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Spatio-temporal climate-based model of dengue infection in Southern, Thailand

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ABSTRACT. This study explored the spatio-temporal patterns of dengue infection in southern Thailand. Data on monthly-notified cases of dengue fever, over the period of January 1981-May 2014 were collected from the Bureau of Epidemiology, Department of Disease Control, Ministry of Public Health. Weather data over the period of January 2007-May 2014 were obtained from the Thai Meteorological Department. Box and whisker plots were used to study the spatial temporal patterns of dengue incidence. Spearman correlation analysis and time-series adjusted Poisson regression analysis were performed to quantify the relationship between weather and the number of dengue cases. The results show that the highest dengue cases occurred in July in the Gulf of Thailand. Conversely, for the Andaman Sea, the highest dengue cases occurred in June in Phang-Nga, Phuket and Ranong provinces. Only Krabi province had the most dengue cases occurring in July. When we compared dengue transmission duration between the Andaman Sea and the Gulf of Thailand, we found that for the Andaman Sea, Trang province had the longest dengue transmission duration (i.e. June-September) and for the Gulf of Thailand, Nakhon Si Thammarat had the longest dengue transmission duration (i.e. June-September). The number of rainy days and relative humidity were the main predictors of dengue incidence by the Gulf of Thailand, while the amount of rainfall and the temperature were the main predictors of dengue incidence by the Andaman Sea. The time series Poisson regression models provided such goodness-of-fit that the correlation between observed and predicted numbers of dengue incidence exceeded 80%. These models could be used to optimise dengue prevention by predicting trends in dengue incidence. Accurate predictions, for even a few months, provide an invaluable opportunity to mount a vector control intervention or to prepare for hospital demand in the community.

INTRODUCTION

Dengue viruses have four known antigenically distinct serotypes and are primarily transmitted by the mosquito vector *Aedes aegypti* and possibly *Ae. albopictus* (Hay *et al.*, 2000; Stephenson *et al.*, 2003; WHO, 2009; Yu *et al.*, 2011). These mosquitoes are well adapted to the urban environment and successfully breed in containers where water is allowed to accumulate, such as discarded cans, bottles, plastic containers, and tyres (Luemoh *et al.*, 2003; Wongkoon *et al.*, 2005, 2007). The incidence of dengue has grown dramatically around the world in recent decades. The incidence of dengue disease is now endemic in more than 100 countries, with about 50 million dengue infections worldwide every year and approximately 2.5 billion people living in dengue-endemic countries. The Southeast Asian and Western Pacific regions have the highest burden (WHO, 2008). In Thailand, dengue occurred first only in Bangkok in 1958, but soon spread to other areas (Halstead *et al.*, 1969; Gould *et al.*, 1971). A total of

150,934 dengue cases in Thailand were reported from 77 provinces from January to December in 2013 (234.86 cases per 100,000 population). Southern Thailand has the highest mortality rate at 0.15 cases per 100,000 population (Bureau of Epidemiology, 2013).

The peak periods of dengue infection occur throughout the world from early summer to late fall, when the mosquito numbers are high (WHO, 2009). There are several factors that influence dengue incidence including topography (Wongkoon *et al.*, 2005), water consumption (Luemoh *et al.*, 2003), and environmental and climatic factors (Bi *et al.*, 2007; Wongkoon *et al.*, 2011, 2013a,b). Since, the importance of climatic factors in the survival and egg-laying activity of mosquitoes, weather is often used to predict dengue outbreaks in several countries (Wu *et al.*, 2007; Hsueh *et al.*, 2012; Wongkoon *et al.*, 2013). Neither vaccine nor specific treatments are available against dengue fever (Morrison *et al.*, 2004; Bruno *et al.*, 2011). Well-designed and reliable strategies for specific temporal patterns and a predictive model for the disease are needed (Wongkoon *et al.*, 2013). Mathematical and statistical models have been used to study the spatial or spatio-temporal spread of dengue fever (Nishiura, 2006; Maidana & Yang, 2008; Otero *et al.*, 2008; Yu *et al.*, 2011).

During recent years, with the rapid development of geographic information systems (GIS), methods of spatial analysis have been increasingly applied to infectious diseases, especially dengue fever (Eisen & Lozano-Fuentes, 2009; Wen *et al.*, 2010; Li *et al.*, 2012). Identification of spatial high-risk areas can help guide the local health departments to formulate public health strategies, initiate early preventive measures, and conduct enhanced surveillance, thereby reducing the risk of epidemics (Mammen *et al.*, 2008; Siqueira-Junior *et al.*, 2008; Hu *et al.*, 2011). In this study, we aim to explore the spatial-temporal modelling of dengue fever cases in Southern Thailand, and to predict the number of dengue cases by the Andaman Sea and by the Gulf of Thailand, thus to identify the temporal risk factors in the provinces and thereby help plan resource allocation for dengue prevention and intervention.

MATERIALS & METHODS

Study area

Southern Thailand comprises 14 provinces. In this study, we selected the provinces divided by the topographical areas by both the Gulf of Thailand and by the Andaman Sea. The Gulf of Thailand side consists of Chumphon, Surat Thani, Nakhon Si Thammarat and Phatthalung, while the Andaman Sea side comprise Krabi, Trang, Phang-Nga, Phuket and Ranong provinces (Figure 1). The Andaman Sea is bound in the north by the Irrawaddy River delta of Myanmar (Burma); in the east by peninsular Myanmar, Thailand, and Malaysia; in the south by the Indonesian island of Sumatra and by the Strait of Malacca; and in the west by the Andaman and Nicobar Islands, which constitute a union territory of India. The Gulf of Thailand is bordered by Cambodia, Thailand and Vietnam. The northern tip of the gulf is the Bay of Bangkok at the mouth of the Chao Phraya River. The gulf covers roughly 320,000 km^2. The sea boundary of the gulf is defined by the line segment from Cape Bai Bung in southern Vietnam (just south of the mouth of the Mekong River) to the city Kota Bharu on the Malaysian coast. The summer season by the Gulf of Thailand is from February to May, and the rainy season starts in June and ends in January.

Data Collection

We obtained the computerised data set on monthly dengue cases in Southern Thailand (Gulf of Thailand: Chumphon, Surat Thani, Nakhon Si Thammarat, Phatthalung; Andaman Sea: Krabi, Trang, Phang-Nga, Phuket, Ranong) for the period of January 1981-May 2014 from the Bureau of Epidemiology, Department of Disease Control, Ministry of Public Health. Weather data over the period of 2007-May 2014 were obtained from the Thai Meteorological Department (TMD). These data consisted of

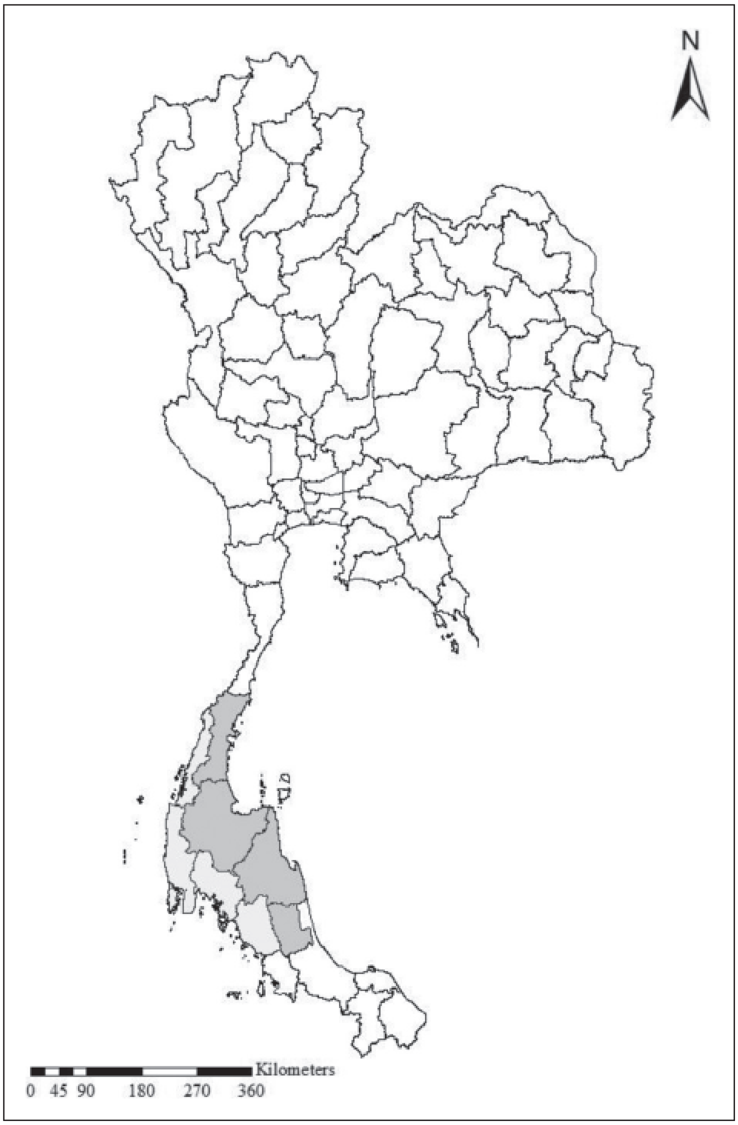

Figure 1. Study area by the Gulf of Thailand (■) and by the Andaman Sea (□), Southern Thailand

monthly rainfall, the number of rainy days, the relative humidity, and the min/mean/max monthly temperatures.

Data analysis

Box and whisker plots were used to study the distribution of dengue incidence in the Gulf of Thailand and the Andaman Sea. We performed Spearman rank correlation tests to examine the relationship between monthly dengue incidence and weather variables with a lag of zero to two months. The monthly dengue incidence was modelled using a generalised estimating equations (GEE) approach, with a Poisson distribution. This model enabled both specification of an over-dispersion term and a first-order autoregressive structure that accounted for the autocorrelation of monthly numbers of dengue cases. A basic multivariate Poisson regression model can be written as:

$$\ln(Y) = \beta_0 + \beta_1 X_{\text{Tmean}} + \beta_2 X_{\text{Tmin}} + \beta_3 X_{\text{Tmax}} + \beta_4 X_{\text{RH}} + \beta_5 X_{\text{Rain}} + \beta_6 X_{\text{Rainydays}} \quad \text{(Eq. 1)}$$

The model adjusted for first-order autocorrelation was:

$$\ln(Y_t) = \beta_0 + \beta_1 \ln(Y_{t-1}) + \beta_2 X_{\text{Tmean}} + \beta_3 X_{\text{Tmin}} + \beta_4 X_{\text{Tmax}} + \beta_5 X_{\text{RH}} + \beta_6 X_{\text{Rain}} + \beta_7 X_{\text{Rainydays}} \quad \text{(Eq. 2)}$$

Here, X_{Tmean}, X_{Tmin}, X_{Tmax}, X_{RH}, X_{Rain} and $X_{\text{Rainydays}}$ stand for mean temperature, minimum temperature, maximum temperature, relative humidity, amount of rainfall, and number of rainy days, respectively.

In order to control for potential long-term trends in the number of cases over the study period, a year variable was included in the regression model. In order to evaluate the alternative models, data were split into two sets: training and validation. The data from January 2007 to December 2012 (the training data) was used to build the time series model. Then the forecasting accuracy of this model was assessed using the data from January 2013 to May 2014 (the validation data) to evaluate the time series model. Data analysis was performed using *Mathematica* software with a Time series package.

RESULTS

The highest dengue cases occurred in July by the Gulf of Thailand (Figure 2a-d). Furthermore, along the Andaman Sea, the highest dengue cases occurred during June in Phang-Nga, Phuket, Ranong and Trang provinces (Figure 3b-d). Only the Krabi province had the highest dengue cases occurring in July (Figure 3a).

When we compared dengue transmission duration between the Andaman Sea and the Gulf of Thailand, we found that Nakhon Si Thammarat had the longest dengue transmission duration (i.e. June-September) by the Gulf of Thailand (Figure 2c). Trang province had the longest dengue transmission duration (i.e. June-September) by the Andaman Sea (Figure 3d).

Poisson regression Model: Gulf of Thailand
The dengue incidence rate in the current month was related to the incidence rate during the previous month for Chumphon (Poisson regression Model: Incidence rate with lag 1, Table 1). The number of rainy days at a lag of one month, relative humidity at a lag of two months had a negative effect on dengue incidence in Chumphon (Poisson regression Model: Rainy days with lag 1, Relative humidity with lag 2, Table 1).

The dengue incidence rate in the current month was related to the incidence rate during the previous month for Surat Thani (Poisson regression Model: Incidence rate with lag 1, Table 2). The relative humidity had a negative effect on dengue incidence for Surat Thani (Poisson regression Model: relative humidity with lag 2, Table 2).

The dengue incidence rate in the current month was related to the incidence rate during the previous month for Nakhon Si Thammarat (Poisson regression Model: Incidence rate with lag 1, Table 3). The number of rainy days at a lag of 3 months had a negative effect on dengue incidence for Nakhon Si Thammarat (Table 3).

The dengue incidence rate in the current month was related to the incidence rate during the previous month for Phatthalung (Poisson regression Model: Incidence rate with lag 1, Table 4). The number of rainy days had a positive effect on dengue incidence in Phatthalung (Poisson regression Model: Rainy days with lag 1, Table 4).

Poisson regression Model: Andaman Sea
The dengue incidence rate in the current month was related to the incidence rate during the previous month for Krabi (Poisson regression Model: Incidence rate with lag 1, Table 5). The maximum temperature at a lag of two months had a positive effect on dengue incidence in Krabi (Table 5).

The dengue incidence rate in the current month was related to the incidence rate during the previous month for Trang (Poisson regression Model: Incidence rate with lag 1, Table 6). The minimum and maximum temperature had a positive effect on dengue incidence in Trang (Poisson regression

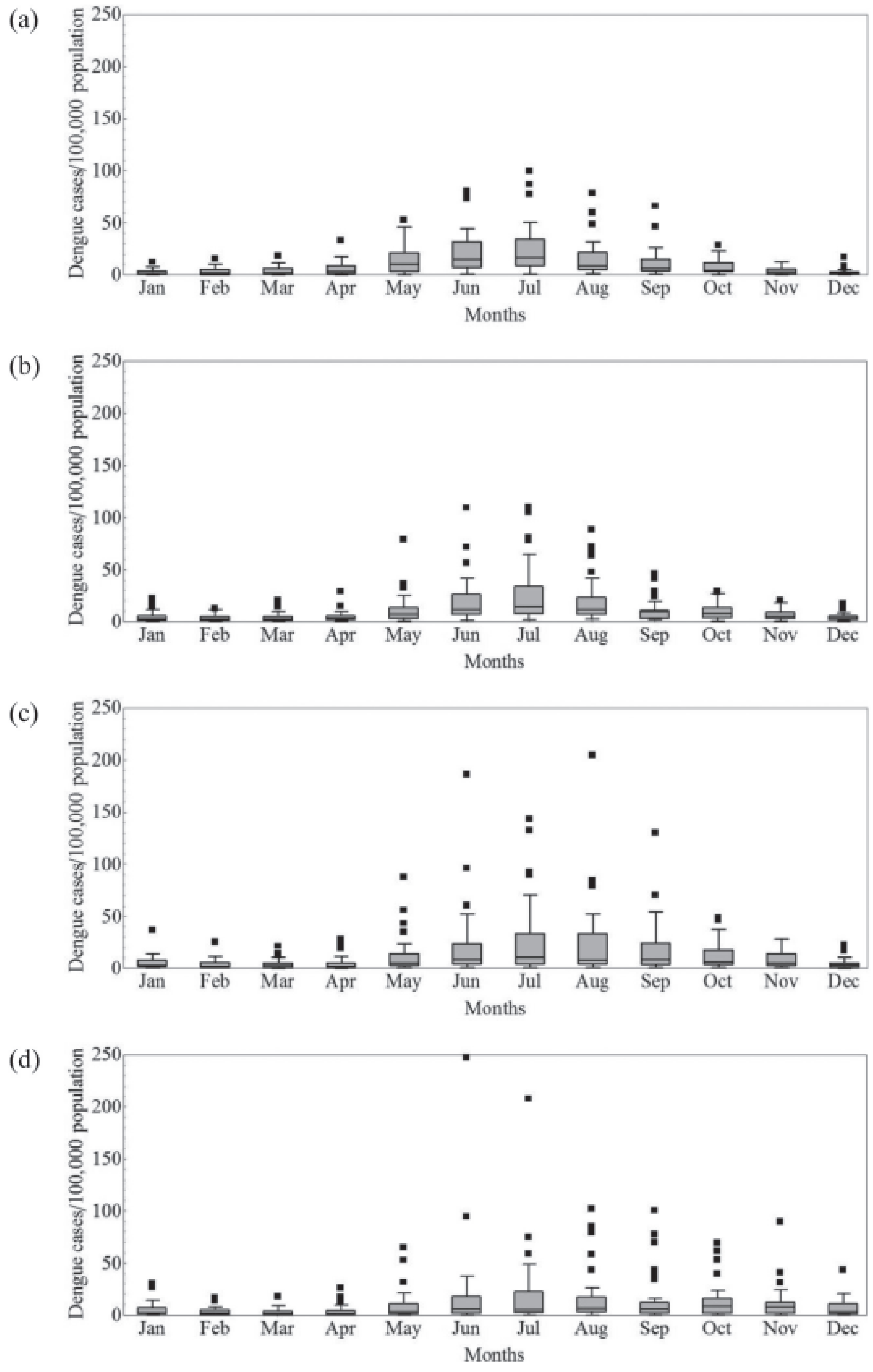

Figure 2. The spatial temporal patterns of dengue infection rates, from 1981 to May 2014 adjacent to the Gulf of Thailand: (a) Chumphon, (b) Surat Thani, (c) Nakhon Si Thammarat and (d) Phatthalung.

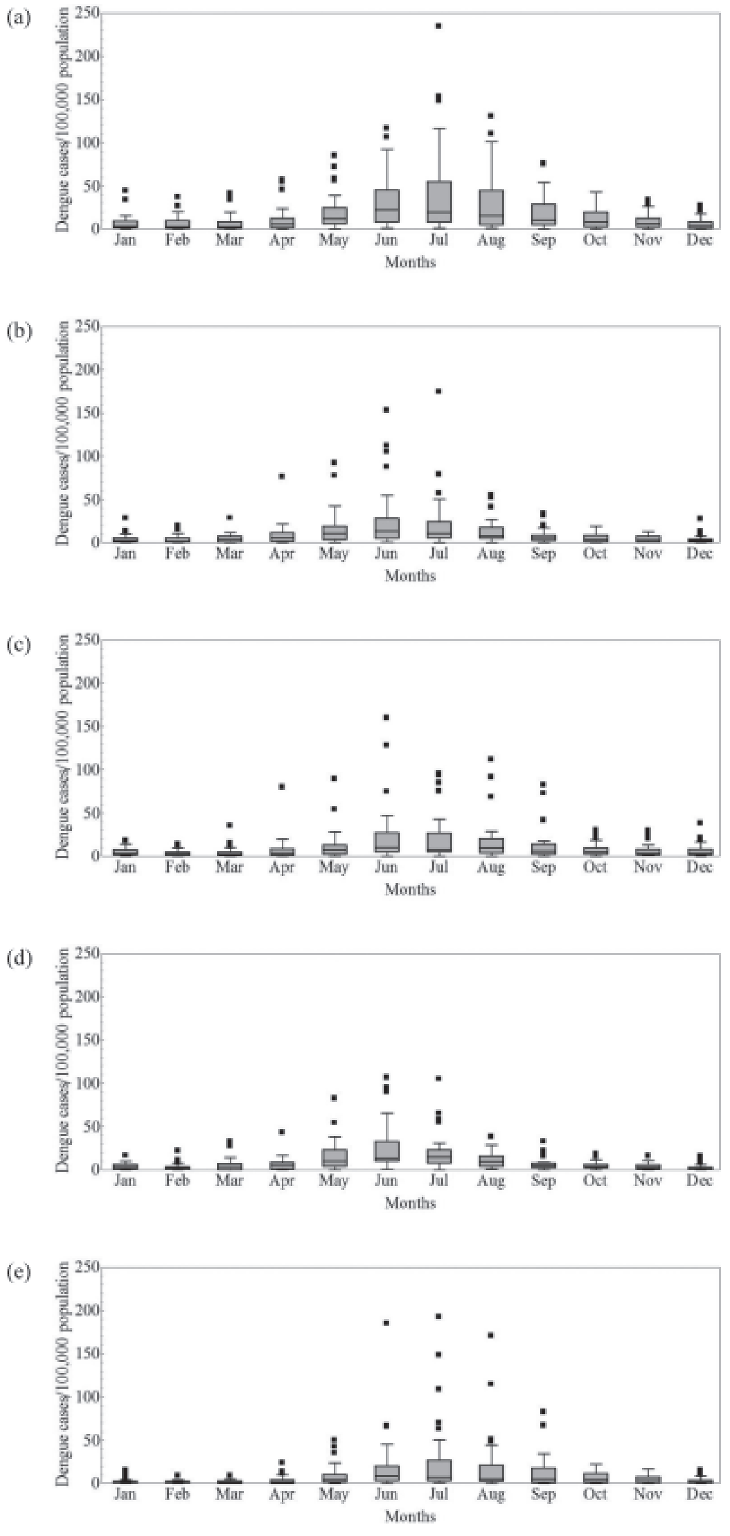

Figure 3. The spatial temporal patterns of dengue infection rates from 1981 to May 2014 adjacent to the Andaman Sea (a) Krabi, (b) Phang-Nga, (c) Phuket, (d) Ranong and (e) Trang.

Table 1. Estimated coefficients in an adjusted Poisson regression model between the weather variables and the dengue cases, from January 2007 to June 2012 in Chumphon, Thailand

Variables	β	S.E.	z-Statistic
Incidence rate (lag 1)	0.809	0.072	11.1788***
Rainy day (lag 1)	-0.023	0.014	-1.684*
Relative humidity (lag 2)	-0.053	0.021	-2.576**
Year (lag 1)	-0.006	0.025	-0.248
Constant	15.104	49.103	0.308

β : coefficients, S.E.: standard error.
*, **, *** Significant at the 0.1, 0.01 and 0.001 level (two-tailed).

Table 2. Estimated coefficients in an adjusted Poisson regression model between the weather variables and the dengue cases, from January 2007 to June 2012 in Surat Thani, Thailand

Variables	β	S.E.	z-Statistic
Incidence rate (lag 1)	0.8.8	0.058	14.472***
Relative humidity (lag 2)	-0.076	0.025	-3.080**
Year (lag 1)	0.005	0.023	0.243
Constant	-4.920	44.173	-0.111

β : coefficients, S.E.: standard error.
*, **, ** Significant at the 0.05, 0.01 and 0.001 level (two-tailed).

Table 3. Estimated coefficients in an adjusted Poisson regression model between the weather variables and the dengue cases, from January 2007 to June 2012 in Nakhon Si Thammarat, Thailand

Variables	β	S.E.	z-Statistic
Incidence rate (lag 1)	0.862	0.054	15.906***
Rainy day (lag 3)	-0.021	0.010	-2.141*
Year (lag 1)	-0.009	0.023	-0.377
Constant	17.443	46.623	0.374

β : coefficients, S.E.: standard error.
*, **, *** Significant at the 0.05, 0.01 and 0.001 level (two-tailed).

Model: Min Temp with lag 0, Max Temp with lag 2, Table 6).

The dengue incidence rate in the current month was related to the incidence rate during the previous month for Phang-Nga (Poisson regression Model: Incidence rate with lag 1, Table 7). The mean temperature at a lag of 0 month had a positive effect on dengue incidence in Phang-Nga (Table 7).

The dengue incidence rate in the current month was related to the incidence rate during the previous month for Phuket

Table 4. Estimated coefficients in an adjusted Poisson regression model between the weather variables and the dengue cases, from January 2007 to June 2012 in Phatthalung, Thailand

Variables	β	S.E.	z-Statistic
Incidence rate (lag 1)	0.813	0.083	9.847***
Rainy days (lag 1)	0.025	0.012	2.033*
Year (lag 1)	-0.039	0.027	-1.443
Constant	80.247	55.217	1.453

β : coefficients, S.E.: standard error.
*, **, *** Significant at the 0.05, 0.01 and 0.001 level (two-tailed).

Table 5. Estimated coefficients in an adjusted Poisson regression model between the weather variables and the dengue cases, from January 2007 to June 2012 in Krabi, Thailand

Variables	β	S.E.	z-Statistic
Incidence rate (lag 1)	0.687	0.074	9.240***
Max temperature (lag 2)	0.243	0.077	3.156**
Year (lag 1)	0.022	0.026	0.853
Constant	-50.199	52.381	-0.958

β : coefficients, S.E.: standard error.
*, **, *** Significant at the 0.05, 0.01 and 0.001 level (two-tailed).

Table 6. Estimated coefficients in an adjusted Poisson regression model between the weather variables and the dengue cases, from January 2007 to June 2012 in Trang, Thailand

Variables	β	S.E.	z-Statistic
Incidence rate (lag 1)	0.672	0.071	9.463***
Max temperature (lag 2)	0.182	0.098	1.859*
Min temperature (lag 0)	0.162	0.070	2.321**
Year (lag 1)	-0.002	0.027	-0.066
Constant	-3.988	55.426	-0.072

β : coefficients, S.E.: standard error.
*, **, *** Significant at the 0.1, 0.05 and 0.001 level (two-tailed).

(Poisson regression Model: Incidence rate with lag 1, Table 8). The mean temperature at a lag of 2 months had a positive effect on dengue incidence in Phuket (Table 8).

The dengue incidence rate in the current month was related to the incidence rate during the previous month for Ranong (Poisson regression Model: Incidence rate

Table 7. Estimated coefficients in an adjusted Poisson regression model between the weather variables and the dengue cases, from January 2007 to June 2012 in Phang-Nga, Thailand

Variables	β	S.E.	z-Statistic
Incidence rate (lag 1)	0.778	0.064	12.162***
Mean temperature (lag 0)	0.406	0.092	4.400***
Year (lag 1)	-0.026	0.029	-0.978
Constant	42.6909	53.801	0.794

β : coefficients, S.E.: standard error.
*, **, *** Significant at the 0.05, 0.01 and 0.001 level (two-tailed).

Table 8. Estimated coefficients in an adjusted Poisson regression model between the weather variables and the dengue cases, from January 2007 to June 2012 in Phuket, Thailand

Variables	β	S.E.	z-Statistic
Incidence rate (lag 1)	0.734	0.067	10.988***
Mean temperature (lag 2)	0.232	0.085	2.735**
Year (lag 1)	-0.018	0.028	-0.647
Constant	30.884	56.522	0.546

β : coefficients, S.E.: standard error.
*, **, *** Significant at the 0.05, 0.01 and 0.001 level (two-tailed).

Table 9. Estimated coefficients in an adjusted Poisson regression model between the weather variables and the dengue cases, from January 2007 to June 2012 in Ranong, Thailand

Variables	β	S.E.	z-Statistic
Incidence rate (lag 1)	0.427	0.094	4.537***
Min temperature (lag 0)	0.370	0.097	3.794***
Rainfall (lag 1)	0.001	0.0003	2.222*
Year (lag 1)	0.036	0.034	1.051
Constant	-81.153	68.378	-1.187

β : coefficients, S.E.: standard error.
*, **, *** Significant at the 0.05, 0.01 and 0.001 level (two-tailed).

with lag 1, Table 9). The minimum temperature at a lag of 0 month and minimum temperature had a positive effect on dengue incidence in Ranong (Table 9).

The time series Poisson regression model was constructed with the observed dengue incidences for the period of January 2007 to December 2012, and its ability to predict was tested with data for the period of January 2013-May 2014 (Gulf of Thailand: Chumphon, Fig. 4a; Surat Thani, Fig. 4b; Nakhon Si Thammarat; Fig. 4c; Phatthalung, Fig. 4d; Andaman Sea: Krabi, Fig. 5a; Trang, Fig. 5b; Phang-Nga, Fig. 5c; Phuket, Fig. 5d; Ranong, Fig. 5e).

The goodness-of-fit analyses reveals that the model fit the data reasonably well (Gulf of Thailand: Chumphon: R^2 = 80.82%, Surat Thani: R^2 = 85.76%, Nakhon Si Thammarat: R^2 = 85.17%, Phatthalung: R^2 = 66.43%; Andaman Sea: Krabi: R^2 = 90.21%, Trang: R^2 = 78.39%, Phang-Nga: R^2 = 74.25%, Phuket: R^2 = 69.65%, Ranong: R^2 = 45.16%).

The correlations between the observed and the predicted dengue incidences were 87.83% in Chumphon, 88.67% in Surat Thani, 88.79% in Nakhon Si Thammarat, 77.43% in Phatthalung; Andaman Sea: 86.93% in Krabi, 85.12% in Trang, 82.97% in Phang-Nga, 80.40% in Phuket and 64.40% in Ranong.

DISCUSSION

The present study proposed a spatio-temporal dengue prediction approach based on time series analysis with Poisson regression model. These methods have been applied to vector-borne diseases to study the distribution patterns of the disease, and to identify the dengue transmission areas (Yu *et al.*, 2011; Wongkoon *et al.*, 2013b). However, this is the first attempt to examine a spatio-temporal climate-based model of dengue fever by the Gulf of Thailand and by the Andaman Sea, in southern Thailand, and to provide basic information for estimating the dengue incidence trends.

In general a temporal trend can fully represent the occurrence of dengue fever cases, and this suggests that climate variables play an important role in the dengue outbreaks of the study area (Yu *et al.*, 2011). Our findings indicate that the dengue transmission occurs in July by the Gulf of Thailand, and in June-July by the Andaman Sea. When we compared dengue transmission duration between the Andaman Sea and the Gulf of Thailand, we found that for the Andaman Sea, Trang province had the longest dengue transmission duration (i.e. June-September) and for the Gulf of Thailand, Nakhon Si Thammarat had the longest dengue transmission duration (i.e. June-September). By the Gulf of Thailand, the main predictors are the number of rainy days and the relative humidity, whereas by the Andaman Sea the main predictors are the temperature and the amount of rainfall.

Similar temporal patterns in dengue fever prediction were observed in all townships with different adjusted magnitudes (e.g. a major outbreak occurred during June-August). The general temporal trend can meaningfully represent the occurrence of dengue cases, and it suggests that climate variables play an important role in the dengue outbreaks of the study area (Yu *et al.*, 2011). Temperature and rainfall conditions affect the suitability of environment for *Aedes* breeding.

The breeding of mosquitoes is determined by the availability of suitable and sufficient habitat for the larval stages, and this is dependent on rainfall (Russell, 1998). Rainfall and the number of rainy days have been found to correlate with dengue in many provinces in Thailand, such as Prachaup Khiri Khan, Phetchabun, Sing Buri, Suphan Buri, Trat, Pattani, Phuket (Thammapalo *et al.*, 2005), Sisaket (Wongkoon *et al.*, 2011), and Nakhon Si Thammarat (Wongkoon *et al.*, 2013). This study found that the number of rainy days and the amount of rainfall were positively associated with the dengue incidence in Phatthalung and Ranong, respectively. Mosquitoes spend their larval stages in water; then hatch into adult mosquitoes. Increased rain may increase larval habitat and vector population size by creating a new habitat or by improving adult survival (Gubler *et al.*, 2001). Many studies have demonstrated a time lag between the onset of rainfall and DHF occurrence. In Taiwan and the Philippines, dengue virus transmission appears to be closely related to rainfall, with a time lag of 1-2 months (Ko, 1989; Schultz, 1993). Our findings may be influenced by the topographical similarity of Phatthalung and Ranong, and by the long rainy season in Ranong.

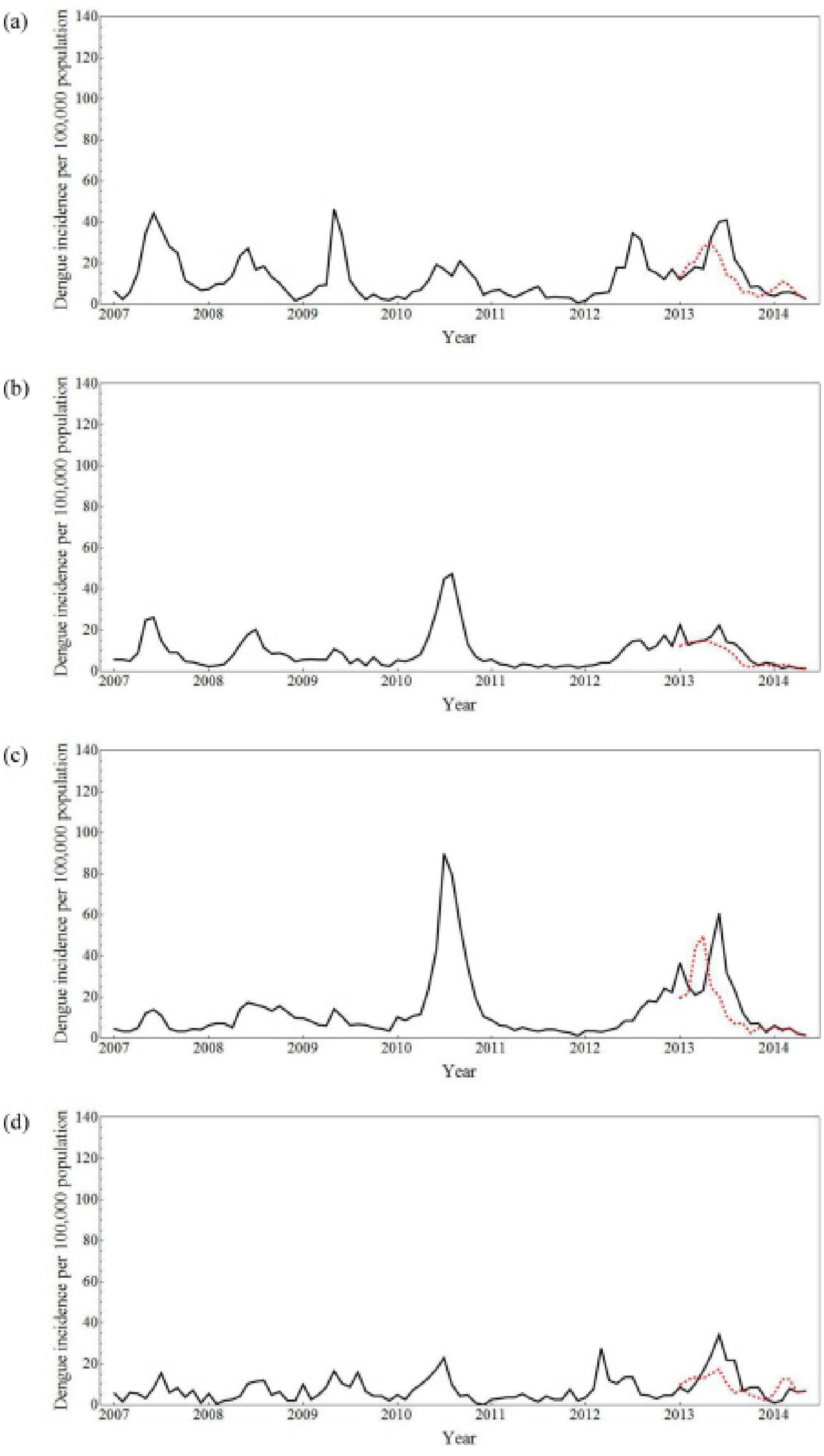

Figure 4. The actual monthly dengue cases per 100,000 population (solid line) and the predicted monthly dengue cases per 100,000 population (red dashed line), from January 2007 to May 2014. The time series Poisson regression modelsfor provinces adjacent to the Gulf of Thailand: (a) Chumphon, (b) Surat Thani, (c) Nakhon Si Thammarat and (d) Phattalung.

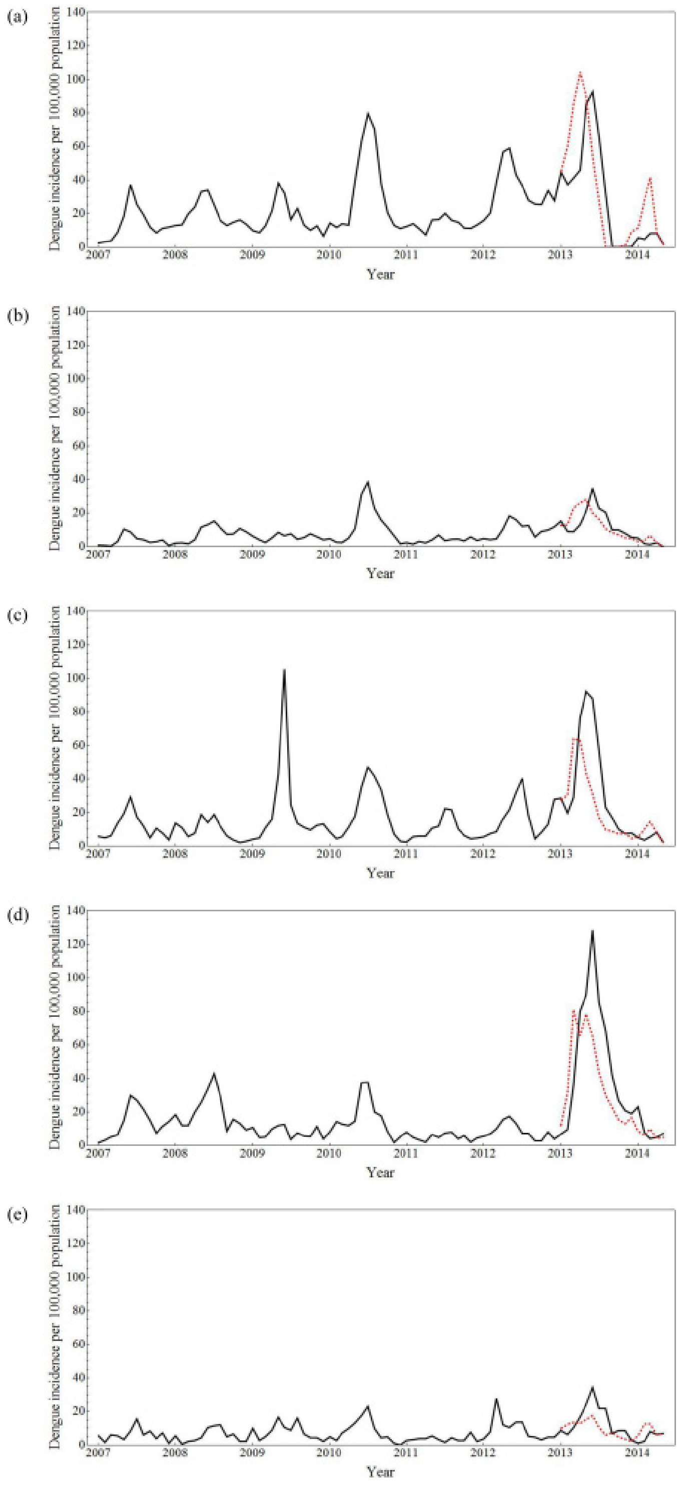

Figure 5. The actual monthly dengue cases per 100,000 population (solid line) and the predicted monthly dengue cases per 100,000 population (red dashed line) from January 2007 to May 2014. The time series Poisson regression models for provinces adjacent to the Andaman Sea: (a) Krabi, (b) Trang, (c) Phang-Nga, (d) Phuket and (e) Ranong.

Our results support Thammapalo *et al.* (2005) that the number of rainy days was negatively associated for the dengue incidence in Chumphon and also for Nakhon Si Thammarat. Heavy rain may have an immediate negative impact on the *Aedes* house index since the larvae can be washed away during the heavy downpours, as has been reported in Malaysia (Foo *et al.*, 1985). However, this explanation may be more plausible in areas where *Ae. albopictus*, the outdoor breeders, predominate. *Ae. aegypti*, an indoor breeder, is less likely to be affected by this mechanism. Our findings may have important public health implications through disease forecasting. As extra rainfall beyond its normal fluctuation limit is not associated with an extra rise in incidence, the control program does not need to increase its resources much in heavy rain periods (Thammapalo *et al.*, 2005).

Temperature and humidity are the most important weather factors in the growth and dispersion of mosquito vector and potential predictors of dengue outbreak (Wu *et al.*, 2007; Chen *et al.*, 2010). Our findings also indicate that relative humidity contributes to dengue transmission adjacent to both the Gulf of Thailand and the Andaman Sea, with the longest lags of two months. These results are consistent with findings of other studies in Thailand (Tipayamongkholgul *et al.*, 2009; Wongkoon *et al.*, 2013a,b). Relative humidity influences the mosquitoes' survival, longevity, mating, dispersal, feeding behavior, egg production, oviposition, and their dengue virus transmission (McMichael *et al.*, 1996; Tong & Hu, 2001; Lu *et al.*, 2009). Humidity also affects the rate of water evaporation at breeding sites. This might be because a decrease in relative humidity can reduce the flow of water in streams and thus produce stagnant pools, often high in organic matter, which make perfect breeding sites for a number of mosquito species (Tong & Hu, 2001). A relatively lower humidity in the surrounding environment could assist mosquitoes in seeking target hosts and facilitate disease transmission (Wu *et al.*, 2007).

Our results showed that the temperature contributes to dengue transmission adjacent to the Andaman Sea side, as its inclusion in the predictive model for dengue incidence provided a better fit. This finding is in general agreement with other studies (Hurtado-Diaz *et al.*, 2007; Wu *et al.*, 2007; Wongkoon *et al.*, 2013), in which temperature is reported as a precipitating factor for dengue transmission. Temperature influences the life cycle of *Aedes* mosquitoes, including their growth rate and larval survival, and the length of their reproductive cycle (Hopp & Foley, 2001; Patz *et al.*, 2005). Temperature also affects the virus replication, maturation and period of infectivity. A higher temperature decreases the length of viral incubation within the vector, and thus increases the chance of mosquitoes to become infective in their life span (Patz *et al.*, 1998; Hopp & Foley, 2001; Yang *et al.*, 2009). Temperature also influences biting rates, gonotrophic cycle lengths, and vector size (Schoof, 1967; Rueda *et al.*, 1990), most likely, since an increase in the metabolism of the adult mosquito and the replication speed of the virus (Westbrook *et al.*, 2009). Therefore, temperature affects vectorial efficiency (Bangs *et al.*, 2006) and risk of an epidemic (Schoof, 1967). Given the relationship between temperature and dengue, the projected change in temperature due to climate change may exacerbate disease transmission by the Andaman Sea side. The temperature was not associated with dengue transmission by the Gulf of Thailand. This might be because the monsoon periods differ between the Gulf of Thailand and the Andaman Sea.

The two most important mosquito species for the transmission of dengue are namely *Ae. aegypti* and *Ae. albopictus*, have long since become established in southern Thailand. Nakhon Si Thammarat and Surat Thani are the provinces with the highest population densities of *Ae. aegypti* and *Ae. albopictus*, due to favourable natural climate for mosquito breeding (Thavara *et al.*, 2001; Wongkoon *et al.*, 2007). The rapid development of urbanisation and construction in this region (Gulf of Thailand:

Samui, Surat Thani; Andaman Sea: Phuket) may also contribute to the transmission of dengue (Li *et al.*, 2012). Increasing overseas commercial investment, mobility of labour, and foreign tourism have led to a high rate of international exchanges in this region, increasing the risk of importing dengue fever cases from endemic areas (Li *et al.*, 2012).

Identification of spatial risk areas can help guide local health departments to formulate public health strategies, initiate early preventive measures and conduct enhanced surveillance, thereby reducing the risk of epidemics (Mammen *et al.*, 2008; Siqueira-Junior *et al.*, 2008; Hu *et al.*, 2011). This will assist public health officials in determining whether the most effective plan for disease control would include comprehensive coverage of the entire area at risk, as opposed to focusing attention on suggested or known spatio-temporal distributional trends.

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