The Seasonal Reproduction Number of Dengue Fever: Impacts of Climate to Transmission

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ABSTRACT

Background: The dengue fever is a mosquito-borne viral disease and a regular epidemic in Thailand. The peak of the dengue epidemic period is around June to August during the rainy season. It is believed that the climate is an important factor for dengue transmission.
Method: A mathematical model for vector-host infectious disease was used to calculate the impacts of climate to the transmission of dengue virus. In this study, the data of climate and dengue fever cases were derived from Chiang Mai during 2004-2014, Thailand. The value of seasonal reproduction number was calculated to evaluate the potential, severity and persistence of dengue infection.
Results: The mosquito population was increasing exponentially from the start of the rainy season in early May and reached its the peak in late June. The simulations suggest that the greatest potential for the dengue transmission occurs when the temperature is 28.7°C. The seasonal reproduction numbers were larger than one from late March to end of August and reaching the peak in June. The highest incidences occurred in August due to the delay of transmission humans-mosquito-humans. Increasing mean temperature by 1°C, the number of incidences increases 30%. However, a very high or very low temperature reduces the number of infection.
Discussion and Conclusion: The results show that the dengue infection depends on the seasonal variation of the climate. The rainfall provides places for the mosquitoes to lay eggs and develop to adult stage. The temperature plays an important role in the life cycle and behavior of the mosquitoes. A very high or very low temperature reduces the risk of the dengue infection.

Keywords: dengue, infectious disease, mathematical model, reproduction number

INTRODUCTION

The dengue fever is the most frequent mosquito-borne viral disease in the humans and has become a major international public health concern in recent decades. Over 50 millions people living in tropical and subtropical urban areas from Latin America to South East Asia are infected with dengue virus annually. Infected individuals may be asymptomatic or have high fevers, headache, muscle and joint pain, and a characteristic skin rash similar to measles. These symptoms can develop into the life-threatening dengue hemorrhagic fever and into the dengue shock syndrome. The dengue fever is caused by one of the four distinct serotypes of dengue virus (DENV), DENV1-4

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(World Health Organization, 2014). A recovery from the infection by one serotype provides lifelong immunity against that particular serotype but confers only temporary immunity against the other serotypes for approximately 2 years (Montoya et al., 2013). For dengue virus, the infection is transmitted through an intermediate vector, the infected mosquitoes. The primary vector of DENV is *Aedes aegypti* and the secondary vector is *Aedes albopictus*. Aedes mosquitoes are found throughout the tropical and subtropical areas and they have adapted to cohabiting with humans in both the urban and the rural environment. *Aedes aegypti* bites primarily during the day and it is most active for approximately two hours after the sunrise and several hours before the sunset, but it can bite at night in well lit areas. Only females bite to obtain blood in order to gain nutrients for eggs laying (Centers for Disease Control and Prevention, 2014).

Thailand is a tropical country, with relatively high temperature and humidity all year-round. These conditions are ideal for Aedes mosquito to establish. The dengue fever is a local epidemic in Chiang Mai, Thailand, throughout the year with the highest peak in June-August (Campbell et al., 2013). The counter dengue programs provided by public health services that consisted of educating people how to remove breeding sites of mosquitoes inside and outside residential areas, preventing from mosquito biting, mosquitoes population control during high dengue season. Statistically data suggested that the programs are still unable to stop the disease. The number of dengue fever incidences is increasing. All four dengue serotypes have been detected (Anantapreecha et al., 2005). Major dengue outbreaks have occurred irregularly every 3-4 years.

The environment, climate variables such as temperature, humidity, season and rainfall significantly influence the mosquito development. Several studies suggest that entomological parameters are temperature sensitive as the dengue fever normally occurs in tropical regions (Liu-Helmersson et al., 2014). The high temperature increases the life span of a mosquito and shortens the extrinsic incubation period of the dengue virus, thereby increasing the number of infected mosquitoes (Wu et al., 2009). The rainfall provides places for eggs and for larva development (Chompoosri et al., 2012). The climate change will certainly affect the abundance and distribution of dengue vectors (Khasnis, 2005). Exploring the relationships between the climate and the dengue transmission is an important task.

In recent decades, mathematical models were developed to investigate the infectious epidemiology. Most of the models incorporate several factors of the disease to predict the possible magnitude of the outbreaks. The basic reproduction number, R_0, is defined as the number of infected people generated by a single infectious person in an entirely susceptible population during infectious period. Typically, if $R_0 > 1$ an epidemic occurs while $R_0 < 1$, indicates no outbreak. The larger value of R_0 means the harder to control the epidemic (Heffernan et al., 2005). Estimations of the reproduction number of the dengue fever have varied widely which suggests highly heterogeneous levels of population immunity, vector density coupled with weather conditions.

The objectives of this study were i) to improve knowledge of the relationships between the climate sensitive variables and the dengue transmission dynamics, ii) to identify optimal conditions for a dengue epidemic potential, and iii) to develop a model for the dengue transmission.

THEORY AND METHODS

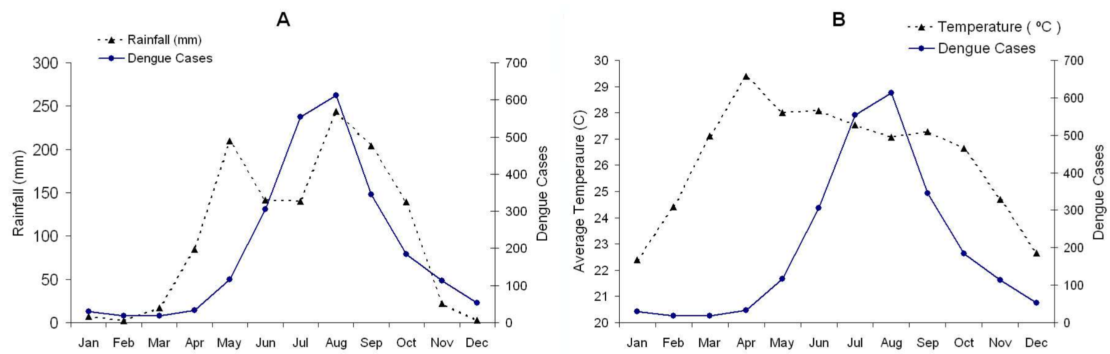

Figure 1. The average monthly incidence rate of dengue during 2004-2014 in Chiang Mai, Thailand is indicated by the complete line. The broken lines are (A) the average monthly rainfall and (B) the mean temperature during the same period.

The Dengue Situation in Chiang Mai, Thailand

This study was conducted using a mathematical model based on the demographic information of Chiang Mai province, Thailand. Chiang Mai is the largest province in the northern Thailand with a population of approximately 1.6 millions. The mean daily temperature is 22-29^{o}C and the rainy season starts in May and last until September. The dengue fever is one of the major public health concern in Chiang Mai. According to Vector borne disease bureau of Thailand (2014), the largest outbreak in the last decade was reported in 2013 with 11,432 cases compared to 664 in 2006 and 2,733 on the average, which is 226 cases per 100000 people per year during 2004-2014. Figure 1 shows the average monthly dengue incidences in Chiang Mai from 2004 to 2014 with (A) the average monthly rainfall during the same period and (B) the average monthly temperature (Meteorological Department of Thailand, 2014). The average dengue incidences range from 18 in February to 612 in August (Vector-Borne Diseases Bureau, Department of Disease Control, 2014). It is evident in the figure that the dengue incidences and the amount of rainfall are well correlated. The correlation between the dengue fever and the rainfall could be explained by increases in adult survival, breeding sites for eggs and feeding activity of the mosquitoes. Humidity increases the oviposition rate and extends the life span of adult mosquito (Canyon et al., 1999). However, the available data relationship between the humidity and the dengue transmission parameters is still insufficient to allow for a precise mathematical description.

Temperature Dependent Parameters

There are several parameters of the dengue transmission and mosquito life cycle that are temperature sensitive (T). Our approach is based on scientific literature on the dengue transmission with climate sensitive and vector parameters. Several works have shown that such a relationship exist and it can be described by means of mathematical equations (Liu-Helmersson et al., 2014).

Vector-Host Transmission Parameters

Transmission processes involve in infected mosquitoes bit humans then after virus incubation period and humans become infectious and able to transmit the virus to mosquitoes. The daily biting rate, extrinsic incubation period and probability of infection from human to mosquito or mosquito to human are temperature sensitive and can be illustrated as follow:

1) The daily biting rate (b) of a female *Aedes aegypti* increased linearly with temperature for 21°C$< T <$32°C as described by Scott et al. (2000):

$$b(T) = 0.0943 + 0.0043T,$$

2) The probability of infection from human to mosquito per bite (b_m) can be described as:

$$b_m(T) = -0.9037 + 0.0729T,$$

for the temperature range 12.4°C$< T <$26.1°C and it is equal to 1 for 26.1°C$< T <$32.5°C (Lambrechts et al., 2011).

3) The probability of transmission of the virus from an infected mosquito to human per bite (b_h) is a linear relation and it increases when 12.4°C$< T <$28°C decreases sharply when $T >$28°C and equal to zero $T >$32.5°C (Lambrechts et al., 2011). The following equation describes b_h:

$$b_h(T) = 0.001044T(T - 12.286)\sqrt{32.461 - T},$$

4) Extrinsic incubation period was demonstrated by Focks et al. (1995) as a decreasing relationship to temperature by using an enzyme kinetics model for 12°C$< T <$35°C. We let c denote the reciprocal of the extrinsic incubation period. It can be described by following equation:

$$c(T) = -0.1393 + 0.008T,$$

The Mosquito's Life Cycle Parameters

The temperature also was an impact on the entomological parameters regarding the mosquito's life cycle. Depending on the temperature and the availability of food, *Aedes aegypti* can complete larval development in 4-7 days. The sensitivity of temperature can be described as follows:

1) The mortality rate (μ_m) of the mosquito *Aedes aegypti* was explored by Yang et al. (2009) using the enzyme experiment. The results showed that the mortality rate ranged form 0.027 to 0.092 per day as 10.54°C$< T <$33.4°C.

$$\mu_m(T) = 0.8692 - 0.159T + 0.01116T^2 - 3.408 \times 10^{-4}T^3 + 3.809 \times 10^{-6}T^4,$$

2) The oviposition rate (a): Yang et al. (2009) showed that the oviposition rate increases with temperature. The value was nearly zero where the temperature was 15°C and large values of $T >$30°C.

$$a(T) = -15.837 + 1.2897T - 0.0163T^2$$

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3) Pre-adult mosquito maturation rate (s) from egg to adult mosquitoes (Yang et al., 2009).

$$s(T,t) = (0.00483T - 0.00796)(p_s - c_s\cos(\frac{\pi t}{365} + \theta))\Theta(p_s - c_s\cos(\frac{\pi t}{365} + \theta)),$$

θ is adjusted year cycle for s. The Heaviside Θ-function prevent $s(T,t)$ from becoming negative. This term is derived from Coutinho et al. (2006) to describe seasonal pre-adult mosquito maturation rate.

The Impact of Rainfall on *Aedes aegypti* Population

Mogi et al. (1988) examined the hatching rate and the amount of eggs in containers in Chiang Mai and reported that the peak of the population was approximately 1 month after the start of the rainy season from June until the end of September. The egg population remained low in the dry season but increased exponentially during the first half of the rainy season and then decreased sharply in the second half of the rainy season. Although the rain still continued, the population of aquatic stage mosquito was actually decreasing as the food supply in containers declined and the competition among larval increased. The amount of rainfall is associated with the mosquito population by increasing breeding sites or egg carrying capacity. An equation of the population dynamics of *Aedes aegypti* is created. The egg carrying capacity indicates the maximum population of aquatic mosquitoes (egg, larva, pupae) such that resources are sufficient and equation is as follows:

$$K(t) = (K_m + (1 - K_m)\sin^2(\frac{\pi t}{365} + \phi))K_E, \quad (1)$$

where $K(t)$ is the egg carrying capacity related to the amount of available food and space for eggs and then larvae will be able to develop, K_m is fraction of the minimum egg carrying capacity in the area, K_E is constant egg carrying capacity, ϕ is adjusted year cycle. K_E is always positive because several containers are rainfall independent. To demonstrate the mosquito population under the influence of the rainfall and temperature, we set $K_E = 100,000$, $K_m = 0.18$ is chosen to be the ratio between the egg hatching rate in dry and rainy seasons in Chiang Mai (183:1023) (Mogi et al., 1988).

Vector-host Dynamic Models

The mosquito population is divided into 5 categories: infected aquatic stage, I_E, susceptible aquatic stage, S_E, susceptible adult mosquito, S_M, latent adult mosquito, L_M, and infectious adult mosquito, I_M. Note that, the mosquito life span is too short to recover from dengue virus. The life of a mosquito consists of four stages: egg, larvae, pupae and adult stage. The first three stages live in the water and the last one stays in the air. In this study, we included the first three stages as aquatic stage and the last one as adult stage. The lifespan of each stage depends on several factors, for example, temperature, food supply and places for eggs hatching. The human population is classified into susceptible, S_H, infectious, I_H, and recovered individuals, R_H. Flows from the susceptible to infected classes of both populations depend on the biting rate of the mosquitoes, the transmission probabilities, as well as the number of infectious and susceptible individuals in each of the species. The parameters description is shown in Table 1. The model is described as

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following;

Human Compartment

The total human population, N_H, is $S_H + I_H + R_H$. The equations for the human compartment are the following:

$$\frac{dS_H}{dt} = \lambda_h N_H - \frac{x_1 b b_h I_M S_H}{N_H} - \mu_h S_H \tag{2a}$$

$$\frac{dI_H}{dt} = \frac{x_1 b b_h I_M S_H}{N_h} - (\mu_h + r) I_H \tag{2b}$$

$$\frac{dR_H}{dt} = (1 - \mu_d) r I_H - \mu_h R_H \tag{2c}$$

$$\frac{dC_H}{dt} = \frac{x_1 b b_h I_M S_H}{N_h}. \tag{2d}$$

where C_H is the cumulative number of infection. It describes the total number of infections in humans during a given period.

Adult Mosquito Compartment

The total population of adult mosquitoes, $N_M = S_M + L_M + I_M$. The equations are as follows:

$$\frac{dS_M}{dt} = sS_E - \frac{x_2 b b_m S_M I_H}{N_H} - \mu_m S_M \tag{3a}$$

$$\frac{dL_M}{dt} = \frac{x_2 b b_m S_M I_H}{N_H} - (\mu_m + c) L_M \tag{3b}$$

$$\frac{dI_M}{dt} = cL_M + sI_E - \mu_m I_M. \tag{3c}$$

where x_1 and x_2 are the transmission factors which control the simulation results fit to the actual data. x_1 and x_2 in this study are the factors such that unaccounted in laboratory experiments. For example, mosquito suck the human blood but fail to transmit the virus or humans live in the places that mosquito unable to contact. Also the mosquito counter measures are applied in the community.

Aquatic stage Mosquito Compartment

DENV can transfer from infected mosquitoes to eggs. The process is called vertical transmission (Adams, 2010). In this part, we divide the aquatic stage into susceptible and infectious population groups. The total population of aquatic mosquitoes (egg, larva and pupae), N_E, is $S_E + I_E$. The birth rate of the mosquitoes is described in term of logistic equations. We used the same assumption as Coutinho et al. (2006) that latent mosquitoes are unable to transmit dengue virus to theirs eggs. The populations of the aquatic stage are as follows:

$$\frac{dS_E}{dt} = a\left(1 - \frac{S_E + I_E}{K}\right)(S_M + L_M + (1-\gamma)I_M) - (s + \mu_e)S_E \tag{4a}$$

$$\frac{dI_E}{dt} = a\left(1 - \frac{S_E + I_E}{K}\right)\gamma I_M - (s + \mu_e)I_E. \tag{4b}$$

The parameter γ represents the proportion of infected eggs (0.5 (Coutinho et al., 2006)) laid by infected female mosquitoes.

An Approximated Threshold Condition and The Seasonal Reproduction Number

The Seasonal reproduction number, R_S, is another form of the basic reproduction number as the climate factors are included. The value will alternate during the year and it can be calculated using the van den Driessche and Watmough method (van den Driessche, 2002). The seasonal reproduction number is

$$R_S = \frac{\alpha}{2} + \sqrt{\frac{\alpha^2}{4} + \beta}, \tag{5}$$

where

$$\alpha = a\left(1 - \frac{N_E}{K_E}\right)\frac{sr}{(s+\mu_e)\mu_m}$$
$$\beta = \frac{x_1 x_2 b^2 b_h b_m z c}{\mu_m(\mu_m + c)(\mu_h + r)}.$$

where z is the ratio between the adult mosquito and human population. If R_S is less than 1, the disease does not invade the population and R_S is greater than 1, the disease becomes outbreak (Massad et al., 2011). By not invading population, it is the number of infected individuals always decreases in subsequent seasons of transmission. All calculations in this study were carried out by Matlab with ODE45 function for solving non linear equations. Our aim is to evaluate the dengue incidences using the mathematical model and estimate the effects of climate to the dengue transmission.

RESULT

Number of Incidences; Actual Data vs Simulation Results

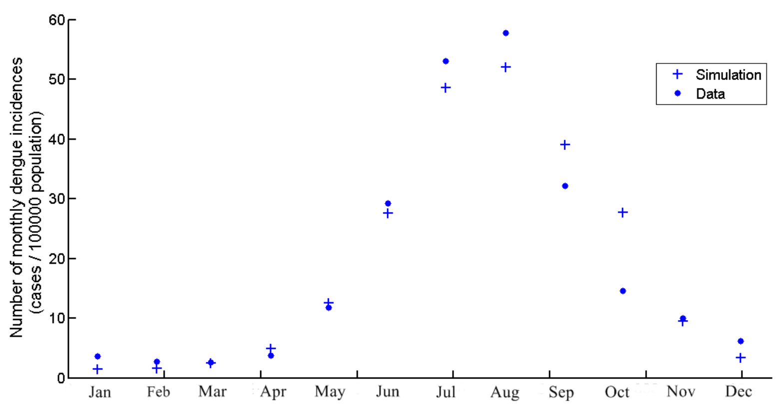

Figure 2. The number of monthly dengue incidences generated by the model and actual data of Chiang Mai from 2004 to 2014.

The initial conditions $S_H(0)$, $I_H(0)$, and $R_H(0)$ were assumed to be 100000, 25, and 0, respectively, in that the infectious population was estimated to be 5 cases in accordance with the number of confirmed cases in December. The initial values $S_M(0)$, $L_M(0)$, $I_M(0)$, $S_E(0)$, and $I_H(0)$ were set to be 10000, 0, 0, 10000, 100. We assumed

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Table 1. The description of symbols in this study

Parameters	Meaning	Values
λ_h	Human birth rate	0.00004
μ_h	Mortality rate of the humans	0.000035
r	Recovery rate of the humans	0.143
γ	Infection rate in mosquito's egg	0.5
μ_e	Mortality rate of the aquatic stage mosquito	0.143
μ_d	Death due to dengue	0.001
μ_m	Mortality rate of the mosquitoes	-
a	Oviposition rate	-
s	Pre-adult mosquito maturation rate	-
b	Daily biting rate	-
b_m	Probability of infection from human to mosquito per bite	-
b_h	Probability of transmission of dengue virus	-
	from infected mosquitoes to humans per bite	-
c	Inverse of extrinsic incubation period	-
K	Egg carrying	-
K_m	Fraction of minimum egg carrying	0.18
K_E	Egg carrying capacity	100000
ϕ	Adjusted year cycle for K	$\pi/3$
θ	Adjusted year cycle for s	$\pi/12$
p_s	Climatic factor modulating winters	0.55
c_s	Climatic factor modulating winters	0.45
x_1	Transmission mosquito-human factor	0.36
x_2	Transmission human-mosquito factor	0.2
t	Time	-
T	Mean daily temperature	-
S_H	Susceptible human	-
I_H	Infectious human	-
R_H	Recovery human	-
S_M	Susceptible adult mosquito	-
L_M	Latent adult mosquito	-
I_M	Infectious adult mosquito	-
S_E	Susceptible aquatic stage mosquito	-
I_E	Infectious aquatic stage mosquito	-
z	Ratio between human and mosquito population	-

The symbol $-$ means that the parameter is not constant.

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the egg carrying capacity equal to human population. The parameters are as Table 1, temperature and season as illustrated above.
The data from our model is obtained from the average monthly dengue incidences during 2004-2014 in Chiang Mai. Figure 2 shows the dengue incidences generated by the model, the cumulative number of infection in that month, and the average monthly incidences. The numbers are new infections in the month in question. The temperature is the temperature in Chiang Mai and seasonal factors as described in Table 1. The highest number of dengue incidences occurred in August. It is important to remind that the asymptomatic dengue fever represents 75.7%-90.2% of the total dengue infections (Seyler et al., 2009). In this study, we assumed that the actual infection number was 5 times greater than the reported cases, which is the same ratio as Seyler et al. (2009). However, the actual data showed only reported or symptomatic cases. Asymptomatic symptoms are generally ignored and unreported. In the model simulation, the infection is a combination of asymptomatic and symptomatic cases. Therefore, the number of infectious human generated by model was divided by 5 before fit to the actual data.

The Mosquito Population

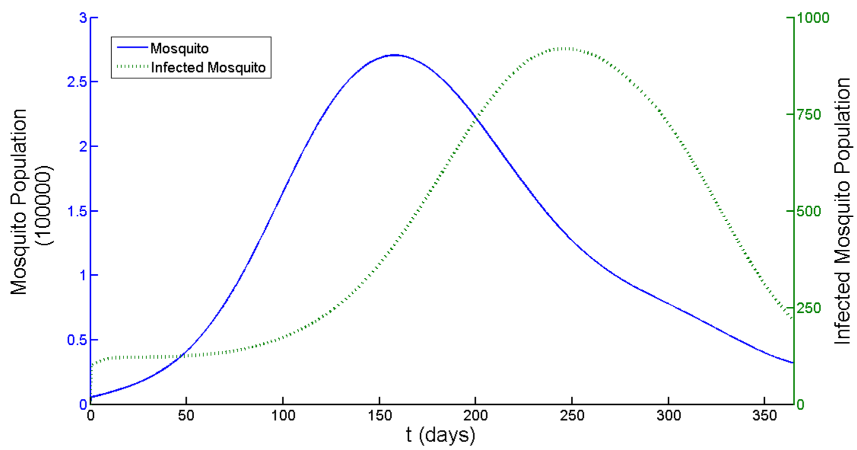

Figure 3. The number of mosquito and infected mosquito population generated by the model as a function of time (days). $t = 1$ is January 1^{st} and $t = 365$ is December 31^{st}. The peak points are $t = 157$ and $t = 247$ for the mosquito and infected mosquito population respectively. Note that different scale, left side for mosquito and right side for infected mosquito population.

Figure 3 illustrates the population of adult and infected mosquito by using model. The temperature used in this simulation was daily temperature of Chiang Mai and the seasonal factors also included. The running duration was one year ($t = 1$ is January, 1^{st}). The simulations show the peak of mosquito population is 270,000 and infected mosquito population is 900. It implies that the highest ratio between mosquito and human is 2.7. The time that both population groups successfully reach the highest number is $t = 157$ and $t = 247$ for mosquito and infected mosquito respectively. After that the infected mosquito population start to declined and also the number of human infection also reduce.

Seasonal Reproduction Number

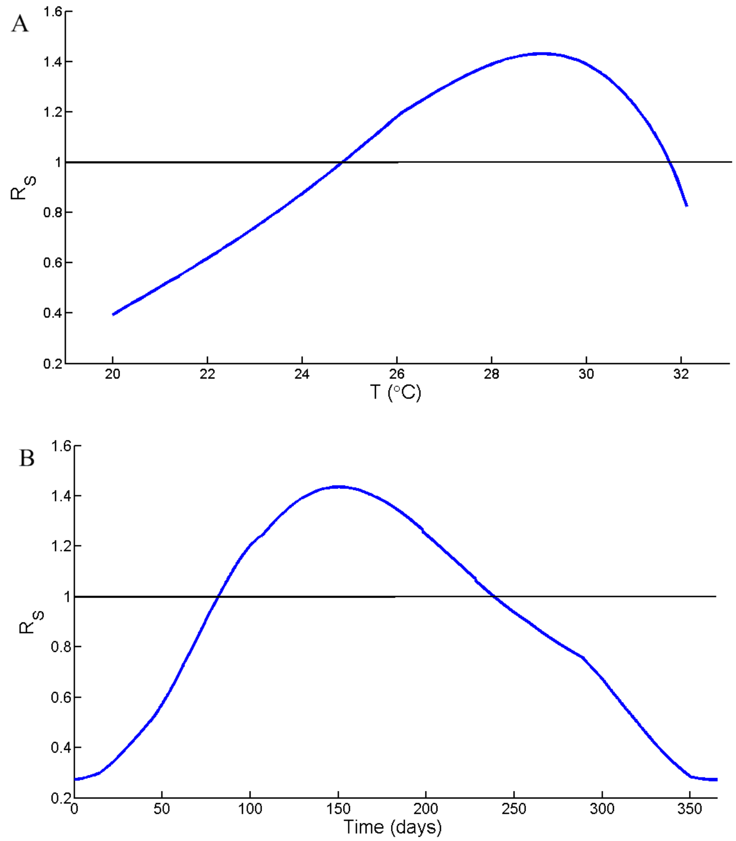

Figure 4. The seasonal reproduction number (R_S) as a function of mean temperature (A) and time (B). The horizontal line indicates $R_S = 1$. A: the ratio between mosquito and human z is 3. B: the mean temperature is from the mean temperature of Chiang Mai during 2004-2014

The optimal temperature for R_S is calculated by using a constant ratio between the humans and the mosquitoes (z). Figure 4A illustrates R_S as a function of the temperature (18°C< T <32°C) with constant value $z = 3$, which is above the highest number of results in figure 3. The function R_S is increasing and larger than one as the temperature is 24.9-31.7°C. The highest values of R_S 1.45 occurred at 28.9°C, equal to 1.45 decreasing rapidly thereafter. Figure 4B simulates the values R_S as a function of time for a period of one year. The temperatures are the daily mean temperature in Chiang Mai. The value of R_S reached its peak 1.43 in June ($t = 157$) and was larger than one when from $82 < t < 238$.

The Impact of Temperature to Dengue Incidences

The average yearly temperature in Chiang Mai is 26.7°C. To investigate the impacts of changing mean temperature to the on the dengue incidences, the term T_x was introduced. The new mean temperature is $T^* = T + T_x$. T_x is increasing or decreasing temperature from mean value from 2004 to 2014. Figure 5 shows the total yearly dengue incidences

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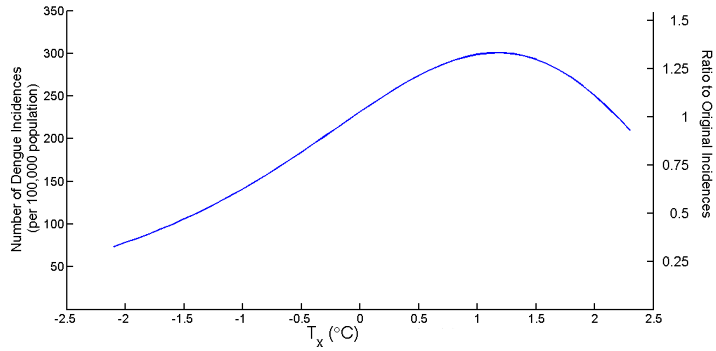

Figure 5. The number of total incidences in one year as the temperature changes (T_x) from the mean temperature of Chiang Mai during 2004-2014 ($T_x = 0$).

as a function of T_x and the ratio between the new total number of incidences and original number of incidences. The figure suggests that the highest incidence yielded at the temperature increased 1.1^{o}C equal to 300 cases per 100,000 population or an increase of 30.2% from original mean temperature. After that, the number of incidences decreases and lower than original mean temperature at $T_x = 2^o$C. When the mean temperature is reduced 2^{o}C ($T_x = -2^o$C),the number of dengue incidences is only one third of original number.

DISCUSSION

Mathematical models are very useful tools in describing infectious diseases and in developing control strategies. We believe that the dynamic results were caused by the comprehensive effects of temperature-dependent parameters. In this study, we incorporated seven temperature-dependent and two seasonal parameters for the dengue transmission model and considered the potential outbreak of the dengue infection. The study showed the severity and persistence of the disease with seasonal fluctuation. The mosquito population dynamics were difficult to evaluate and most of the previous studies assumed that population remained unchanged. The climate factors, such as rainfall and temperature, will shorten or extend the life cycle of the mosquito population. The ratio between the mosquito and the human population ranges from 0.3 to 20 (Chen, 2012). In this study, the mosquito population dynamics were set to be a function that corresponds to rainy season and life cycle of mosquito largely depend on temperature. After the start of the rainy season, the egg populations increased exponentially toward the peak abundance in the middle of the rainy season. The peak density tended to be higher in the rural area than in the urban area. This peak was followed by exponential decline despite continuing rains and high temperatures. The seasonal pattern foreshadowed by 1 month the epidemic pattern of dengue infection (Mogi et al., 1988). It is believed that the population burst tended to consume all the food supply accumulated in the containers during the dry season, so the later generations were subjected to a more severe competition through food exploitation.

The reproduction number in this study is low compared to the other studies (Nishiura, 2006). The reason is that the transmission mosquito-human-mosquito factors (x_1, x_2) are introduced in order to fit the model to the actual data. The previous studies using transmission probability were based on the data from experiments. In reality, there are several factors that could increase or decrease transmission rate.In this study, we attempted to simulate the results to match the actual data of the dengue incidences.

The optimal temperature of dengue transmission is 28.7^{o}C, which is near the mean temperature of Chiang Mai during the summer and the rainy season (27-29^{o}C). As shown in Figure 4B, R_S is larger than one when t from 82 to 237. The disease starts to invade the population group, the numbers of infected mosquitoes and humans are rising until reaching the peak and declining thereafter. The peak of R_S occurred in the early June ($t = 157$) but the highest number of incidences occurred in August. The mosquito population reach the peak in the early rainy season but the highest infection occur months later. The delay between the peak in the mosquito population and the peak in the dengue epidemic is nearly 90 days in this study, which corresponds to the actual data of mosquito population (Mogi et al., 1988) and the dengue incidences reported from Vector Borne Disease Bureau of Thailand (2014). This delay is due to the cyclic pattern of the mosquito population density. During unfavoured season, the mosquito population drops to a very low level with $R_S < 1$ (for transmission). In the beginning of the summer, the mosquito population begins to increase until it reaches a critical level at which R_S is greater than 1 and then the transmission begins, thus the delay occurs. This delay also mentioned in Coutinho et al. (2006) study.

In this study, an increasing of 1^{o}C in the mean temperature causes an increase of 30% in the number of the dengue incidences. Wu et al. (2009) shows that with every 1^{o}C increase in the monthly average temperature in Taiwan, the total population at risk for dengue fever by 95%. The reason for this difference is that the mean temperature in Chiang Mai is near the optimal temperature (28.7^{o}C) for several months. However, a very high temperature will cause a high mortality rate and will expand the extrinsic incubation period which results to mosquito to die before transmitting the virus to the humans.

CONCLUSION

The number of mosquito population varies according to seasonal variations. During favourable periods when the size of the mosquito population increases, the potential for dengue infection in the humans also increases. The potential for the dengue transmission requires the following four factors: 1) a number of susceptible humans, 2) a number of mosquitoes, 3) virus transmission potential, and 4) a suitable climate.

The temperature plays a significant role in the dengue transmission and influences the dynamic modelling of vector-host interaction.The most suitable temperature for the dengue transmission is 28.7^{o}C. Rainfall provides breeding sites for the mosquitoes to hatch and develop into the adult stage. Both factors have a significant impact to the mosquito population and the dengue transmission dynamics. Our simulations confirm the impact of climate to dengue transmission is significant and suggest that the greatest potential of dengue transmission in Thailand occur in June to August which average temperature is 28-29^{o}C in the mid of rainy season. The mosquito population reach the peak three months before the peak of infection in mosquito human. This study provides how the transmission of dengue affected by climate especially temperature and seasonal

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variations.

Acknowledgement

Author would like to thank Prof. Raimo Nakki of the University of Jyväskylä, Finland, for carefully read and comments the manuscript and also anonymous reviewers for suggestions and comments.

Declaration of Interests

This study was funded by faculty of science Silpakorn university grant number SRF-PRG-2557-05. The authors state that they have no conflicts of interest.

APPENDIX

The disease free equilibrium points of the model are as follow
$S_H = \dfrac{\lambda_h N_H}{\mu_h}$, $S_E = \dfrac{\mu_m K_E(a-(s+\mu_e))}{as}$, $S_M = \dfrac{K_E(a-(s+\mu_e))}{a}$
The reproduction number R_0 can be obtained using the method introduced by van den Driessche (2002). We write the system of differential equations as $\psi = f - v$ where

$$\psi = \begin{bmatrix} I_H \\ I_E \\ L_M \\ I_M \end{bmatrix} \quad ,f = \begin{bmatrix} \dfrac{x_1 bb_h I_M S_H}{N_H} \\ a(1-\dfrac{S_E+I_E}{K_E})\gamma I_M \\ \dfrac{x_2 bb_m S_M I_H}{N_H} \\ 0 \end{bmatrix} ,v = \begin{bmatrix} (\mu_h+r)I_H \\ (s+\mu_e)I_E \\ (\mu_m+c)L_M \\ -cL_M - sI_E + \mu_m I_M \end{bmatrix} \tag{6}$$

The jacobian matrices F and V, associated with f and v, respectively, at the disease free equilibrium are:

$$F = \begin{bmatrix} 0 & 0 & 0 & x_1 bb_h \\ 0 & 0 & 0 & a\gamma(1-\dfrac{S_E}{K_E}) \\ x_2 bb_m \frac{N_M}{N_H} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$V = \begin{bmatrix} \mu_h + r & 0 & 0 & 0 \\ 0 & s+\mu_e & 0 & 0 \\ 0 & 0 & \mu_m + c & 0 \\ 0 & -s & -c & \mu_m \end{bmatrix} \tag{7}$$

and the next generation matrix $G = FV^{-1}$ is:

$$G = \begin{bmatrix} 0 & 0 & \dfrac{x_2 bb_m c}{(\mu_m+c)\mu_m} & \dfrac{x_1 bb_h}{\mu_m} \\ 0 & 0 & \dfrac{a\gamma(K_E-S_E)c}{K_E(\mu_m+c)\mu_m} & \dfrac{a\gamma(K_E-S_E)}{K_E\mu_m} \\ \dfrac{\mu_m+c}{\mu_h+r} & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 \end{bmatrix} \tag{8}$$

R_0 is then the spectral radius of the next generation matrix, $R_0 = \rho(G)$, the largest eigenvalue of G.
Thus

$$R_0 = \frac{\alpha}{2} + \sqrt{\frac{\alpha^2}{4} + \beta}, \tag{9}$$

where

$$\alpha = a\left(1 - \frac{N_E}{K_E}\right)\frac{sr}{(s+\mu_e)\mu_m}$$
$$\beta = \frac{x_1 x_2 b^2 b_h b_m N_m c}{N_h(\mu_m + e)(\mu_h + r)}.$$

Note that β is the basic reproduction number proposed by MacDonald (1952).

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