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Research

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Temporal Correlation Between Urban Microclimate, Vector Mosquito Abundance, and Dengue Cases

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Abstract

Dengue Hemorrhagic Fever (DHF) is a major mosquito-borne viral disease. Studies have reported a strong correlation between weather, the abundance of *Aedes aegypti*, the vector of DHF virus, and dengue incidence. However, this conclusion has been based on the general climate pattern of wide regions. In general, however, the human population, level of infrastructure, and land-use change in rural and urban areas often produce localized climate patterns that may influence the interaction between climate, vector abundance, and dengue incidence. Thoroughly understanding this correlation will allow the development of a customized and precise local early warning system. To achieve this purpose, we conducted a cohort study, during January-December 2017, in 16 districts in Bandung, West Java, Indonesia. In the selected areas, local weather stations and modified light mosquito traps were set up to obtain data regarding daily weather and the abundance of adult female *Ae. aegypti*. A generalized linear model was applied to analyze the effect of local weather and female adult *Ae. aegypti* on the number of dengue cases. The result showed a significant non-linear correlation among mosquito abundance, maximum temperature, and dengue cases. Using our model, the data showed that the addition of a single adult *Ae. aegypti* mosquito increased the risk of dengue infection by 1.8%, while increasing the maximum temperature by one degree decreased the risk by 17%. This finding suggests specific actionable insights needed to supplement existing mosquito eradication programs.

Key words: *Ae. aegypti*, Bandung, dengue, weather

Dengue a major mosquito-borne viral infection caused by a virus (DENV 1 to 4) transmitted by *Aedes aegypti* and *Aedes albopictus*, has increasingly become a major public health concern worldwide (Halstead 2008, Bhatt et al. 2013, Shepard et al. 2013, Gaye et al 2014). As a vector-borne disease, the temporal variation and spatial distribution of dengue incidence are highly correlated with the distribution of *Ae. aegypti* (Choi et al. 2016, Wangdi et al. 2018). A growing body of evidence worldwide has demonstrated the link between climate variables (temperature, precipitation, and humidity) (Nakhapakorn and Tripathi 2005, Hau et al. 2011, Chen and Hsieh 2012, Cheong et al. 2013, Morin et al. 2013, Choi et al. 2016, Tong et al. 2016, Tseng et al. 2016, da Cruz Ferreira et al. 2017, Servadio et al. 2018, Tosepu et al 2018, Astuti et al 2019) and the distribution of vegetated areas (Koenraadt and Harrington 2008, Delatte et al. 2009, Colón-González et al. 2013, Morin et al. 2013, Townroe and Callaghan 2014, Xiao et al. 2014, Wong and Jim 2016, Benedum et al. 2018, Reinhold et al. 2018, Heinisch et al. 2019) to dengue transmission.

Information on relationships between climate factors and disease incidences provides an opportunity to create and adopt prototypes for early warning disease outbreak systems tailored to some vector-transmitted diseases, as shown for the Rift Valley fever disease outbreak response in the Horn of Africa (Anyamba et al. 2009), malaria risk prediction in Botswana (Thomson et al. 2006), and dengue in Brazil (Lowe et al. 2016) and Colombia (Lee et al. 2017). Some models have already been developed regarding the impact of climate changes on the distribution of mosquitoes and dengue at various geographic scales (Johansson et al. 2009, Mweya et al. 2016). However, these models rarely show the correlation between climate variables and both dengue epidemiology and vector abundance.

The majority of previous studies are based on the assumption of a potential role of mosquito density in the distribution of dengue cases, and vice versa. Moreover, the potential risk of dengue transmission has been measured based on the numbers of eggs, larvae, and other indices developed by these variables (Afrane et al. 2006). However, immature stage indicators were not directly associated with the risk of DENV infection (Liu-Helmersson et al. 2014) and high larval mortality, the short lifespan of larvae and pupae, and the brief time period of data collection have resulted in immature population measures that do not always correlate in space and time with the biologically relevant adult measures (Getis et al. 2003). In these studies, an association between dengue transmission and the existing indices has not proven to be satisfactorily predictive of dengue, compared to the predictive power of the abundance of adult mosquitoes (Cromwell et al. 2017, Murdock et al. 2017).

Another limitation of existing studies is related to the scale of the observation area. The distribution of mosquitoes is correlated with the flight range of the adult *Ae. aegypti* female, from 10 to 600 m (Reiter et al. 1995, Getis et al. 2003, Liew & Curtis 2004, Harrington et al. 2005, Russell et al. 2005, Maciel de Freitas and Lourenco de Oliviera 2009), and the availability of a suitable habitat for breeding (Brown et al. 2017) and rest (Sauer et al. 2021). In nature, mosquitoes respond to environmental variation at the micro-level (Potter et al. 2013, Pincebourde et al. 2016, Murdock et al. 2017, Sauer et al. 2021). In the urban area, the microclimate at different regions varies according to level of infrastructure (density of housing and man-made structure), waste heat, number of and distance to accumulations of standing water, and vegetation cover (Baruah and Rai 2000, Nagao et al. 2003, Afrane et al. 2006, 2008; Kamdem et al. 2012, Cator et al. 2013, Townroe and Callaghan 2014, Larsen 2015, Kumar et al. 2018). Such variations can affect the growth and development of mosquitoes (Li et al. 2014, Murdock et al. 2017), leading to the variation of its abundance which in turn may influence the risk of disease.

One study, in Guangzhou, China, produced a model for the impact of local climate on both dengue epidemiology and its vector abundance (Xu et al. 2017). However, the model has several limitations. First, the lack of an actual population number of mosquitoes at the point of sampling led to limited findings to a correlation between climate (meteorological) factors and dengue incidence based on the intermediary effect of mosquitoes. Second, the possibility of a spatial-related distribution of dengue vector could be biased since the data were not originated from the spatial scale. The meteorological situation varies spatially within a city; and because of the limited number of meteorological stations within a city (usually only one), the effect of local weather on fine-scale distributions of dengue incidence and mosquitoes could not be tested.

Based on the limitations of the prior research, in our study, we applied cohort data for a shorter study period and with the detailed local climate of a smaller area (village level) of some major dengue epidemic areas. This study aims to provide valuable information on how climate, at local level, influences mosquito densities and dengue occurrence. The result of the study will provide valuable information on how mosquito densities and disease interact with climate variability, especially in a local tropical monsoon climate. The findings may then be used to develop a program of dengue outbreak prevention and mitigation for similar endemic regions.

Methods

Study Area

The study was conducted in Bandung City (107°36′ east longitude and 6°55′ south latitude), the capital of West Java Province, with a total area of 16,729.65 Ha and located at 791 m above sea level (asl). The city consists of 30 sub-districts and 151 villages (Fig. 1). It is surrounded by mountains, creating a basin-like topology that produces unique local climates in each part of the city. The highest point is located at the north part of the city (1050 m asl), and the lowest point at the south part (675 m asl).

The number of reported annual confirmed dengue cases in Bandung City ranged from 3,000 to 6,000 in the period 2007–2016 (Bandung City Health Office 2016, Respati et al. 2017). In this study, we used dengue incidence data based on the number of dengue cases, provided by local health institute, diagnosed by antigen NS1 test followed by the qRT-PCR for confirmation. The annual mean proportions of the confirmed dengue patients in febrile suspected dengue patients ranged from 7.6 to 41.8 %, and the mean annual dengue incidence between 2007 and 2016 was 17.3 cases/1,000 person, which was 43 times higher than Indonesia's national average (Kosasih et al. 2016).

For the surveillance of vector mosquito abundance and microclimate, we selected 16 study villages from 151 villages in Bandung City based on the stratified random sampling approach (Wu et al. 2013). The villages were selected such that the spatial distributions of mean elevation, population density, poverty rate, and dengue incidence of each village would be as wide and evenly spaced as possible (Fig. 1).

Data Collection

Epidemiological Data

Monthly dengue incidences for the selected areas, from January 1 to December 31, 2017, were recorded and supplied by the Bandung City Health Office, Ministry of Health, Indonesia. Population data as of 2016 at the village level was obtained from the Central Bureau of Statistics of Bandung, Bandung City Population and Civil Registration Office. The incidence rate of dengue was calculated by the formula

$$Incidence\ rate = \frac{Total\ number\ dengue\ incidence}{Number\ of\ population} x\ 1000$$

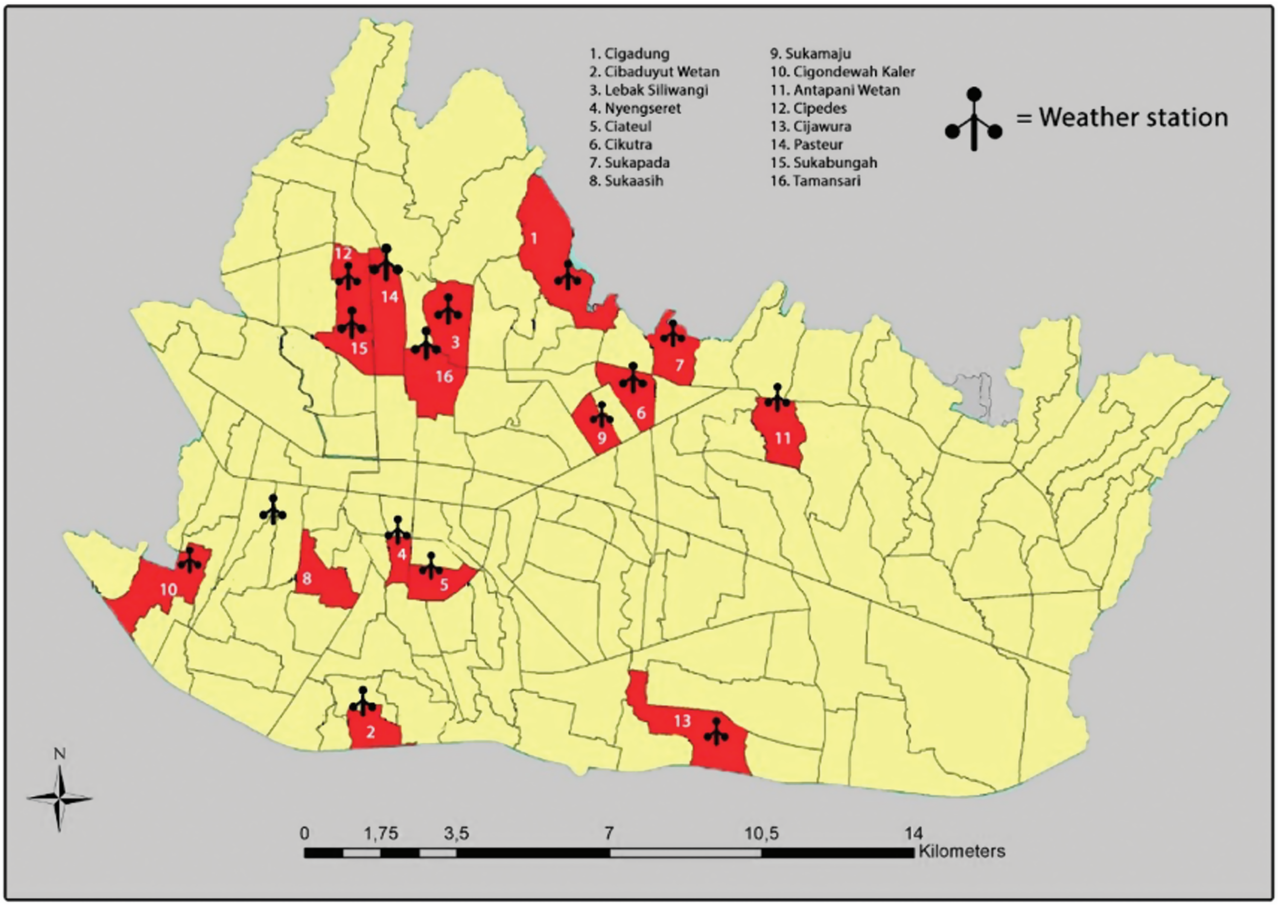

Fig. 1. Map of 16 study villages in Bandung City, Indonesia.

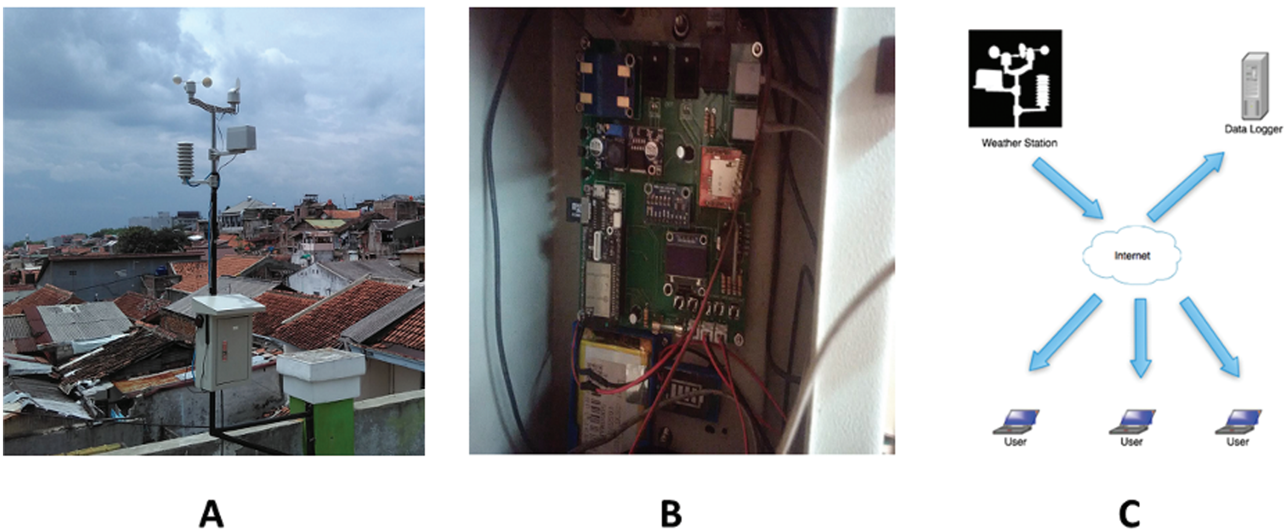

Fig. 2. A) AWS, the weather station, complete modules; B) microcontroller with a low power co-processor, additional external memory (SDCard), GPS and GSM modules; C) logger system for data collection and storage system.

Microclimate Monitoring

Telemetric automated weather stations (AWS) were constructed at one location per study village (n = 16) to collect continuous and real-time in situ microclimate data (Fig. 2). The parameters measured by the weather stations were precipitation (mm); air temperature (°C), air pressure (mbar or hPa), and relative humidity (%); and wind speed (km/h) and direction (intercardinal). Data were collected every minute and kept in a centralized data logger system prior to extraction for analysis. The measurement values were then formatted as a one-line data text record, simultaneously written to internal memory and transmitted via internet protocols on a cellular (GSM) network to the server (Fig. 2C). Based on the device id and GPS timestamp as key identifiers, these records were then appended to each device dataset in the server database. For subsequent analysis based on timestamps, all the AWS records in its dataset were accumulated into 24 h timescale. Web-based interfaces were built to provide access to the real-time data of the accumulated data in the server database.

All the AWSs were operated on a trial basis at the same location before installation in the study villages and were confirmed to show the same observations over 2 wks outdoors. In addition, one AWS unit was used for batch validation and calibration with the official and certified weather station device at Badan Geofisika, Meteorologi, Klimatologi dan Geofisika (BMKG, Meteorological, Climatological and Geophysical Agency) AWS. The difference (delta) of measurements between the AWS and the official weather station was then taken as a correction value for our AWS that was applied automatically by the server, in the database system, for each measured parameter.

The data observed every minute were converted to a weekly average value based on the average gonotrophic cycle of mosquitoes at 7 d. The average, as well as the minimum and maximum measurements of the microclimate parameter for the week, were used in the subsequent analysis.

Mosquito Surveillance

Adult *Ae. aegypti* and *Ae. albopictus* were collected from the 16 villages using commercially available mosquito UV light traps (Krissbow Mosquito Killer Set 7w) equipped with the hay infusion that attracts mosquitoes (Reiter et al. 2001). Mosquitoes were collected from 20 households randomly selected from each village every week from January to December 2017 (48 wks), for a total of 320 households. Two mosquito traps were installed for 24 h inside the selected houses. Mosquito abundance in each household was evaluated as the catch per unit effort, i.e., the number of individuals per trap, and the data were collected daily. The collected adults were morphologically identified as *Ae. aegypti* or *Ae. albopictus* using the keys (Rueda 2004). Only female *Aedes* mosquitoes, which transmit the dengue virus, were counted and used for our data analysis. The abundance of the mosquitoes then divided into temporal level of dry and raining season.

Data Analysis

The dataset consisted of 768 weekly observations (48 wks in 16 villages) of dengue incidence, microclimate parameters, and a total 15,360 data of mosquito abundance (48 wks, 16 villages, and 20 houses) (Fig. 3). Before analysis, the village-level data were aggregated into spatial average values within the 16 villages and daily mosquito abundance data also aggregated into weekly data.

Because the data were not normally distributed, based on the Kolmogorov-Smirnov test, we applied a Spearman correlation test to analyze the temporal correlations of dengue incidences, female *Aedes* mosquitoes mosquito abundance, and the microclimate parameters (maximum, mean, and minimum temperature; maximum, mean, and minimum humidity; minimum and maximum rainfall). The Spearman correlation test was conducted using PAST 4.05.

We used a generalized linear model (GLM) to examine the influence of microclimate parameters and mosquito abundance on dengue incidence. In this study, microclimate parameters and female *Aedes* mosquitoes abundance (as a major vector of dengue) were designated as independent variables, while the natural log of the number of dengue incidences was used as the dependent variable. To determine the appropriate time lag for each microclimate parameter and mosquito abundance, we applied from 0- to 12-week lags in each dependent variable and found the best lag-time for each variable based on a comparison of the Akaike's Information Criterion (AIC) (Akaike 1973). The best model in comparison to other candidate models has the smallest AIC (Burnham and Anderson 2004) as it provides the best approximates of the reality given by the data. The models with the lowest AIC were selected to determine the significant lag effect per climate variable and female mosquito abundance as a predictor for the dengue incidence. All of this process was conducted in the MASS package of R studio following the instructions written in Zhang et al. (2016).

Results

Dengue Incidence, Microclimate, and Mosquito Abundance

The microclimate data showed small fluctuation in temperature and rainfall during the study period while humidity showed more fluctuation value (Table 1, Fig. 4).

Altogether, 201 dengue cases were reported from the 16 study villages between January and December 2017. The average number of total cases per week was 4.2 cases, ranging from 0 to 10 weekly cases. High numbers of dengue cases were recorded during the dry season in Bandung, especially during June (Fig. 4).

The Spearman Correlation Analysis

There was a strong indication of the temporal distribution of dengue cases related to mosquito population and the seasonal pattern of microclimate parameters, especially maximum temperature. The abundance of female *Aedes* mosquitoes appeared to be independent of the change of local microclimate, as none of the observed variables developed any correlation to the abundance of mosquitoes (Table 2).

In general, the correlation between dengue incidences and local microclimate was weak and nonlinear. There was a negative correlation between dengue incidences and maximum temperature, minimum temperature, and maximum humidity.

Dengue Cases and Female Mosquito Abundances

A total of 1,428 female adults *Ae. aegypti* of a total number of 8,216 mosquitoes were collected from the 16 villages. The number of mosquitoes also showed a clear temporal pattern in which the number during the rainy season (January to May and October to December) was significantly higher than that in the dry season (June to September) (t-test, $P < 0.001$). Humidity produced during the

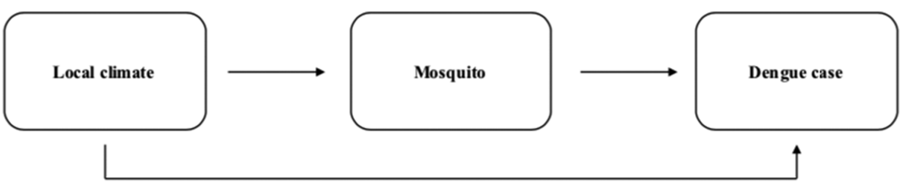

Fig. 3. Hypothetical interaction among local climate, mosquito, and dengue incidence.

Table 1. Microclimate of study area

	Case	Mosquitoes	Mean Temp. (° C)	Max Temp. (° C)	Min Temp. (° C)	Mean Humidity (%)	Max Humidity (%)	Min Humidity (%)	Mean Rainfall (mm)	Max Rainfall (mm)
Mean	4.188	29.750	26.344	35.260	21.688	76.712	94.854	41.225	0.008	3.671
Standard Deviation	2.447	17.204	0.399	1.433	0.794	5.879	2.974	3.607	0.010	1.541
Minimum	0.000	0.000	25.573	32.060	20.180	63.571	84.410	32.950	0.000	1.740
Maximum	10.000	80.000	27.159	38.010	23.420	88.499	98.990	47.530	0.060	8.380

rainy season acted as the significant positive factor for vector abundance (Fig. 5).

In Indonesia, the raining season, with sporadic heavy rainfall, usually occurs from October to March (West Moonsoon) and the dry season usually occurs from April to September (East Moonsoon) (Fig. 5A). Correlation analysis showed a strong significant and positive correlation between female mosquito abundance and dengue incidence (Table 2).

Generalized Linear Models (GLMs)

GLM analysis showed mosquito abundance at lag 0 (week) is the most important factor for dengue to happen, followed by the maximum temperature at lag 3 and mean temperature at lag 0. Both the number of mosquitos and maximum temperature proved to be significant, yet they affect the number of dengue cases in a different way. Following the trend in the latest lag, mosquito abundance had a positive correlation with dengue cases, while the maximum temperature showed the opposite (Table 3). Based on these significant values, our model suggests that increasing one unit mosquito from normal abundance level could increase the risk of dengue incidence by 1.8%, while reducing the maximum temperature by one unit could improve the risk of dengue by 12.4%.

Based on AIC calculation, the best prediction model for dengue incidence was vector abundance (156.4) followed by the combination of both microclimate data and vector abundance (183.41). In contrast, the non-significant effect of local climate on female mosquito abundance showed the highest AIC value (202.41) (Fig. 6).

Based on both calculations (GLM and AIC value), the final model for the effect of local microclimate and female mosquito abundance on dengue incidence is as follow:

Dengue case ~ Σ mosquitoes (lag (0)) + mean temp (lag (0)) + max temp (lag (3)) + cum rainfall (lag (1)) + mean humidity (lag (1)) + min temp (lag (0)).

Discussion

Vector Abundance and Microclimate

This correlational study showed humidity to be the microclimate variable that strongly and positively affects the abundance of dengue vectors. This result supports the hypotheses on the strong effect of humidity on *Ae. aegypti* populations (Lega et al. 2017, Evans et al. 2019, Tuladhar et al. 2019). This positive correlation may be related to the improvement of oviposition activities and egg survival rate at higher humidity, especially during the high-temperature period (Costa et al. 2010). As a tropical country, high temperatures are common in Indonesia and can rise above 30°C (our study area had the country's highest daily temperature, between 32 and 38°C). However, although many studies have reported an effect of temperature on the survival and host finding and reproduction behaviors related to dengue infestation (Beck-Johnson et al. 2017, Haider et al. 2017, Wong and Jim 2016, Asigau and Parker 2018), our study showed a lack of correlation between vector abundance and temperature. This result may be related to the endophilic behavior (high preference to taking shelter inside a closed structure like a house) of *Ae. aegypti* (Reinhold et al. 2018) which allows them to benefit from a controlled indoor temperature (Jansen and Beebe 2010).

Vector Abundance and Dengue Cases

Recent studies have produced growing evidence that *Aedes* abundance correlates positively with the occurrence of dengue cases in endemic areas (Potter et al. 2013, Agha et al. 2017,

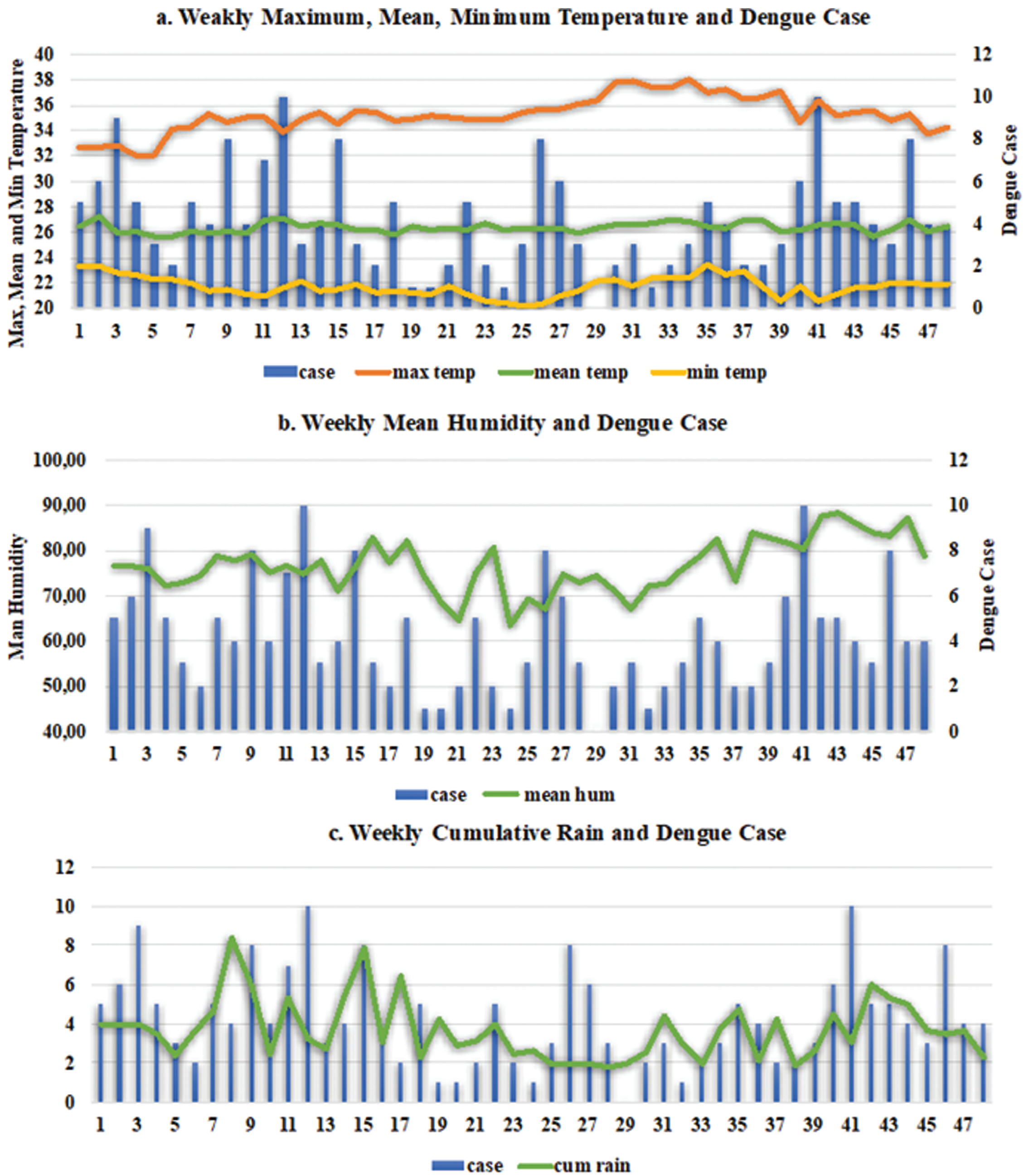

Fig. 4. Weekly transition of total dengue cases and mean microclimate data in the 16 study villages in Bandung City between January and December 2017.

Betanzos-Reyes et al. 2018, Ong et al. 2018, 2021), a finding that accords with our study. By incorporating information on the actual population and number of dengue cases in a specific region, our GLM further predicted that the addition of one individual adult female *Ae. aegypti* in a household may increase dengue incidence by 1.8%.

Although our study did not directly observe the DENV in the vector, we based our quantitative influence on two assumptions: (1) a higher abundance of *Ae. aegypti* can increase the risk of dengue because of their biting behavior, which will lead to an increase in virus transmission (Scott et al. 2000, Medlock et al. 2009, Harrington et al. 2014): and (2) silent circulation of dengue virus occurrence (Ferreira de Lima et al. 2020) due to natural vertical transmission of DENV may be added as another consideration, as reported in another area in Indonesia (Mulyatno 2012). This addition may be applicable for endemic areas, like our study area, where cases occur every week (except week 29 in our data) and thus the source of DENV is always available. However, further studies are required to confirm these hypotheses for our study area.

Dengue Case and Microclimate

This study showed a significant negative correlation between dengue case and maximum temperature at lag 3 wks, which may indicate that infection is less likely to occur during the hottest week (incubation and symptomatic period for dengue usually last for 2–3 wks). Additionally, our GLM showed that increasing the maximum temperature by one unit would reduce the incidence of dengue cases by about 12.4%. This finding is consistent with a study by Campbell et al. (2013) which reported a significant general correlation between

Table 2. Spearman's rank correlation coefficients and probability (p) values between dengue incidence, microclimate parameters, and mosquito abundance

	Case	Mosquitoes	Mean Temp. (° C)	Max Temp. (° C)	Min Temp. (° C)	Mean Humidity (%)	Max Humidity (%)	Min Humidity (%)	Mean Rainfall (mm)	Max Rainfall (mm)
Case		7.80×10^{-6}	0.386	0.026	0.710	0.094	0.190	0.713	0.271	0.059
Mosquitoes	0.596		0.886	0.823	0.441	0.033	0.489	0.360	0.058	0.190
Mean Temperature	0.128	-0.021		0.021	0.336	0.964	0.849	0.108	0.953	0.974
Max Temperature	-0.322	-0.033	0.331		0.418	0.754	2.01×10^{-5}	3.29×10^{-5}	0.346	0.325
Min Temperature	-0.055	-0.114	0.142	-0.120		0.599	2.85×10^{-5}	0.021	0.250	0.743
Mean Humidity	0.244	0.308	-0.007	-0.046	0.078		0.023	0.166	0.291	0.107
Max Humidity	-0.192	0.102	-0.028	0.574	-0.565	0.327		0.007	0.282	0.547
Min Humidity	0.054	-0.135	-0.235	-0.699	0.332	0.203	-0.381		0.155	0.059
Mean Rainfall	0.162	0.276	0.009	-0.139	0.169	0.156	-0.158	0.208		0.075
Max Rainfall	0.275	0.192	-0.005	-0.145	0.049	0.236	0.089	0.275	0.259	

incidence of cases and temperature and slightly between cases and humidity, albeit a lack of information on the quantitative influence of each unit of temperature or humidity.

Lower dengue cases at high temperature could be related to lowering the vectorial capacity (VC), the number of infectious bites that could potentially arise from one fully infectious host (Smith et al. 2012, PlOs Pathogens). Further, our study recorded the extreme highest temperature (on average more than 35°C) which could produce a negative effect on mosquito blood-seeking behavior (Carrington et al. 2013, Reinhold et al. 2018), survivorship of adults (Gonidin 2015, Marinho et al. 2016), and longevity (Costa et al. 2010, Marinho et al. 2016) which are related directly to virus transmission by *Ae. aegypti*. Also, highly fluctuating diurnal temperature (about 12–13°C in this study) reportedly causes a negative effect on vector competence and life history (Lambrechts et al. 2011, Mohammed and Chadee 2011, Carrington et al. 2013, Ernst et al. 2017), which may also explain the negative correlation between maximum temperature and dengue incidences.

Future Implication

Global climate change, especially global warming, is a major concern worldwide, and a study on the climate model has showed the possibility of increasing mean and maximum daily temperatures and humidity in the tropical region (Zhang et al. 2021). Although our research showed the negative correlation between temperature and dengue transmission, however, the possibility of increasing installation of indoor temperature regulator systems and the endophilic behavior of *Aedes aegypti* may increase the possibility of dengue incidence as the number of eggs deposited indoor relatively similar to outdoor (Putra, unpublished data).

However, although temperature is an important determinant of biting rate, egg and immature mosquito development, development time of virus in the mosquito, and survival at all stages of the mosquito life cycle (Mordecai et al. 2017), the effect is not always linear or very localized (Brady et al. 2014). Therefore, due to the complex interaction of weather and other factors, changes in the incidence of dengue are difficult to predict based only on microclimate data (Viennet et al. 2016), although such data could provide baseline information for an early warning system.

We hope our study will strengthen the basis for improvements in mosquito eradication policy. Our model supports a previous study on the efficient ability to transmit the virus at a very low level of the population (Gubler 2002a,b; Kuno 1997). Although we aggregate the data, individual data at finer scale showed the correlation among microclimate, dengue vector (adult mosquitoes), and dengue incidence at all sampling area which may explained the dynamic of the virus transmission at endemic areas. The rapid changes of microclimate at finer scale allowed the changed of epicenter of the virus and could explain the unpredictable pattern of dengue incidence at both spatial and temporal. In addition, our study emphasizes the importance of a sustainable public-health program that can lower and maintain the vector population under the threshold (Achee et al. 2015; Bowman et al. 2014; Scott et al. 2000).

Conclusion

Our model showed a positive correlation between vector abundance and dengue incidence, while maximum temperature showed a negative correlation. In general, an increase in vector abundance by a single unit may increase the possible dengue incidence by 1.8%,

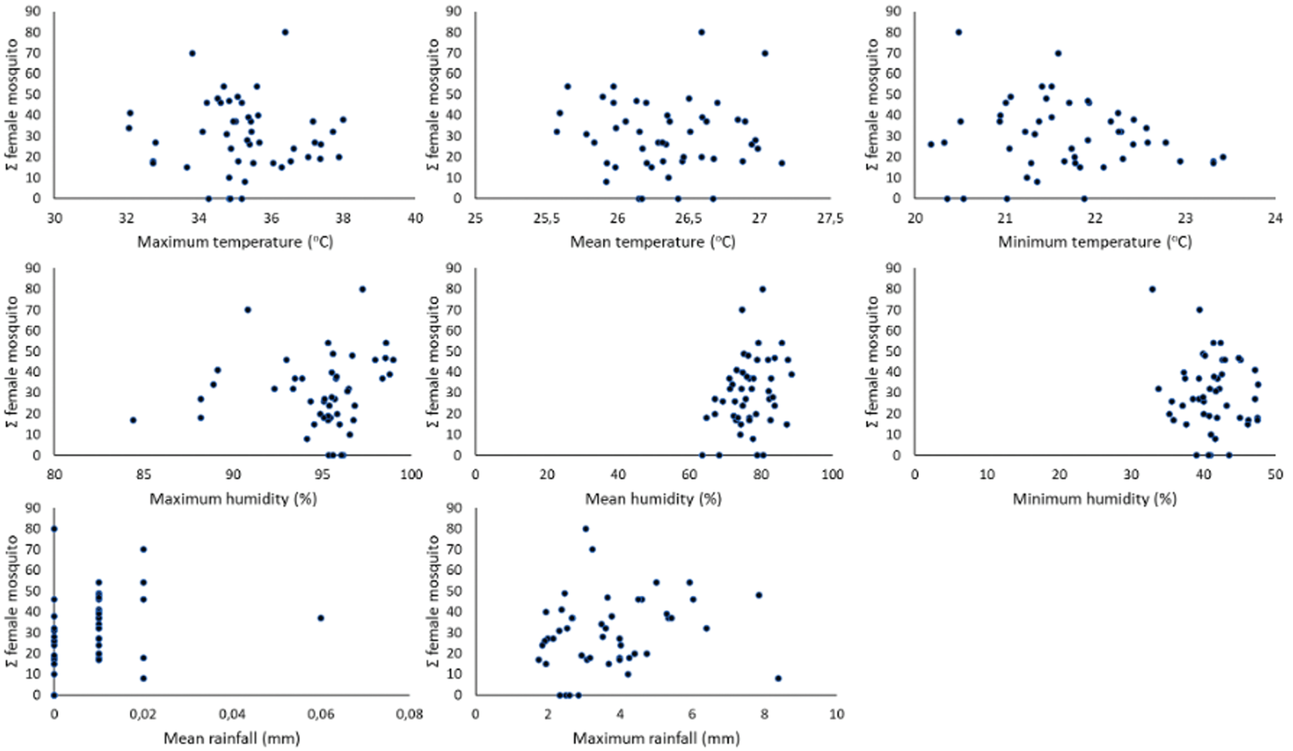

Fig. 5. Temporal correlation of weekly female mosquito abundance and microclimate parameters.

Table 3. GLM analysis of correlation of local climate and mosquito on dengue case

Coefficients	Estimate	Std. Error	z value	Pr(>|z|)
(Intercept)	-4.072	5.714	-0.713	0.476
Σ Female mosquito lag (0)	0.018	0.004	4.339	1.43×10^{-5}***
Mean temperature lag (0)	0.423	0.221	1.917	0.055
Max temperature lag (3)	-0.124	0.063	-1.979	0.048*
Cumulative rainfall lag (1)	0.001	0.001	0.347	0.728
Mean humidity lag (1)	0.006	0.014	0.427	0.669
Min temperature lag (0)	-0.112	0.115	-0.978	0.328

Significance codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

while a small increase in maximum temperature may reduce the possible dengue incidence by 12.4%.

This study shows the effect of climate, in the urban area, on vector abundance and dengue incidence and benefit of utilization of collection of small-scale data for various sampling point to generate a prediction model based. This study also points to the importance of developing a more localized early warning system for dengue prevention, especially based on vector abundance.

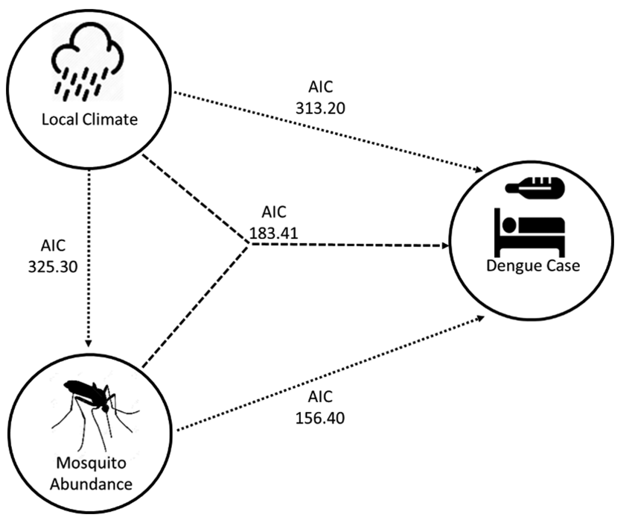

Fig. 6. AIC value for four models.

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