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Research Article

Generalized Linear Regression Model to Determine the Threshold Effects of Climate Variables on Dengue Fever: A Case Study on Bangladesh

Shamima Hossain

Department of Mathematical and Physical Sciences, East West University, Dhaka, Bangladesh

Correspondence should be addressed to Shamima Hossain; shh@ewubd.edu

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One of the leading causes of the increase in the intensity of dengue fever transmission is thought to be climate change. Examining panel data from January 2000 to December 2021, this study discovered the nonlinear relationship between climate variables and dengue fever cases in Bangladesh. To determine this relationship, in this study, the monthly total rainfall in different years has been divided into two thresholds: (90 to 360 mm) and (<90 or >360 mm), and the daily average temperature in different months of the different years has been divided into four thresholds: (16°C to ≤20°C), (>20°C to ≤25°C), (>25°C to ≤28°C), and (>28°C to ≤30°C). Then, quasi-Poisson and zero-inflated Poisson regression models were applied to assess the relationship. This study found a positive correlation between temperature and dengue incidence and furthermore discovered that, among those four average temperature thresholds, the total number of dengue cases is maximum if the average temperature falls into the threshold (>28°C to ≤30°C) and minimum if the average temperature falls into the threshold (16°C to ≤20°C). This study also discovered that between the two thresholds of monthly total rainfall, the risk of a dengue fever outbreak is approximately two times higher when the monthly total rainfall falls into the thresholds (90 mm to 360 mm) compared to the other threshold. This study concluded that dengue fever incidence rates would be significantly more affected by climate change in regions with warmer temperatures. The number of dengue cases rises rapidly when the temperature rises in the context of moderate to low rainfall. This study highlights the significance of establishing potential temperature and rainfall thresholds for using risk prediction and public health programs to prevent and control dengue fever.

1. Background

Dengue fever is a widely distributed and rapidly spreading mosquito-borne viral disease worldwide. This disease is transmitted through the bite of a female Aedes mosquito infected with dengue virus serotypes (DENVs 1–4) of the Flaviviridae family [1]. All four serotypes of the dengue virus can cause disease, and prior infection with one dengue serotype is a risk factor for developing later infections. There is a limited vaccine and no specific medical treatment for dengue. Dengue fever affects people of all sexes and ages. Anywhere that *Aedes aegypti* mosquitoes are present, dengue fever can exist. The risk is, therefore, significant in areas where the Aedes mosquito can breed and survive.

Aedes mosquitoes generally flourish in tropical and subtropical regions. Nowadays, it is one of the top ten global health threats. Already, about 141 countries are affected, and more than half of the world's population is at a risk of dengue infection. An estimated 390 million dengue infections and 36,000 deaths occur worldwide annually [2]. Geographically, dengue fever is spread over tropical and subtropical areas. Most dengue epidemics have occurred in America, Southeast Asia, and the Western Pacific [3]. Due to the accompanying ideal meteorological conditions for mosquito population expansion, Asia has the highest dengue risk areas, accounting for over 70% of the disease's total worldwide burden, followed by Africa (16%) and America (14%) [4].

Bangladesh, a country in South Asia, is situated along the Tropic of Cancer, northeast of India and south of Nepal, becoming a high dengue risk area. When dengue fever was first discovered in Bangladesh in 1964 [5], it was not considered a severe health threat to the general public. Nevertheless, in 2000, an outbreak resulted in 5,551 reported cases and 93 deaths that were verified [6]. Between 2000 and 2010, the average annual number of dengue cases declined. However, Bangladesh has seen a sharp rise in annual dengue cases since then. The largest outbreak the nation has ever seen occurred recently in 2019. The second largest outbreak occurred in 2021. In 2018, dengue cases were the third largest in the country. Although the DGHS recorded a comparatively smaller number of dengue cases in 2020, which was 1,193, this is not the full extent of dengue illness because of the gravely affected healthcare system by the ongoing COVID-19 issue [7]. The Directorate General of Health Services of Bangladesh (DGHS) data showed 31,699 confirmed cases of dengue virus infections between 2000 and 2015 or an average of roughly 1,981 cases per year. However, the DGHS documented 1,510,165 confirmed dengue cases between 2016 and 2021 or an average of 25,027 cases annually. Thus, compared to the period from 2000 to 2015, the yearly number of dengue cases has increased by 374%. Moreover, Bangladesh is struggling with different serotypes of the dengue virus. In 2000, the first case of dengue hemorrhagic fever (DHF) was found in Bangladesh, where classic DF caused by multiple serotypes had been previously reported [6, 8].

A variety of factors influence the acceleration of dengue transmission. For instance, growing populations, worldwide trade, international tourism, and unregulated urbanization are significant variables that could explain the dengue virus's quick spatial spread worldwide [2, 9]. Inadequate public health infrastructure and awareness of dengue fever may also be to blame for the disease's geographical spread [10, 11]. Before dengue fever can be established in the setting of these socioeconomic elements, the interactions between the three spheres, namely, human, mosquito, and viral components in a specific country, need to be linked with acceptable weather and climate circumstances [12, 13]. The density of *Ae. aegypti* is highly linked with the number of dengue fever cases. Many studies have presented evidence for positive associations between vector indices (e.g., Breteau (BI), container (CI), and home indices (HI)) and human dengue cases [14–16]. Chen et al. [17] discovered the relationship between Aedes mosquitoes and epidemics of dengue disease in Taiwan between 1988 and 1990. Chen et al. [18] found a positive association between the Breteau index of *Ae. aegypti* and the number of confirmed cases during the 1987–1988 dengue outbreak in Taiwan. To prevent dengue outbreaks and assess disease control in dengue-endemic countries, the World Health Organization (WHO) currently advises routine vector surveillance [19]. Again, the principal mosquito vectors, *Ae. aegypti* and *Ae. albopictus*, are directly impacted by ambient temperature and rainfall. Temperature increases are positively correlated with increases in Aedes density. Rainfall is also significantly associated with the Aedes population peak. Climatic parameters, including ambient temperature, rainfall, and relative humidity, directly impact the length of the gonotrophic cycle, the larval development period, and the larval and adult survival of the primary dengue vector, *Ae. aegypti* [6, 8]. According to Focks et al. [20], the rate of mosquito egg survival varies dramatically when the temperature is between 22°C and 34°C. In a different investigation by Rowley and Graham [21], it was discovered that female *Ae. aegypti* could fly sustainably between 15°C and 32°C. Maximum flight speed (34.1 m/s) was observed at 32°C and 50% humidity, whereas 21°C was the ideal flight temperature for the duration and distance travelled. Bishop and Gilchrist [22] state that *Ae. aegypti* females were found to consume blood at a pretty high rate at temperatures of 42°C when the blood meal was 4°C (71%) less warm than the environment's average temperature, compared to the scenario when the environment and blood temperatures were the same. *Ae. aegypti* has been seen to stop biting below 15°C, while they are most active at 28°C [23]. Gubler [24] suggested that *Ae. aegypti* numbers frequently increase because of the optimal environmental conditions frequently created by fast population growth in tropical metropolitan areas. According to numerous past studies, meteorological conditions can considerably enhance the risk of dengue transmission depending on the local ecology [23, 25–28]. The duration of the virus's incubation period will also shift as a result of climate change. By influencing mosquito growth dynamics, virus replication, and mosquito-human interactions, climatic conditions have an impact on dengue ecology both directly and indirectly. Tseng et al. [29] discovered that the climate significantly impacts dengue. They showed that the number of dengue patients increased by 5.75% and 11.83% in Kaohsiung and Pingtung, respectively, when the temperature increased by 1℃. Due to worldwide climate change, numerous vector-borne human infectious diseases are predicted to spread more comprehensively geographically [30]. Dengue may have spread in recent years due to climatic changes in the areas bordering northern India. Warming climates enhance the risk of dengue transmission because temperature and humidity significantly impact mosquito growth and development. The longer rainy seasons and rising temperatures in Southeast Asia's subtropical regions may create ideal circumstances for the dengue vector Aedes mosquito population to increase [4, 31–33].

Additionally, dengue cases have lately been noted in temperate areas, including Nepal, suggesting that the disease may spread from the subtropics to cooler regions and threaten northern India, Pakistan, and their neighbors [34, 35].

Various studies [36–38] using data from or close to subtropical locations have stated that meteorological conditions can influence dengue incidence and mosquito abundance up to 5 months before the season starts. However, during the dengue season, climate conditions are the main focus of most investigations. Understanding the connection between seasonal climate fluctuation and annual incidence can provide insight into whether dengue spreads through a region. Using a generalized additive model (GAM), Chen et al. estimated the linear relationship between precipitation and dengue disease in Taiwan between 1994 and 2008 by fitting Poisson regression as the sum of a nonparametric smooth function of predictor variables [39]. They discovered a significant correlation between time-lagged effects following precipitation of up to 350 mm and a higher incidence of dengue. Fan et al. [40] performed a meta-analysis of 33 relevant articles to determine the dengue risk related to global temperature change. The study employed multivariate Poisson models and multiple linear regression. Their findings suggest that there is a positive correlation between temperature and dengue.

Given that the average temperature ranges between 23.2 and 27.7°C, they calculated that the incidence of dengue would increase by 35% for every 10°C increase. Using a piecewise linear spline function, Xiang et al. investigated the temperature-dengue relationship in Guangzhou, China, between 2005 and 2014. According to the study, the ideal range for dengue disease transmission is between 21.6 and 32.9°C. When the temperature surpassed 21.6°C, dengue cases began to rise; however, when the temperature rose above 32.9°C, they sharply decreased. Additionally, they discovered that when the daily relative humidity exceeded 79%, there was a negative correlation between relative humidity and dengue transmission. Some studies considered spatial components in modelling the climate-related spread of dengue. Yu et al. [41] suggested a spatiotemporal dengue fever prediction approach based on Bayesian maximum entropy analysis to evaluate the climatic effects on dengue distribution in southern Taiwan. They discovered significant positive associations between rainfall, minimum temperature, and dengue incidence after applying a space-time Poisson process to surveillance data collected from 2002 to 2006. The actual distribution of dengue cases recorded in 2007 and the expected spatio-temporal dengue fever distribution were similar. Several studies have used climate data to predict dengue incidence in Bangladesh [42–45]. Temperature and rainfall were discovered to be essential contributing elements in these earlier investigations [45–48].

Additionally, earlier studies proposed that the impacts of climate factors were not seasonal. However, climate variables can also have time-dependent effects. For example, several studies have shown that the impact of rainfall on dengue incidence might vary throughout the year. Since rain can damage potential mosquito habitats, heavy rain falling during the monsoon season will harm the mosquito population's growth. On the other hand, rain in the dry seasons could leave stagnant bodies of water that are ideal for mosquito breeding.

Understanding how the climate affects the spread of dengue in different areas is crucial because it can act as an early warning system and enable the implementation of preventive measures before outbreaks become established. To effectively reduce the risk of dengue, it is essential to create an alarm system that can be relied upon to verify and track the existence of a threshold effect of temperature on vector occurrence. Plans for preventing dengue fever outbreaks could be improved by monitoring the average temperature and daily average rainfall to determine if they have reached the thresholds. There may be regional, national, or even provincial differences in the correlation between climate and dengue [49]. In many research studies, dengue incidence and climate change have been closely examined, but the threshold impacts of climate on dengue vector indices is yet to receive many studies. Therefore, this study aims to calculate the threshold impacts of temperature and rainfall on the annual incidence of dengue in Bangladesh. Policymakers can use these findings as vital information for future public health initiatives to prevent and control dengue fever. We first examine the daily average temperature and monthly total rainfall data obtained from the Bangladesh Metrological Department (BMD). Then, we considered some thresholds for the daily average temperature in different months of different years, which are (16°C to ≤20°C), (>20°C to ≤25°C), (>25°C to ≤28°C), and (>28°C to ≤30°C). Regarding monthly total rainfall, the thresholds are (90 mm to less than 360 mm per hour) and (less than 90 mm to greater than 360 mm per hour). A quasi-Poisson and zero-inflated Poisson regression model was applied to assess the nonlinear relationship between meteorological factors and monthly dengue incidences.

2. Methods

2.1. Data on Dengue Fever. The Directorate General of Health Services (DGHS) receives reports of suspected, probable, and confirmed dengue cases that have been seen in medical facilities around the nation. Suspected cases are those who have an acute febrile illness with or without nonspecific symptoms. In contrast, likely cases are those with an acute febrile illness with a serological diagnosis. The confirmed cases should have an acute febrile illness with a positive dengue NS1 antigen or PCR test. Details of dengue case definition and management are available from the DGHS [50]. Daily reports of dengue cases are compiled and circulated by the DGHS's communicable disease control (CDC) unit. Monthly dengue cases were collected from the DGHS from January 2000 to December 2021.

2.2. Meteorological Data. The Bangladesh Meteorological Department (BMD) tracked and handled accumulated meteorological data nationwide at 35 weather stations. These meteorological data, which include daily average temperatures and daily total rainfall, were obtained from the BMD. Here, temperature and precipitation are measured in degrees Celsius (°C) and millimetres (mm), respectively. Here, the daily average temperature of a particular month in different years was calculated by averaging the daily data of that month in different years of the 32 stations. In this way, we calculated the daily average temperature of different months (January to December) in different years. In addition, the total rainfall for a particular month in different years was calculated by summing the daily total rainfall for all stations of that month for different years.

2.3. Model Formulation and Selection. Various analytical techniques are typically used according to the distributional assumptions (such as Poisson, normal etc.) and the response's spatial and/or temporal dynamics. Several studies concluded that the relationship between climate and dengue should be nonlinear. In contrast, many earlier studies assumed that their models' relationship between climate conditions and dengue transmission is linear [51, 52].

From the scatter plot (Figures 1–3), we found there is a nonlinear relationship between dengue incidence and climate variables (temperature and rainfall). Here, the dependent variable, dengue cases in various months in different years, is a non-negative integer random variable. By considering all scenarios, count data regression models were used. Most earlier studies used Poisson regression models to calculate the association between environmental variables and dengue cases. However, the Poisson model is severely constrained by the assumption that the variance and mean are equal, which is frequently broken in real datasets. The count data are overdispersed when the conditional variance is greater than the conditional mean. As a result of the estimation, including underestimated standard errors of parameter estimation, hypotheses concerning Poisson regression parameters may be rejected more frequently than they should be [53, 54]. We next fitted two regression models, quasi-Poisson, and zero-inflated regression models to address this problem.

Here, y_{ij} is the monthly dengue cases in the i^{th} month and j^{th} year such that $y_{ij} \sim$ quasi-Poisson (μ_{ij}), where μ_{ij} represents the expected number of dengue cases in the i^{th} month and j^{th} year, i.e., $E\ (y_{ij}) = \mu_{ij}$.

Therefore, the quasi-Poisson regression model can be expressed as follows:

$$\log\left(\mu_{ij}\right) = \mathbf{X}^{\mathbf{T}}\boldsymbol{\beta} = \beta_1 + \beta_2 T_{ij} + \beta_3 R_{ij}. \tag{1}$$

(The quasi-Poisson regression model is one of the generalised linear models with link function log or log link as follows:

$\log(\mu_{ij}) = \mathbf{X}^{\mathbf{T}}\beta = \beta_1 + \beta_2 T_{ij} + \beta_3 R_{ij}$)

The zero-inflated Poisson regression model can be expressed as follows:

$$\log\left(\mu_{ij}\right) = \mathbf{X}^{\mathbf{T}}\boldsymbol{\beta} = \beta_1 + \beta_2 T_{ij} + \beta_3 R_{ij}, \tag{2}$$

where the probability distribution of the zero-inflated Poisson random variable y_{ij} can be written as

$$p_r\left(y_{ij} = k\right) = \begin{cases} \pi_i + \left(1 - \pi_i\right)\exp\left(-\mu_i\right), & \text{if } k = 0, \\ \\ \left(1 - \pi_i\right)\dfrac{\mu_i^{y_{ij}}\exp\left(-\mu_i\right)}{y_{ij}!}, & \text{if } k > 0, \end{cases} \tag{3}$$

Here, T_{ij} = daily average temperature in the i^{th} month and j^{th} year ($i = 1, 2, 3, \ldots, 12$; $j = 2000, 2001, 2002, \ldots, 2021$). R_{ij} = Monthly total rainfall in the i^{th} month and j^{th} year ($i = 1, 2, 3, \ldots, 12$; $j = 2000, 2001, 2002, \ldots, 2021$).

Here, for the daily average temperature, T_{ij} takes the values 1, 2, 3, and 4 for the average temperature (16 to ≤20°C), (>20°C to ≤25°C), (>25°C to ≤28°C), and (>28°C to ≤30°C), respectively. Monthly total rainfall R_{ij} takes the value 1 for the threshold (90 to ≤360 mm per hour) and takes the value 0 for the threshold (<90 mm and >360 mm per hour). β_2 and β_3 are the coefficients of daily average temperature and monthly total rainfall in various months of different years, respectively.

After fitting two regression models, the quasi-Poisson regression model and the zero-inflated Poisson regression model, AIC is used to compare the two models.

3. Results

3.1. Dengue Cases in Bangladesh. From the outbreak in 2000 to 2010, there was a tendency towards a decrease in dengue cases (Supplementary Figure S-1). After 2010, the number started to rise until it fell in 2014 and then started to rise once more until 2018. In 2000, 2002, and 2016, more than 5,000 illnesses were reported. In contrast, more than 10,000 cases were reported in 2018 and around 28,000 in 2021. The number of recorded dengue cases in 2019 was 101354, which is alarming. From 2015 to 2021, the lowest number of dengue cases was reported in 2020, which was 1193; this is not the actual scenario of dengue causes due to the drastically affected healthcare system by the ongoing COVID-19 issue. Dengue cases are distributed seasonally. The highest number of dengue cases was found in August; 88% occurred between July and October (Supplementary Table S-1 and Supplementary Figure S-4). Descriptive statistics of different dengue cases in various months of different years are shown in supplementary Table S-1.

3.2. Climate Variabilities. To assess the threshold impacts of temperature and rainfall on the monthly incidence of dengue in Bangladesh, the daily average temperature and total rainfall in various months (January to December) of different years (2000 to 2021) were used. The daily average temperature in Bangladesh increased after January. It continued to increase until June or July, with the highest temperature of 29.8°C measured in May 2019 and the lowest temperature of 16.3°C measured in January 2003 (Supplementary Figure S-5). Bangladesh saw rising temperatures over the years (Supplementary Figure S-2). Winters are warming up, while summers are becoming hotter and lasting longer (Supplementary Figures S-2 and S-5). The graph shows an unbalanced distribution of total rainfall over the years (2000–2021) (Supplementary Figure S-3). The number of wet months is found to increase, and the number of dry months is found to decrease in Bangladesh, but the annual total rainfalls show a decreasing trend (Supplementary Figures S-3 and S-6). Monthly total rainfall increased between April and October (Supplementary Figure S-6). The highest amount of rainfall usually occurs between May and September, with low levels of rainfall recorded in January and December, and the monsoon seasons are extended from

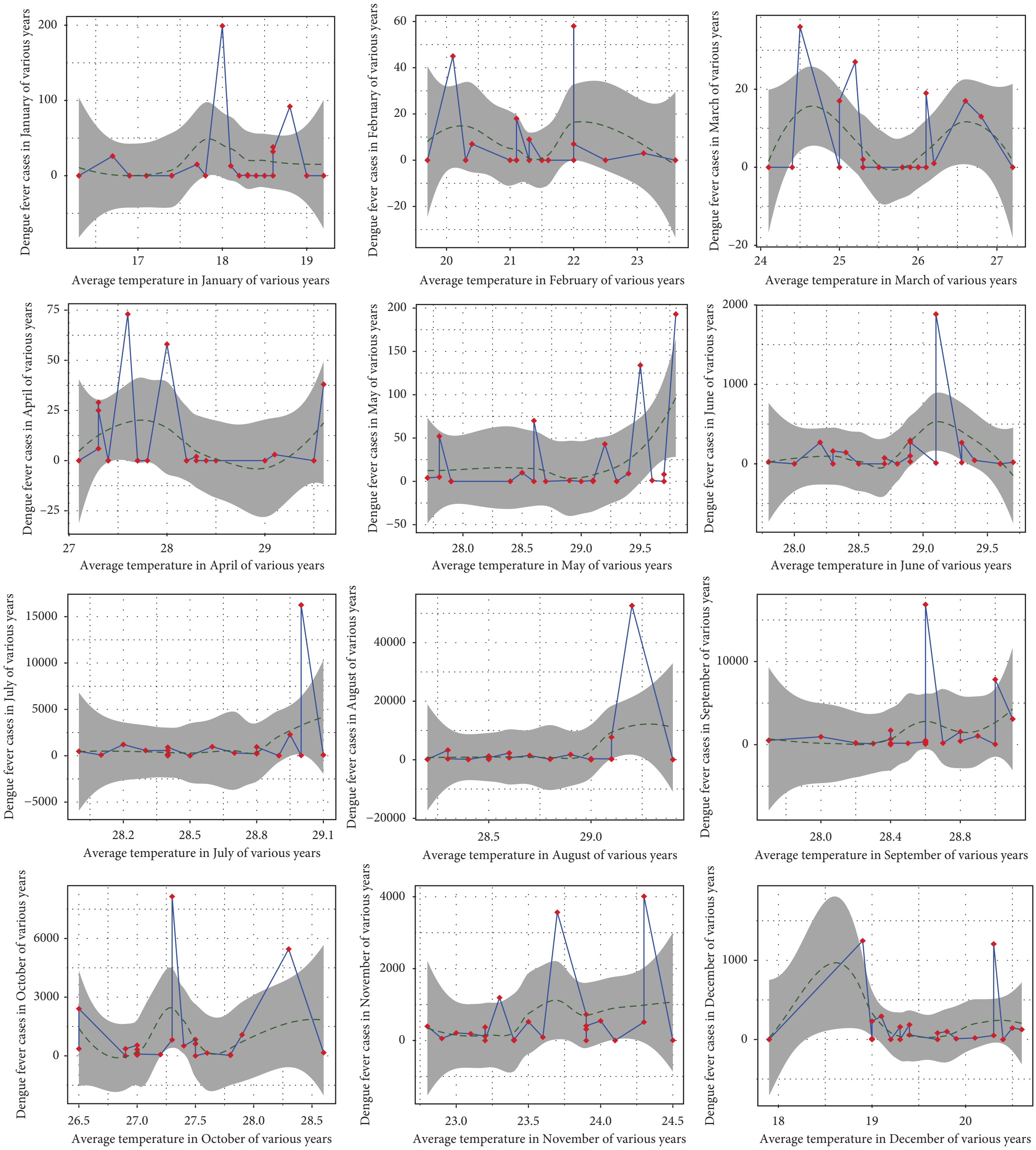

Figure 1: The impact of the daily average temperature on monthly dengue cases. Dots represent monthly dengue cases at different values of the daily average temperature in that particular month of different years. A LOESS smoothing function is used to obtain a smooth line representing the trend of dengue cases for different average temperature values for a particular month over the years. The shaded area denotes the 95% confidence interval of monthly dengue cases at the different daily average temperatures for that month over the years.

February to October (Supplementary Figure S-6). Descriptive statistics of daily average temperature and total rainfall in various months of different years are shown in Supplementary Tables S-2 and S-3, respectively.

3.3. The Marginal Impact of Climate Variables on Dengue Cases. We evaluated the marginal impacts of climate variables, temperature and rainfall, to see how each climate variable affected dengue incidence. The incidence of dengue

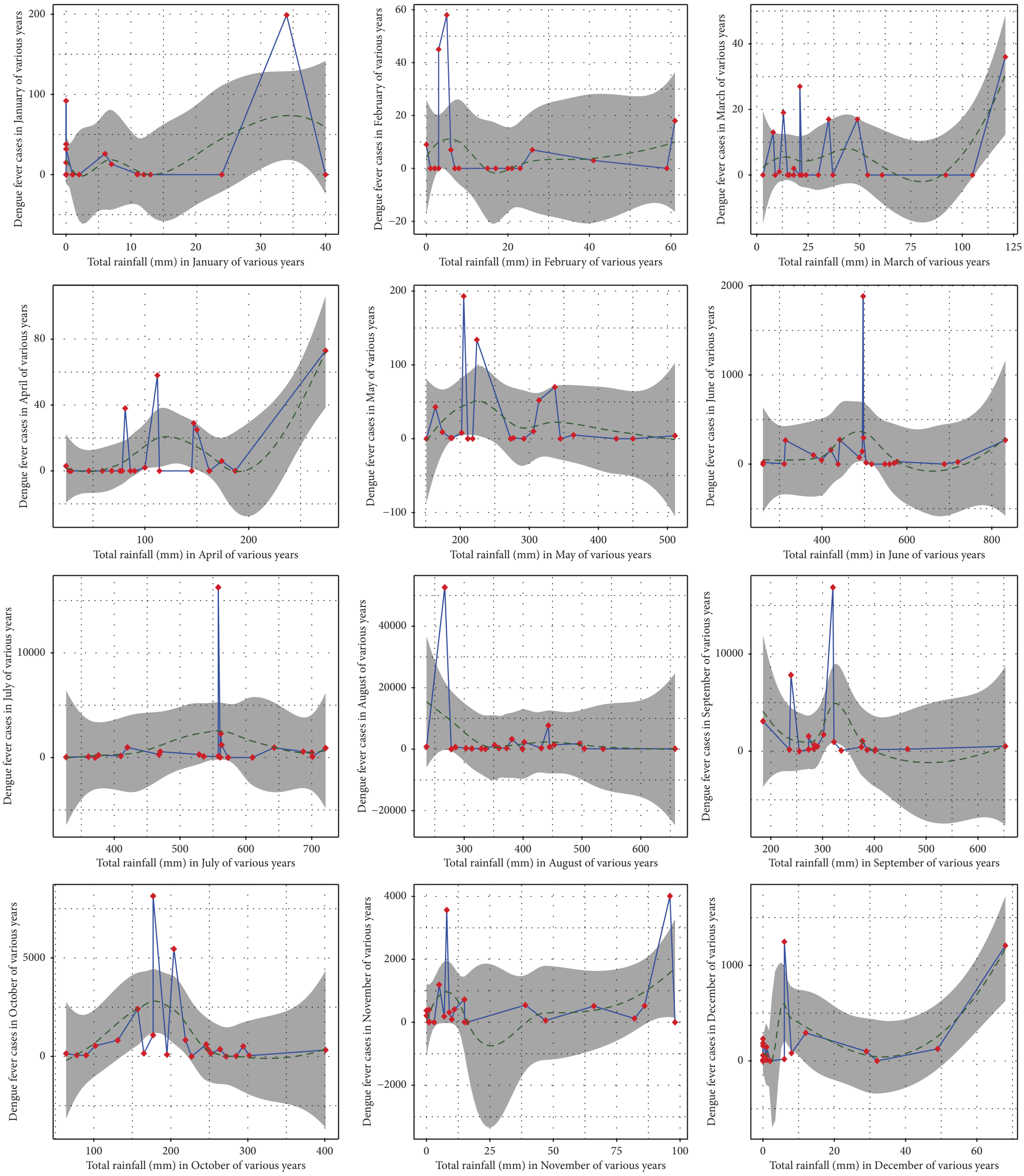

FIGURE 2: The impact of monthly total rainfall on monthly dengue cases. Dots represent monthly dengue cases at different values of the total rainfall in a particular month in different years. A LOESS smoothing function is used to obtain a smooth line to represent the trend of dengue cases at different values of the total rainfall in a particular month over the years. The shaded area denotes the 95% confidence interval of monthly dengue cases at different values of total rainfall for a particular month over the years.

fever is significantly correlated with temperature. As the temperature increases, the transmission rate of dengue fever also increases (Figure 1). The peak of the dengue epidemic period is around July to October, during the rainy season (Figure 2). It is believed that rainfall is an essential factor in dengue transmission. Dengue cases are displayed more during light to moderate rainfall (Figure 2). On the contrary, very few rainfalls or no rainfall and heavy rainfall can lower dengue fever transmission (Figure 2).

3.4. Interactive Impact of Temperature and Rainfall on Dengue Cases. Integrating influences of temperature and rainfall on dengue transmission is highly significant (Figure 3). Dengue fever cases are prevalent in Bangladesh during July, August, September, and October, when the daily average temperatures are very high, around 28°C and generally moderate rainfall occurs every week of these months (Figure 3). In June, the temperature is too high at about 28°C, with heavy rainfall in many weeks of this month. As a result, we found

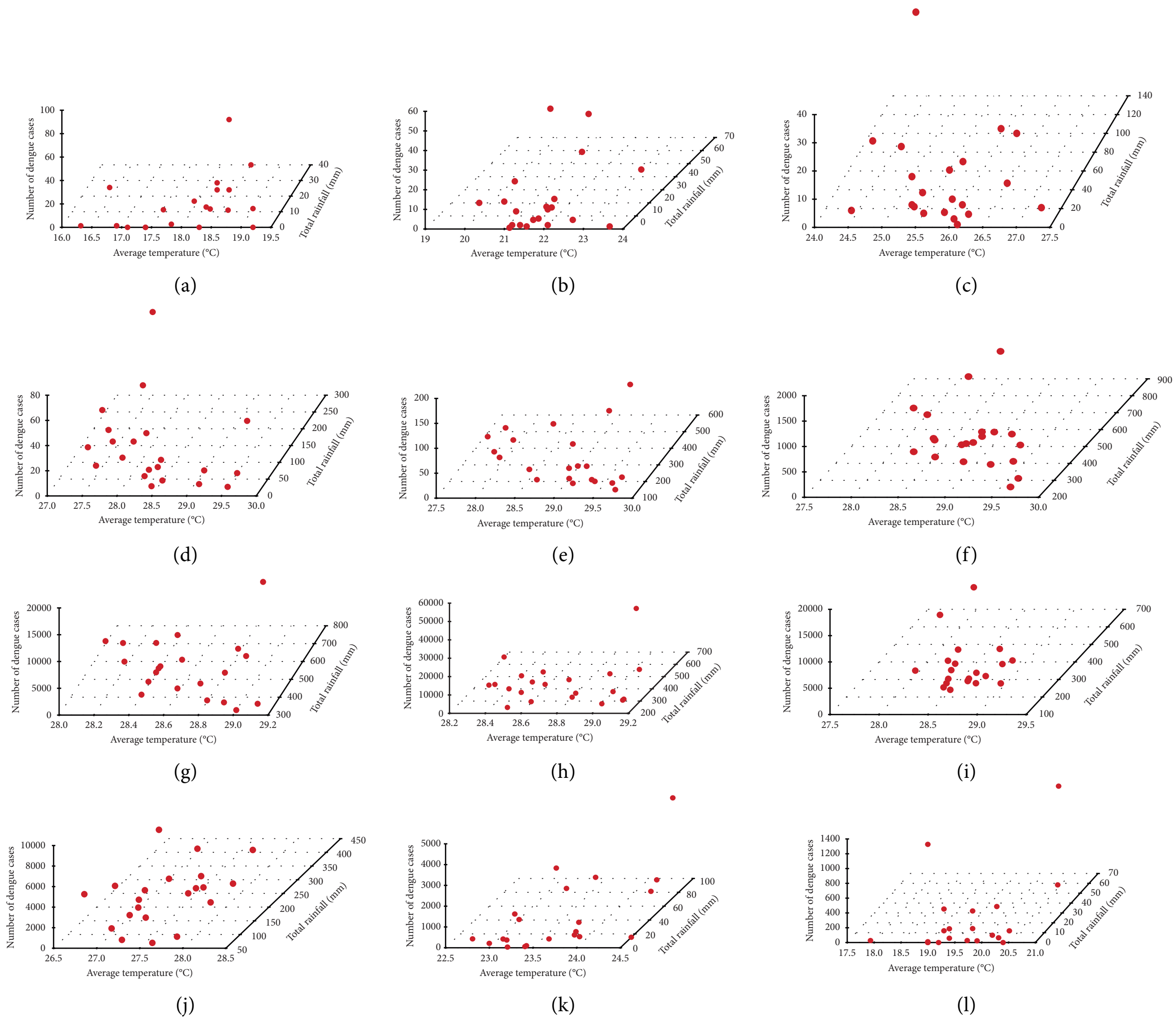

Figure 3: The impact of a particular month's daily average temperature and total rainfall on monthly dengue cases. Dots represent monthly dengue cases at different values of the total rainfall and daily average temperature in a particular month (January to December) of different years (2000 to 2021). Here, (a) January, (b) February, (c) March, (d) April, (e) May, (f) June, (g) July, (h) August, (i) September, (j) October, (k) November, and (l) December month's dengue cases at different values of the total rainfall and daily average temperature of different years (2000 to 2021).

that the number of dengue cases is lower than from July to October (Figure 3). The daily average temperature in March, April, and May is high enough at about 26°C, 28°C, and 29°C degrees, respectively, and there is often no or very little rainfall, and in these months, the number of dengue cases is much lower in comparison to July to October (Figure 3). In Bangladesh, the winter months, such as January, February, November, and December, are getting warmer. During this time, there is light to moderate rain falling. It has been observed that there are also more dengue patients throughout the winter (Figure 3).

3.5. Estimating Threshold Effects of Meteorological Factors on Dengue Cases. We found a nonlinear relationship between climate variables and dengue cases from the previous graphs (Figures 1–3). Here, the dependent variable, dengue cases in various months in different years, is a non-negative integer random variable. By considering all scenarios, count data regression models were used. Most earlier studies used Poisson regression models to calculate the association between environmental variables and dengue cases. However, the Poisson model is severely constrained by the assumption that the variance and mean are equal, which is frequently broken in real datasets. As a result, the count data are overdispersed when the conditional variance is greater than the conditional mean. As a result of the estimation, including underestimated standard errors of parameter estimation, hypotheses concerning Poisson regression parameters may be rejected more frequently than they should be. In this study, we applied a count data regression model to examine the effects of daily average temperature and total monthly rainfall on dengue incidence. We used quasi-Poisson and zero-inflated Poisson regression models to fix the overdispersed problem of the Poisson regression model.

3.6. Quasi-Poisson Regression Model. We considered y_{ij} the monthly dengue cases in the i^{th} month and j^{th} year. The response variable, $y_{ij} \sim$ quasi-Poisson (μ_{ij}), here μ_{ij} represents the expected number of dengue cases in the i^{th} month and j^{th} year, i.e., $E(y_{ij}) = \mu_{ij}$.

Therefore, the quasi-Poisson regression model can be expressed as follows:

$$\log\left(\mu_{ij}\right) = \mathbf{X}^{\mathbf{T}}\boldsymbol{\beta} = \beta_1 + \beta_2 T_{ij} + \beta_3 R_{ij}, \tag{4}$$

Here, T_{ij} = daily average temperature in the i^{th} month and j^{th} year ($i = 1, 2, 3, \ldots, 12$; $j = 2000, 2001, 2002, \ldots, 2021$). R_{ij} = Monthly total rainfall in the i^{th} month and j^{th} year ($i = 1, 2, 3, \ldots, 12$; $j = 2000, 2001, 2002, \ldots, 2021$). β_2 and β_3 are coefficients of daily average temperature and total rainfall in various months of the different years, respectively. Here, for daily average temperature, T_{ij} takes the values 1, 2, 3, and 4 for the average temperature (16 to ≤20°C), (>20°C to ≤25°C), (>25°C to ≤28°C), and (>28°C to ≤30°C), respectively. Monthly total rainfall, R_{ij}, takes the value 1 for the threshold (90 to ≤360 mm per hour) and takes the value 0 for the threshold (<90 mm and >360 mm per hour).

3.7. Zero-Inflated Poisson Regression Model. We considered y_{ij} as the monthly dengue cases in the i^{th} month and j^{th} year. In many months of some years, the number of dengue cases is zero. Now, let us consider the response variable $y_{ij} \sim$ zero-inflated Poisson (μ_{ij}), where μ_{ij} represents the expected number of dengue cases in the i^{th} month and j^{th} year, i.e., $E(y_{ij}) = \mu_{ij}$.

Therefore, the zero-inflated Poisson regression model can be expressed as follows:

$$\log\left(\mu_{ij}\right) = \mathbf{X}^{\mathbf{T}}\boldsymbol{\beta} = \beta_1 + \beta_2 T_{ij} + \beta_3 R_{ij}, \tag{5}$$

where the probability distribution of the zero-inflated Poisson random variable y_{ij} can be written as follows:

$$p_r\left(y_{ij} = k\right) = \begin{cases} \pi_i + \left(1 - \pi_i\right)\exp\left(-\mu_i\right), & \text{if } k = 0, \\ \\ \left(1 - \pi_i\right)\dfrac{\mu_i^{y_{ij}}\exp\left(-\mu_i\right)}{y_{ij}!}, & \text{if } k > 0, \end{cases} \tag{6}$$

Here, T_{ij} = daily average temperature in the i^{th} month and j^{th} year ($i = 1, 2, 3, \ldots, 12$; $j = 2000, 2001, 2002, \ldots, 2021$). R_{ij} = Monthly total rainfall in the i^{th} month and the j^{th} year ($i = 1, 2, 3, \ldots, 12$; $j = 2000, 2001, 2002, \ldots, 2021$). β_2 and β_3 are coefficients of daily average temperature and total rainfall in various months of different years, respectively. Here, daily average temperature, T_{ij}, takes the values 1, 2, 3, and 4 for the average temperature threshold (16 to ≤20°C), (>20°C to ≤25°C), (>25°C to ≤28°C), and (>28°C to ≤30°C), respectively. Monthly total rainfall R_{ij} takes the value 1 for the threshold (90 to ≤360 mm per hour) and takes the value 0 for the threshold (<90 mm and >360 mm per hour).

After fitting two regression models, the quasi-Poisson regression model and the zero-inflated Poisson regression model, AIC is used to compare the two models. Table 1 includes the model selection index Akaike's information criterion (AIC). The results indicated that the quasi-Poisson regression model was preferred over the zero-inflated regression model for our data.

Table 1: Comparison of quasi-Poisson and zero-inflated regression models based on AIC.

Model	AIC
Quasi-Poisson regression model	9.027097
The zero-inflated Poisson regression model	12114

Table 2: Estimation results for the effects of daily average temperature and total rainfall on dengue cases.

Variables	Coefficients $(\widehat{\beta})$	$s.e(\widehat{\beta})$	p value	Rate ratio
T_{ij}	1.66	0.258	0.001^{**}	5.25
R_{ij}	0.63	0.2811	0.076	1.87
Constant	4.20	0.9991		

Significance. codes: 0.0001 "***"; 0.001 "**"; 0.01 "*"; 0.05 "."; 0.1.

The regression analysis found that the daily average temperature and total rainfall significantly affect dengue cases. The estimated results are displayed in Table 2.

Table 2 shows the estimated value of coefficients $(\widehat{\beta})$, standard error of coefficients $(s.e(\widehat{\beta}))$, $p-$ value, and rate ratio (RR). The coefficient of daily average temperature (T_{ij}) has a significant effect at 0.1% level of significance, and monthly total rainfall (R_{ij}) has a significant effect at 10% level of significance on dengue cases. The estimation results demonstrated a positive correlation between dengue incidence and climate variables (daily average temperature and total rainfall). The estimates show that the risk of a dengue fever outbreak is about two times higher if the monthly total rainfall is between 90 and 360 mm compared to rainfall of less than 90 mm or greater than 360 mm.

4. Discussion

Bangladesh experienced its first dengue fever outbreak in 2000, after which dengue infection incidence began to decline. However, after 2010, the number of dengue cases began to almost climb until now (Supplementary Figure S-1). Dengue fever cases are seasonal. In Bangladesh, most dengue cases occur from July to October. In this study, we found that dengue fever incidence is significantly correlated with temperature; as the temperature rises, so does the transmission rate of dengue fever (Figure 1). Here, we found that dengue fever cases increased with light to moderate rainfall (Figure 2). On the contrary, very light rainfall, no rainfall, and heavy rainfall all reduce dengue fever transmission (Figure 2). Rainfall is necessary for dengue transmission, and warm temperatures provide a suitable environment for this transmission (Figure 3). Therefore, dengue fever cases are widespread in Bangladesh during the warm months (July to October) with moderate rainfall (Figure 3). We found that the temperature in June was too high, with heavy rains in many weeks of the month. Therefore, dengue cases are lower in June than in July through October (Figure 3). Months (March to May) with high temperatures and little rainfall have fewer dengue cases than July to October (Figure 3). Due to global warming, the winter months in Bangladesh are becoming warmer, with light to moderate rain falling. It has also been noticed that there are more dengue patients throughout the winter (Figure 3).

It is well known that there is a positive correlation between the rise in vector indices and the rise in disease outbreaks. This study estimated the nonlinear effects of climate factors on dengue incidence. We found a significant effect of temperature and rainfall on dengue cases. In addition, we discovered a positive correlation between dengue incidence and the daily average temperature. Here, average temperatures have been categorised into four thresholds: (16 to ≤20°C), (>20°C to ≤25°C), (>25°C to ≤28°C), and (>28°C to ≤30°C), and it was found that a warmer temperature significantly increases the total number of dengue cases. This study also found a positive correlation between dengue incidence and monthly total rainfall. We divided the monthly total rainfall into two thresholds: (90 to 360 mm) and (<90 or >360 mm) and discovered that less and moderate rainfall has a significant impact on the increase of the number of dengue cases; on the other hand, heavy rainfall or no rainfall decreases the number of dengue cases.

The findings of our estimation are consistent with earlier research on the ideal climatic conditions for mosquito growth dynamics. Many studies found that the number of dengue cases increases in warm temperatures. Female mosquitoes have a higher chance of surviving once the temperature reaches 25°C [27]. Furthermore, *Ae aegypti* was most active at temperatures around 28°C [55]. Wu et al.'s study similarly addressed the nonlinear relationship between temperature and dengue incidence and found a specific temperature at 28°C [28]. Again, between 20°C and 30°C, female mosquitoes have a maximum survival rate of roughly 88–93% [56]. The ideal temperature threshold for mosquito egg survival is 22 to 34°C [20]. The temperature range is 15°C to 32°C, where mosquitoes can fly most effectively [21]. It is believed that rain has beneficial and detrimental impacts on the expansion of the mosquito population. Rainfall can generate standing water for mosquito breeding. However, it has long been believed that excessive precipitation, such as that experienced during monsoons or cyclones, has the power to destroy prospective mosquito habitats [58]. Therefore, our findings were consistent with other research and can support the use of monthly total precipitation and daily average temperature to forecast the risk of dengue in practice.

5. Conclusion

5.1. Contributions of the Study. However, the possible threshold impacts of climate factors on dengue indices still need to be estimated in Bangladesh, despite significant research on the relationships between climate factors and dengue cases. Our empirical findings suggest that different temperatures will affect dengue cases differently. In this study, we found a positive relationship between daily average temperature and dengue incidence, and among the four thresholds of average temperature (16 to ≤20°C), (>20°C to ≤25°C), (>25°C to ≤28°C), and (>28°C to ≤30°C), the total number of dengue cases is maximum if the temperature falls into the threshold (>28°C to ≤30°C) and minimum for the threshold (16 to ≤20°C). This study also discovered a significant effect of monthly total rainfall on dengue incidence. Between the two thresholds of the monthly total rainfall: (90 to 360 mm) and (<90 or >360 mm), the likelihood of a dengue fever outbreak is around two times higher if the monthly total rainfall is within the (90 to 360 mm) threshold than if it is less than 90 mm or larger than 360 mm. Based on the estimation results, we concluded that dengue incidence rates would be substantially more vulnerable to climate change in areas with warmer temperatures. When the weather warms up, the effects of rainfall on dengue cases become more severe. This study emphasises the importance of identifying potential temperature thresholds for applying public health policies and risk prediction to prevent and control dengue fever.

5.2. Implications of the Study. Future extreme weather and climate events, including those with extremely high temperatures, are likely to occur more frequently and with greater intensity. Determining potential thresholds is essential to quantify the impacts of temperature on the climate-related spread of dengue and better support early warning systems for dengue epidemics [45]. Therefore, our research's conclusions can be handy for future epidemiological studies looking into the association between environmental variables and the incidence of dengue fever. Bangladesh's main dengue fever prevention strategies are designed to eliminate mosquito breeding grounds and reduce the density of mosquitoes. These dengue-preventative techniques could be effectively supported by determining specific temperature thresholds. Identifying temperature thresholds, in particular, is essential to build a reliable alarm system for residents and disease prevention personnel. Home and environmental sanitation should be improved when the average temperature is close to the threshold value to eliminate sources that vectors might breed. Integrated strategies and practices for dengue prevention and control (such as environmental approaches to eliminate container habitats; chemical, biological, and genetic approaches; and individual actions regarding dengue prevention interventions) are urgently needed when the temperature continues to rise and exceeds the threshold value, notably in high-risk areas and communities like Dhaka, Bangladesh. Our research may have significant policy implications for the future implementation of public health initiatives and risk assessments to prevent and control dengue fever.

5.3. Limitations of the Study and Recommendations for Further Research. Even though we found possible threshold dengue effects of climatic variables, our research had some limitations. Because of asymptomatic infections, dengue cases may be underreported. Due to variations in the method and level of effort put into the surveillance, the number of cases and the quality of the data collected during vector surveillance may also vary from county to county. Because of this, regional empirical estimates could be more precise than national empirical estimates. Due to the lack of specific dengue surveillance data, our empirical analysis relied on county-level panel data, which did not adequately account for the spatial dimension. However, the study of dengue should not be restricted to analyzing panel data to estimate the effects of climate conditions. Dengue epidemics' spatial distribution and transmission patterns may be better understood using spatiotemporal techniques and more specific dengue surveillance data. It is advised that future studies create regional models using more precise spatial data and community-level data.

Additionally, other locations or nations could estimate the association between meteorological variables and dengue incidence using the technique suggested in this study. To help with an early warning, this would be a constructive mechanism for tracking dengue outbreaks globally because dengue's ecological range has been discovered. As the temperature increases, vectors have moved from low-latitude locations to mid- or high-latitude regions. Future research is thus recommended to concentrate on the spread and habitat expansion of dengue vectors due to climate change.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The author declares that they have no conflicts of interest.

Supplementary Materials

Figure S-1: trends in annual dengue cases from 2000 to 2021. The trend over the years is represented by a smooth line that was obtained using the LOESS smoothing function; the shaded area displays the pointwise 95% confidence interval. Dots represent the total number of dengue cases in a given year. Figure S-2: average temperatures (°C) in Bangladesh from 2000 to 2021: A LOESS smoothing function is used to obtain a smooth line to represent the trend over the years. The shaded region represents the 95% confidence interval. Dots represent the average temperature of a given year. Figure S-3: total rainfall (mm) in Bangladesh from 2000 to 2021: A LOESS smoothing function is used to obtain a smooth line to represent the trend over the years. The shaded region represents the 95% confidence interval. Dots represent the total rainfall of a given year. Figure S-4: trends in dengue cases in various months (January to December) from 2000 to 2021. A LOESS smoothing function is used to obtain a smooth line to represent the trend over the years. The shaded region represents the 95% confidence interval. Dots represent the monthly dengue incidence in different years. Figure S-5: daily average temperatures (°C) in different months in Bangladesh between January 2000 and December 2021. A LOESS smoothing function is used to obtain a smooth line to represent the trend over the years. The shaded region represents the 95% confidence interval. Dots represent a given month's daily average temperature for different years. Figure S-6: monthly total rainfall in Bangladesh between January 2000 and December 2021. A LOESS smoothing function is used to obtain a smooth line to represent the trend over the years. The shaded region represents the 95% confidence interval. Dots represent the monthly total rainfall of a given month for different years. Table S-1: descriptive statistics of dengue cases in various months of different years (2000 to 2021). Table S-2: descriptive statistics of the variable daily average temperature (°C) in various months of different years (2000 to 2021). Table S-3: descriptive statistics of the variable monthly total rainfall (mm) in various months of different years (2000 to 2021). (*Supplementary Materials*)

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