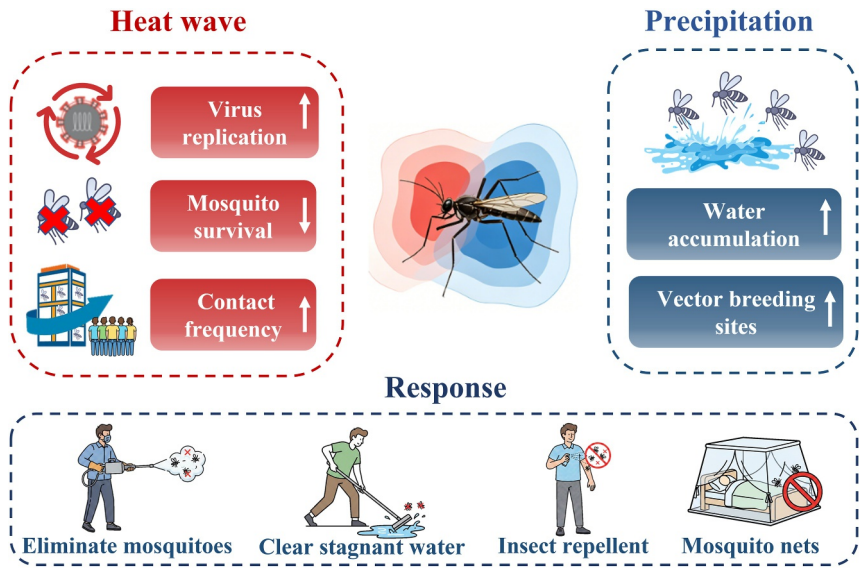


Figure 4. A framework for the impact of heat wave and effective precipitation on mosquito-borne infectious diseases.

waves has the potential to motivate the public to increase ventilation. A reduction in outdoor activity due to these conditions can result in an increase in the time spent indoors, thereby elevating the probability of human-mosquito interaction. This phenomenon may serve as a contributing factor to the observed escalation in case numbers. Despite heat waves increasing mosquito mortality, their net effect was a substantial amplification of transmission. This counterintuitive outcome is attributable to two concurrent processes that outweighed the negative effect of vector mortality: accelerated viral extrinsic incubation in surviving mosquitoes, and increased human-vector contact driven by prolonged indoor stays and ventilation during extreme heat. Heat waves thus act as a "dual driver"—simultaneously suppressing vector populations and enhancing transmission efficiency—with the net balance favoring amplification.

The abundant effective precipitation that occurred in 2025 is a key factor contributing to the rapid and substantial increase in the population of mosquitoes, thereby creating optimal conditions for their propagation (Figure 3b). Unlike the double-edged effect of heat waves, the abundant effective precipitation in 2025 exerted a unidirectional positive influence. The anomalously abundant and well-distributed effective precipitation in 2025, compared with 2024, was a key factor enabling the rapid and sustained growth of mosquito populations, thereby amplifying outbreak scale.

Presently, the implementation of control measures stands as the most efficacious strategy for curtailing the propagation of Chikungunya fever. In comparison to extreme weather events, human interventions (such as breeding site cleanup and spatial spraying) demonstrated a stronger effect in the model. This highlights the importance of strengthening active surveillance and rapid response for containing mosquito-borne diseases in the context of climate change (Nama et al., 2025).

3.4. Underlying Mechanisms of Outbreak Amplification

In summary, the present study elucidated the underlying mechanism of the CHIKV outbreak in Foshan (Figure 4). The findings demonstrate that heat waves act as a "dual driver," exerting a concurrent effect of suppressing mosquito populations while accelerating viral incubation period and modifying human behavior. Effective precipitation operates as a "risk amplifier," thereby expanding the mosquito breeding habitat and consequently amplifying the outbreak's risk. Control measures serve as a "controllable brake," representing a pivotal factor in the mitigation of transmission. This conclusion emphasized that we must consider the complex effects of climate change and the coordination of human interventions when preventing and controlling mosquito-borne diseases.

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4. Conclusion and Discussion

Through integrating heat wave and effective precipitation parameterizations into an SEI-SEIR model, this study quantified the individual contributions of extreme weather events to the 2025 Foshan CHIKV outbreak. Heat waves exerted a net amplifying effect of 76.0%, as accelerated viral incubation and behavioral changes outweighed a 9.7% reduction in mosquito suitability. Effective precipitation increased mosquito abundance by 205.0% and amplified transmission by 10.5%. Control measures remained the decisive factor in limiting transmission (Nama et al., 2025), preventing a 611.7% increase in infected cases. The SEI-SEIR framework with extreme weather parameterization can be applied to other regions and mosquito-borne diseases, provided local calibration is performed. The primary advantage of our framework lied in explicitly parameterizing extreme events as dynamic drivers, thereby enabling both attribution and prediction under extreme weather scenarios.

The mechanisms of heat waves can be understood from the perspectives of vector biology and human behavior. One explanation is that heat waves can exceed the physiological threshold for mosquito survival (Dobbs et al., 2026), leading to increased mortality among adult mosquitoes. However, the subsequent drop in temperature and high humidity may provide an opportunity for mosquito development, driving population recovery (Cheng et al., 2020). Concurrently, high temperatures accelerated viral replication, shortening the extrinsic incubation period and enabling faster transmission (Ith et al., 2025; Meher et al., 2025; Shi et al., 2026). From the human behavior perspective, extreme heat during heat waves prompted people to spend more time indoors and increase ventilation, thereby raising the probability of human-mosquito contact (He et al., 2025; D. Wang et al., 2026). Following the heat wave, increased outdoor activities further expand the spatiotemporal window for contact (Cheng et al., 2020; Ith et al., 2025). Our study advances understanding by integrating them into a process-based model and quantifying that their net effect result in a substantial amplification of transmission.

Furthermore, abundant effective rainfall acted as an amplifier of outbreaks, significantly expanding mosquito breeding habitats and consequently raising the probability of viral transmission (Wu et al., 2023). The underlying mechanism lies in the highly nonlinear response of breeding sites to precipitation patterns (Lowe et al., 2021). Moderate and dispersed precipitation continuously replenish water levels in containers, creating stable conditions for mosquito development (Edillo et al., 2024; Prabowo et al., 2025; Sutriyawan et al., 2024; X. Wang et al., 2019). In contrast, excessive concentrated and high intensity precipitation reduces vector populations by flushing eggs and larvae from breeding sites (Y. Liu et al., 2025; Y. Wang et al., 2022). Our contribution lies in quantifying its conditional contribution to outbreak magnitude through counterfactual simulation.

It is worth noting that chikungunya fever outbreaks in China have primarily occurred after imported cases. Until 2026, chikungunya fever was not designated as a notifiable infectious disease, the lack of routine surveillance meant that imported cases were highly likely to trigger local transmission. Therefore, the imported case is the fundamental cause of the outbreak, while extreme weather events serve as contributing factors that amplify the transmission process. The effects of heat waves and effective precipitation quantified in this study are conditional on this prerequisite.

However, this study has several limitations. Attribution analysis simulations assumed all other conditions remained unchanged and the effects of heat waves and precipitation may have been confounded by control measures, leading to an underestimation of their actual impact. In addition, parameters describing the biological processes of mosquito vectors in the model were often derived from functions based on laboratory conditions, which were significant differences from actual conditions. The model was sensitive to initial conditions, which cannot be directly observed and were therefore estimated by inversion, limiting the potential for improving prediction accuracy. To address these, we will incorporate additional disease-related covariates to optimize model performance and reduce the sensitivity of forecast results to initial conditions. In addition, we will introduce data assimilation methods to constrain initial states and parameter and incorporate more parameterization schemes to improve applicability and accuracy.

At present, the impacts of climate change are intensifying, with extreme weather events occurring more frequently (Chen et al., 2022; Huang, Lian, et al., 2025), especially heat wave frequency shows a significant upward trend (Martinez-Villalobos et al., 2025). At the outbreak scale, heat wave itself serves as short-term triggers, driving the rate and peak of transmission. At the climate scale, the increased frequency of heat waves acts as a long-term contributing factor, driving the probability of risk events occurring. Therefore, this frequency increase may raise both the probability and potential scale of outbreaks by repeatedly suppressing mosquito

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populations and accelerating viral transmission. Additionally, our simplification of the entire Foshan City area as a uniformly mixed compartment fails to capture the spatial heterogeneities of the vector population, extreme weather and the human population. Future advances in observational technologies are expected to provide higher-resolution infectious disease surveillance data, which can be combined with existing comprehensive meteorological data sets to support the development of two-dimension infectious disease models, thereby providing more accurate forecasts and early warnings in the context of climate change (Ban et al., 2024; Huang, Yan, et al., 2025; T. Li, 2023).

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Availability Statement

The chikungunya fever confirmed case data was collected from the report released by Guangdong Provincial Center for Disease Control and Prevention (GDCDC, 2025). The daily maximum 2 m-temperature and precipitation were obtained from ERA5-Land at 0.1° × 0.1° spatial resolution (Muñoz Sabater, 2019).

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