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Estimating the economic impacts of climate change on infectious diseases: a case study on dengue fever in Taiwan

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Abstract Researchers of climate change have suggested that climate change and variability has a significant influence on the epidemiology of infectious diseases, particularly vector-borne diseases. The purpose of this study is to explore how climate conditions and the dengue fever epidemic in Taiwan are related and to estimate the economic impact of climate change on infectious diseases. To achieve these objectives, two different methods, one involving the Panel data model and the other the Contingent Valuation Method (CVM), are applied in this study. At first, we use the Panel data model to assess the relationship between climate conditions and the number of people infected by dengue fever during the period from January 2000 to February 2006 in 308 cities and townships in the Taiwan. The results of the empirical estimation indicate that climate conditions have an increasingly significant impact on the probability of people being infected by dengue fever. The probability of being infected by dengue fever due to climate change is then calculated and is found to range from 12% to 43% to 87% which represent low, mid, and high probabilities of infection caused by climate change when the temperature is increased by 1.8°C. The respondent's willingness to pay (WTP) is also investigated in the survey using the single-bounded dichotomous choice (SBDC) approach, and the results show that people would pay NT\$724, NT\$3,223 and NT\$5,114 per year in order to

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avoid the increased probabilities of 12%, 43%, and 87%, respectively, of their being infected with dengue fever.

1 Introduction

Since the industrial revolution that took place in the mid-18th century, huge quantities of fossil fuels, including gas, oil and coal, have been burning, and this over time has given rise to the presence of greenhouse gases in the atmosphere. These greenhouse gases and their accompanying greenhouse effect have resulted in an increase in the earth's temperature, as well as changes in climate. These changes in climate in turn have affected humans in a variety of ways, for instance by significantly influencing agriculture, water resources, food, human settlements, the ecosystem, biodiversity, and human health.

According to Githeko et al. (2000), the current evidence suggests that global warming will lead to the prevalence of vector-borne diseases. The higher temperatures will enhance their transmission rates and extend their geographic ranges. Among these viral vector-borne diseases, dengue fever is arguably the most important in the world. It affects hundreds of millions of people every year, and is transmitted predominantly by one species of mosquito, *Aedes aegypti*, which has adapted to living near areas of human habitation. In addition, there is no effective vaccine or drug treatment for dengue fever, and thus the effect of dengue fever on human health should not be overlooked.

According to a report by the World Health Organization (WHO 1998), many countries in Asia experienced unusually high levels of dengue fever in 1998, as compared with other years. At the same time, a period encompassing parts of 1997 and 1998 was the extreme El Niño year and some scholars have suggested that this may be the reason for the outbreaks of dengue fever in many countries in 1998 (Githeko et al. 2000). In Taiwan, 7,284 cases of dengue fever were reported between 1996 and 2005. Hwang (1997) noted that if a dengue fever epidemic were to break out in Taiwan and if 30% of the population were to be hospitalized for a week, the total cost of dealing with the epidemic would be NT$7.3 billion (i.e. US$230 million). These figures indicate that the potential economic damage arising from an outbreak of dengue fever needs to be given close attention.

Global climatic conditions have changed due to the large emissions of greenhouse gases. According to research conducted by the Global Change Research Center (GCRC), over the past 35 years the average global temperature has risen by more than 0.6°C. Though the average precipitation has not changed significantly, the variation in the precipitation has increased. With rising temperatures and increased variation in the precipitation, the probability of mosquitoes breeding will increase. In a warm ambient climate, adult female mosquitoes digest blood faster and feed more frequently, thereby increasing transmission intensity. Furthermore, the speed at which viruses are replicated also increases under warm climatic conditions.

Many studies that have been performed on the issue of climate change and dengue fever typically focus on the effects of climate change on epidemiology, physiology and public health. However, there have been very few studies that have focused on the economic impacts of climate change on dengue fever. This study will therefore examine the effect of various climatic variables on dengue fever in Taiwan and will also assess the economic impacts using the contingent valuation method (CVM).

The remainder of this article is organized as follows. The second section of this article provides background information on climate change and dengue fever in Taiwan and reviews the literature, addressing both the empirical and theoretical aspects of the climatic factors and dengue fever epidemics. The third section describes the methodology with regard to estimating the relationship between the climatic conditions and the number of people infected with dengue fever. Section four estimates the economic impact of dengue fever due to climate change by using a non-market valuation approach. Finally, our conclusions and policy suggestions are presented.

2 Climate change and dengue fever

Dengue fever, a mosquito-borne disease that originated in Africa, continues to occur in some places and still has not been eradicated. It occurs after one is infected by one of the four serotypes (Types I to IV) of the dengue fever virus, which is transmitted by certain of more than 130 species of mosquitoes in tropical and subtropical regions, particularly the *Aedes aegypti* and *Aedes albopictus* species in Taiwan. Most dengue infections are self-limiting, but a small portion develop into a more serious illness, such as dengue hemorrhagic fever (DHF) or dengue shock syndrome (DSS). The disease usually begins with a sudden onset of fever and other signs and symptoms, including a severe frontal headache, pain behind the eyes, a rash, and muscle and joint pains.

Geographically, dengue fever is now widely distributed in many countries in Southeast and South Asia, Central and South America, and the Western Pacific. It is currently most endemic in South Asia and Southeast Asia. As for the situation in Taiwan, the first case of dengue fever was recorded in 1870, and a number of dengue fever epidemics occurred up until 1945. The most serious occurred in 1942 and at that time about five million people were afflicted by the disease. Of the more recent dengue fever epidemics on this island, one large outbreak was recorded between 1987 and 1988 in Southern Taiwan. So far, there have been cases of dengue fever occurring in every season including winter in Taiwan, while the disease has spread from the south to the north of the island.

The statistics show that there have been 6,333 definite cases of dengue fever during the 1987–1999 period, or an average of about 487 cases in each year. However, there have been 6,626 definite cases of dengue fever during the period 2000–2005, or an average of about 1,104 cases in each year. Thus the average number of cases during the last 6 years (i.e. 2000–2005) has increased by 127% compared with the 1987–1999 period.

Over the past decade, the majority of the research conducted on dengue fever has focused on the relationship between the physiology of mosquitoes and various climatic conditions. A number of studies have shown that the survival of mosquitoes is sensitive to climate change and that the transmission of the disease is strongly influenced by climatic factors. Temperature, rainfall, and humidity are especially important, while other variables, such as population and the density of mosquito populations, also play a significant role in the transmission of dengue fever.

Miu and Lang (1960) investigated the ecology of mosquitoes in the Taipei area during the period from February 1958 to April 1959. They found that the seasonal prevalence of *Aedes albopictus* was related to temperature. Gubler (1986) discovered that a great deal of precipitation which was brought about by the rainy season and the typhoons occurring in summer and fall encouraged the breeding and survival of mosquitoes. Ko (1989) observed that the density of *Aedes aegypti* and precipitation were both positively related to the accumulated incidence of dengue fever. Besides, the precipitation in the previous month was found to be the best predictor of a dengue fever epidemic.

Hwang (1991) explored the relationships between the ecology of *Aedes* mosquitoes and dengue fever epidemics in the Taiwan area. In his study, Hwang inspected the distribution and density of *Aedes aegypti* and *Aedes albopictus* during 1988–1990 in Taiwan. The results indicated that the larval and adult density of *Aedes aegypti* and the larval density of *Aedes albopictus* were correlated with temperature, rainfall and relative humidity. The increase in *Aedes* density was proportional to increases in temperature and rainfall. The peak of the *Aedes* density also exhibited a direct relationship with rainfall. Furthermore, the number of dengue fever cases was significantly correlated with seasonal population fluctuations and the regional density of *Aedes aegypti*.

Koopman et al. (1991) found that the risk of being infected with dengue fever at a temperature under 30°C was four times that of being infected at a temperature under 17°C during the rainy season. Chang (1996) studied the cases of dengue fever in Kaohsiung county, Kaohsiung city, and Pingtung county during 1986–1994 and found that the density of mosquito populations differed from season to season. In his research, the results of analyzing observations obtained in Liouciou, Pingtung over a period of five years suggested that the occurrence index of the larvae of the *Aedes* mosquitoes was at its highest in October and its lowest in March. Moreover, the density of mosquito populations was found to vary by area. Finally, he concluded that such a variation was primarily affected by the human population, the numbers of containers with water, the time of the investigation as well as the area in which the investigation took place.

Wang and Chen (1997) pointed out that the potential for dengue fever transmission was affected by global warming, and that the trend in terms of the density of the mosquito population in Taiwan was increasing. Hwang (1997) in his "Report on Dengue Fever and Dengue Hemorrhagic Fever" indicated that H. Graham (1903) implicated *Aedes aegypti* and *Culex quinquefasciatus* as the vector for dengue fever, while Bancroft (1906) first proved that *Aedes aegypti* was the vector for dengue fever but that *Culex quinquefasciatus* was not. Later, it was also proved that *Aedes albopictus* was a vector of dengue fever.

Githeko et al. (2000) studied climate change and vector-borne diseases and observed that climate change and variability were highly likely to influence vector-borne disease epidemiology besides seasonal weather variations, socio-economic status, vector control programs, environmental changes and drug resistance.

Reiter (2001) reviewed the histories of three mosquito-borne diseases including malaria, yellow fever, and dengue fever, and then stressed the importance of human activities and their impact on local ecology. Reiter thought the principal determinants in terms of the prevalence of these diseases were politics, economics and human activities, and he recommended that there be a creative and organized application of resources to control these diseases in the future.

Hales et al. (2002) used a logistic regression, fitted using the maximum likelihood method, to model the global distribution of dengue fever on the basis of vapor pressure. They found that almost 30% of the world's population lived in the regions where the estimated risk of dengue transmission was greater than 50% in 1990. With population and climate change projections for 2085, they estimated that about 50–60% of the projected global population would be at risk of dengue transmission, compared with 35% of the population if the climate did not change. Therefore, based on this empirical model, climate change really has a significant effect on the distribution of dengue fever.

Tsai and Liu (2005) reviewed several important health issues to demonstrate the impact of climate change on diseases (e.g., malaria, dengue fever and encephalitis). They explored the interaction between climate change and diseases in developing and industrialized countries and found that the impact of climate change on health status was different in developing versus industrialized countries.

These studies show that climatic factors, especially temperature and precipitation, are the major factors affecting the dengue fever epidemic. Besides, the humidity and other variables, including the density of the mosquito population, will also cause a dengue fever epidemic. Therefore, it can be briefly summarized that the relationships between temperature, precipitation, the density of the mosquito population, and the dengue fever epidemic are highly related. Such relationships will be investigated in the next section.

3 The relationship between climate conditions and dengue fever

In this study, a two-stage econometric approach is designed to estimate the impacts of climate conditions on dengue fever in Taiwan. In the first stage, we consider various climatic factors including temperature, humidity, and precipitation to estimate the influence of climatic conditions on the mosquito density level that is linked with the Breteau index. The Breteau index, which has frequently been used in connection with *Aedes aegypti*, is measured in terms of the number of mosquito positive containers per 100 houses inspected and is generally considered to be the best of the commonly-used indices (such as the House Index or the Container Index), since it combines dwellings and containers and is more qualitative besides having epidemiological significance. The index has been linked with the transmission level of the dengue fever and can be used as a warning indicator of this disease. For instance, when the Breteau index is above 50 (i.e. density level >6), it is regarded as highly dangerous in terms of transmission of the disease according to the definition provided by the World Health Organization (WHO). When the Breteau index is above 20 (i.e. density level >4), it is considered to be sensitive, meaning that a dengue fever epidemic could break out anytime. When the Breteau index is under 5 (i.e. density level <2), this means that the disease will not be transmitted. The relationship between the Breteau index and the density level is depicted in Table 1.

Table 1 Breteau index and density level

Density level	1	2	3	4	5	6	7	8	9
Breteau index	1–4	5–9	10–19	20–34	35–49	50–78	79–99	100–199	≥ 200

Source: Center for Disease Control, Taiwan, ROC

In the second stage, the relationship between the density level and the number of people infected with dengue fever is estimated. Please note that the density level in the second stage is a predicted value from the first stage, so the estimation parameters from equation (2) in the second stage will be consistent. The population density is also considered in this stage. The calculations following the two-stage estimation allow us to estimate the impact of climate conditions on the number of people infected with dengue fever. The specific functions of the two stages are as follows:

$$Y_{it} = f(TEM_{it}, WET_{it}, RAIN_{it-1}, Y_{it-1}) \tag{1}$$

$$NDEN_{it} = g\left(\hat{Y}_{it}, POP_{it}\right) \tag{2}$$

where

Y_{it}	is the density level in county i at time t,
Y_{it-1}	is the one-period lagged density level in county i,
TEM_{it}	is the temperature in Celsius in county i at time t,
WET_{it}	is the humidity in county i at time t,
$RAIN_{it-1}$	is the one-period lagged rainfall in county i at time t,
$NDEN_{it}$	is the number of people infected with dengue fever in county i at time t,
$\hat{Y}_{it}$	is the estimated density level in county i at time t from equation (1),
POP_{it}	is the population in county i at time t.

The dataset covers the areas of 308 cities or townships in Taiwan, while the time period extends from January 2000 to February 2006. Monthly data on population, the number of people infected with dengue fever, the density of the mosquito population, as well as climatic data including temperature, humidity, and precipitation in each city and township, are collected from government statistics. After deleting the observations with incomplete information, 210 cities or townships remain. We then divide the 210 cities or townships into 14 counties. The means of this pooling dataset

Table 2 The mean of climate variables and people infected with dengue fever by county

County	Average monthly temperature (°C)	Average monthly humidity (%)	Average monthly rainfall (mm)	Average annual patient number (persons)
Taipei	22.579	76.415	179.137	31.167
Taoyuan	22.362	77.595	151.027	17.000
Hsinchu	21.663	77.595	155.110	2.833
Miaoli	21.722	77.595	150.023	2.167
Taichung	23.522	74.473	146.901	11.000
Changhua	23.330	74.473	126.748	3.333
Nantou	18.744	81.851	172.473	1.500
Chiayi	19.343	78.733	149.421	3.167
Tainan	23.890	77.257	144.811	59.500
Kaohsiung	24.023	75.27	160.607	910.833
Pingtung	24.331	73.108	167.686	163.667
Ilan	22.192	79.966	237.419	2.167
Hualien	21.639	77.919	169.120	1.000
Taitung	21.027	73.308	159.807	2.667

for each climatic variable and patient infected with dengue fever are summarized in Table 2. Table 2 shows that the average annual patient numbers in the southern counties (i.e., Kaohsiung and Pingtung counties) are higher than those in other counties as shown in Fig. 1. In the meantime, the average temperatures in these two southern counties are also higher than in other counties, which suggest that a positive relationship between temperature and the number of people infected with dengue fever might exist.

3.1 The impact of climate conditions on density level

In the first stage estimation, the Poisson model is employed because the dependent variable (i.e., the density level Y_{it}) is a nonnegative integer random variable ranging from 0 to 16. Equation (1) is estimated as a one-way error component

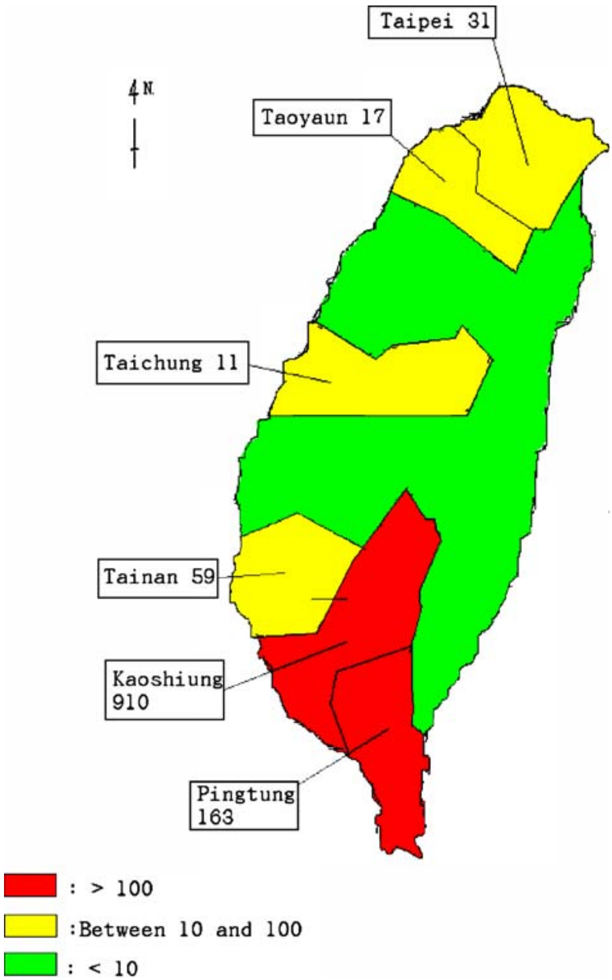

Fig. 1 The average number of dengue fever patients at county level in Taiwan

disturbance panel data model following Wallace and Hussain (1969), Nerlove (1971) and Amemiya (1971) and is shown in equation (3).

$$\begin{aligned} Y_{it} &= f\,(TEM_{it}, WET_{it}, lRAIN_{it}, Y_{it-1}) + u_{it} \\ &= \beta_0 + \beta_1^* TEM_{it} + \beta_2^* WET_{it} + \beta_3^* LRAIN_{it} + \beta_4^* Y_{it-1} + u_{it}. \end{aligned} \tag{3}$$

The error term u_{it} is defined as

$$u_{it} = \mu_i + \lambda_t + v_{it}, \quad i = 1, \ldots, N \quad , \quad t = 1, \ldots, T \tag{4}$$

where μ_i denotes the unobserved individual effect, λ_t denotes the unobserved time effect and v_{it} is the remaining stochastic disturbance term.

The parameter estimates of the climatic factors in relation to the density level (Y_{it}) are presented in Table 3. Overall, the results are quite satisfactory because most of the signs are as expected. The findings in Table 3 indicate that temperature (TEM_{it}), lagged rainfall ($RAIN_{it-1}$), and lagged density level (Y_{it-1}) have positive

Table 3 Estimation results for the impacts of climate factors on density level

County	Temperature	Humidity	Rainfall	Lagged density
Taipei	0.00949**	−0.00114	−0.00008	0.1613**
	(0.0031)	(0.0007)	(0.00009)	(0.0051)
Taoyuan	0.00247**	−0.1465**	0.00002	0.2373**
	(0.0077)	(0.0023)	(0.0003)	(0.0321)
Hsinchu	0.0159	0.0099	0.00049*	0.6173**
	(0.1181)	(0.1464)	(0.00031)	(0.0598)
Miaoli	0.01109	−0.0098**	0.00069**	0.2710**
	(0.0088)	(0.0024)	(0.0002)	(0.0404)
Taichung	0.0390**	−0.01552**	0.0003**	0.1745**
	(0.0093)	(0.0029)	(0.0001)	(0.0273)
Changhua	0.0420**	−0.0183**	0.00025**	0.2834**
	(0.0082)	(0.0025)	(0.0001)	(0.0264)
Nantou	0.0650**	−0.0305**	0.00048*	0.4653**
	(0.0235)	(0.0053)	(0.0002)	(0.0511)
Chiayi	0.0219**	−0.0115**	0.0001	0.3403**
	(0.0063)	(0.0015)	(0.0001)	(0.0249)
Tainan	0.0519**	−0.0183**	0.0003**	0.1652**
	(0.0053)	(0.0016)	(0.0001)	(0.0154)
Kaohsiung	0.0651**	−0.0164**	0.00028**	0.1354**
	(0.0074)	(0.0023)	(0.0001)	(0.0086)
Pingtung	0.0367**	−0.0087**	0.00023**	0.1140**
	(0.0061)	(0.0021)	(0.0001)	(0.0080)
Ilan	0.0119	0.0406**	−0.0005 **	0.0958**
	(0.0088)	(0.0103)	(0.0002)	(0.0177)
Hualien	−0.0134	0.0431**	−0.0003	0.3041**
	(0.0094)	(0.0135)	(0.0003)	(0.0428)
Taitung	0.0250**	−0.0028	−0.0001	0.1116**
	(0.0059)	(0.0017)	(0.0001)	(0.0144)

The numbers in the parenthesis are standard deviations.

*Represents significant at 5% level, which means that the hypothesis of zero parameters is rejected.

**Represents significant at 1% level.

and significant effects on the density of the mosquito population in most counties. In terms of temperature, the estimation results range from 0.00247 to 0.0651 in 10 counties, which mean that the mosquito population density levels increase from 0.00247 to 0.0651 when the temperature increases by 1°C. Similarly, the estimation results for rainfall range from 0.00023 to 0.00069, which indicate that the density level will increase by 0.00023 to 0.00069 when the precipitation level increases 1 mm. However, the estimates for humidity (WET_{it}) are either negative or insignificant except for those counties in the eastern region, indicating that humidity is not a major contributing factor of affected cases for dengue fever in Taiwan.

3.2 The impact of density level on the number of people infected

In the second stage, equation (2) can be estimated using both Least Squares Dummy Variable (LSDV) and Feasible Generalized Least Squares (FGLS) methods following Baltagi (2001) in the following linear form:

$$NDEN_{it} = g\left(\hat{Y}_{it}, POP_{it}\right) = \gamma_0 + \gamma_1^* \hat{Y}_{it} + \gamma_2^* POP_{it} + \varepsilon_{it}, \tag{5}$$

where ε_{it} is the error term. The explanatory variables in equation (5) are the population (POP_{it}) and estimated Breteau index from the 1st stage estimation (Y_{it}), while the dependent variable is the number of dengue fever patients ($NDEN_{it}$). Table 4 shows the estimation results. More than half of the counties in our sample have positive and significant parameter estimates of the population and density level, which are compatible with previous studies. The estimates for the Breteau density index range from 0.016 in Chiayi county to 8.904 in Pingtung county, which suggests that case number of dengue fever will increase by as many as nine persons if the index is increased by one level in Pingtung county.

3.3 The impact of climate conditions on the number of people infected

The main purpose of this study is to estimate the impact of climate conditions on the number of people infected with dengue fever and then evaluate the potential outcomes of global warming on the disease. Combining Tables 3 and 4 could allow us to obtain such outcomes. Here is the calculation procedure:

Step 1. Calculate the impact of temperature on the density level.

$$\frac{\partial Y}{\partial TEM} = \hat{\beta}1 * \exp\left(\hat{Y}\right)$$

Step 2. Calculate the impact of the density level on the number of dengue fever patients.

$$\frac{\partial NDEN}{\partial \hat{Y}} = \hat{\gamma}_1$$

Table 4 Estimation results for the impacts of population and density level on the number of people infected with dengue fever

County	Population	Density level
Taipei	−0.000068**	0.15209**
	(0.000003)	(0.0459)
Taoyuan	0.000016**	0.12358**
	(0.000001)	(0.044)
Hsinchu	0.0000032*	0.06397**
	(0.000002)	(0.0280)
Miaoli	0.000006	0.00102
	(0.00001)	(0.0187)
Taichung	0.000008**	0.0672**
	(0.000001)	(0.0338)
Changhua	0.000001**	0.01734*
	(0.000003)	(0.01077)
Nantou	−0.000012	−0.0143
	(0.00001)	(0.01416)
Chiayi	0.000001	0.01627**
	(0.000005)	(0.00786)
Tainan	0.000018**	0.0332**
	(0.000004)	(0.00771)
Kaohsiung	0.00095**	1.0202
	(0.00041)	(1.428)
Pingtung	0.001925**	8.9041**
	(0.00082)	(1.129)
Ilan	0.000006	0.0142
	(0.000005)	(0.0175)
Hualien	−0.000015	−0.0247
	(0.000010)	(0.0137)
Taitung	0.000002**	0.00887
	(0.0000001)	(0.0165)

The same as Table 3

Step 3. Calculate the potential impact of warming on the number of dengue fever patients in each county as elasticity

$$\frac{\partial NDEN_i \Big/ \overline{NDEN_i}}{\alpha TEM_i \Big/ \overline{TEM_i}} = \frac{\partial Y_i}{\partial TEM_i} * \frac{\partial NDEN_i}{\partial \hat{Y}_i} * \frac{\overline{TEM_i}}{\overline{NDEN_i}}$$

$$= \hat{\beta}_1^* \exp\left(\hat{Y}_i\right)^* \hat{\gamma}_1^* \frac{\overline{TEM_i}}{\overline{NDEN_i}}, \tag{6}$$

where $\overline{NDEN_i}$ and $\overline{TEM_i}$ are the county mean of the number of people infected with dengue fever and temperature, respectively, over time. Equation (6) calculates the percentage change in the number of dengue fever patients due to the percentage change in temperature and the results are shown in the second column of Table 5. For instance, the number in Pingtung is 11.83, which means that the number of dengue fever patients will increase by 11.83% if the temperature increases by 1%.

Table 5 The impacts of temperature change on the percentage change of infected cases for dengue fever

County	$\frac{\Delta NDEN/NDEN}{\Delta TEM/TEM}$ (%)	Scenario 1 (0.9°C increased)	Scenario 2 (1.8°C increased)	Scenario 3 (2.7°C increased)
Taipei	0.447	1.782	3.564	5.345
Taoyuan	0.083	0.334	0.668	1.002
Hsinchu	1.233	5.123	7.684	15.369
Taichung	1.831	7.006	14.012	21.019
Changhua	1.667	6.431	12.862	19.292
Chiayi	0.814	3.788	7.576	11.560
Tainan	0.571	2.151	4.302	6.453
Kaohsiung	5.750	21.562	43.125	64.687
Pingtung	11.829	43.811	87.622	131.433
Ilan	0.443	1.796	3.592	5.389
Taitung	1.342	5.744	11.488	17.232

Later, we apply the possible changes in temperature obtained from the Intergovernmental Panel on Climate Change (IPCC) to simulate the impact of global warming on the dengue fever disease. When considering the IPCC uncertain range for climate sensitivity, a rough and linear back-of-the-envelope estimate of how large the 2% anthropogenic change in the greenhouse effect is within the range of 0.9–2.7°C (Real Climate 2005). Therefore, three scenarios involving increases in temperature of 0.9, 1.8, and 2.7°C are used to facilitate our calculation of the predicted surge of affected case numbers due to warmer temperature. The predicted results are shown in the last three columns in Table 5. We find that the range of the probability of dengue fever occurring in patients will increase by 0.33% to 131.43% if the temperature is raised by 0.9, 1.8, and 2.7°C, which explains that the climate change will give rise to more cases of dengue fever. The effects of the temperature increase on the percentage change of dengue fever infection occurrence is greater in the southern counties like Kaohsiung and Pingtung, which indicates that climate change may play a more important role in sustaining the transmission cycle between human hosts and vectors in a more tropical environment. The increasing number of cases will result in economic damage and such damage will be estimated using a non-market value approach that is addressed in the next section.

4 The economic impact of dengue fever due to climate change

While the previous section reveals the severity of the impact of climate change on the infected cases for dengue fever, an economic assessment of the health threat on human beings is also very important in view of decision-making on public health investment to reduce the spread of vector-borne diseases. A survey-based contingent valuation method is used to inquire the respondents regarding their willingness to pay (WTP) to reduce the probability of dengue fever infection due to climate change. For public health agencies, the information regarding WTP for a reduced exposure to the health threat is often needed to acquire funding to cover the administrative costs on surveillance and reporting system and the costs of scientific development in disease control.

The CVM was originally proposed by Davis (1963) to assess the value of environmental goods. Nowadays, the CVM is widely applied to cases of non-market goods. It allows one to elicit from individuals a definite indication of their preferences when it is difficult to observe their behavior in an existing market. Furthermore, it leads to compensated measurements of welfare, which are expressed in monetary values. Such a method employs specific surveys designed on the basis of the need to induce respondents to reveal their willingness to pay for the object being evaluated. Its principle consists of confronting individuals with a hypothetical market in which non-market goods are traded. Then, the respondents are asked to disclose their preferences for the goods traded by means of a bidding process. In this study, a single-bounded dichotomous choice method (Bishop and Heberlein 1979) is employed to design the survey instrument in which respondents are asked to bid with the answer of “yes” or “no” to express their willingness.

To decide the bids in the questionnaire, a pretest was conducted over a period of 5 days from May 22 to May 26, 2006. The respondents were asked to fill out an open-ended questionnaire, which revealed information concerning the distribution of their WTP. The number of people sampled in this pretest was 44. Among those sampled, there were 31 valid observations, while the other 13 observations were protest samples and were deleted. According to Alberini (1995), we ranked the WTP of these valid samples and selected the 24th, 42nd, 60th, and 78th percentiles to be the designated bids in the real survey. Next, to reduce the problem of starting point bias in the CVM, we rearranged these bids and generated 64 combinations of bid sets. A logic test was then used to eliminate unreasonable ones and 19 sets were left as shown in Table 6. Each set of bids will be assigned to different respondent in a random fashion during the survey.

The probability of people being infected with dengue fever will increase because the activities and breeding habits of the mosquito population are affected by climate change. Therefore, in the design of our questionnaire, we have assumed that the government will establish an authority to implement some surveillance measures and actions to reduce the Breteau index like cleaning containers and areas in which mosquitoes may easy breed in order to mitigate the number of dengue fever cases. The funding source involves levying an extra tax on the general population each year.

Since southern Taiwan areas including Kaohsiung and Pingtung counties are the major infected areas while the central Taiwan including Taichung county is the newly infected areas, three infected ratios (12%, 43% and 87%) were selected for these three counties in Scenario 2 in Table 5 to represent the low, medium, and high probabilities of exposure to dengue fever caused by climate change. We name them as case 1, case 2, and case 3, respectively.

The survey was conducted over a period of three weeks from June 2 to June 22, 2006 using a questionnaire. The questionnaire consists of four parts, including knowledge regarding climate change, awareness of dengue fever, the major WTP question and bids, and socio-economic background. Each respondent was asked to fill out a questionnaire which elicited information concerning his/her WTP to prevent dengue fever epidemics caused by climate change. Since 19 sets of bids were randomly assigned to the respondents and for each set about 22–25 people were interviewed, we obtain 504 samples. After eliminating the protest observations,

Table 6 The 19 sets of bids for the WTP questionnaires

Type	At 12%	At 43%	At 87%
A	100	240	400
B	100	240	600
C	100	240	1,000
D	100	240	1,500
E	100	500	600
F	100	500	1,000
G	100	500	1,500
H	100	700	1,000
I	100	700	1,500
J	100	1,000	1,500
K	300	500	600
L	300	500	1,000
M	300	500	1,500
N	300	700	1,000
O	300	700	1,500
P	300	1,000	1,500
Q	500	700	1,000
R	500	700	1,500
S	500	1,000	1,500

Unit: NT$

471 observations were left. Approximately 25% of the respondents lived in northern Taiwan and 75% lived in the south.[1] Males and females accounted for about 51% and 49% of the total, respectively. With regard to marriage status, about 45% of the respondents were married. As for income, most of the respondents had incomes of NT$50,000–60,000 per month.

More than 90% of the respondents were aware of the climate change and more than 50% are quite concerned about this issue. They attached great importance to global warming and thought the government should undertake some policy measures to reduce greenhouse gas emissions. Almost all respondents knew about dengue fever and also cared about the impact of dengue fever. About 68% of the respondents knew that dengue fever also occurred in northern Taiwan. However, about 63% of the respondents did not know that it also occurred in the winter time.

To estimate the economic impacts of dengue fever due to climate change, a CVM approach based on the expenditure function is applied here. According to Chen's (1997) study, many factors including the cognition of the objects, bids, and backgrounds of respondents will affect the respondent's WTP. Therefore, we select several important explanatory variables and present them in Table 7. Table 7 provides the definitions, expected signs, and the summary statistics of these variables.

Within the literature on the application of the expenditure function, Cameron and James (1987a, b), and Chen (1997) assume that the expenditure function is a linear form. In estimation, either Probit or Logit models can be applied and the estimation results of WTP from the two models are usually quite similar (Wu and Hsieh 1995).

[1] Northern Taiwan includes Taipei, Taoyuan, Hsinchu, Miaoli, and Taichung counties, while southern Taiwan includes the others.

Table 7 The definition of variables, expected signs, and descriptive statistics

Variables	Definitions	Expected sign	Mean	Standard deviation
T_1	The bid in the questionnaire for case 1	+	226.96	148.52
T_2	The bid in the questionnaire for case 2	+	584.50	241.26
T_3	The bid in the questionnaire for case 3	+	1,140.10	378.27
I_{ij}	Index variable (1: accept; 0: reject)	–	–	–
SEX	The respondent's sex (1: male; 0: female)	?	0.51	0.50
AGE	The respondent's age	?	31.60	8.28
AREA	The respondent's living area (1: southern; 0: northern)	+	0.75	0.44
VALUE	The respondent's value on dengue fever	+	3.79	0.88
EDUCATION	The respondent's educational degree (1: university and above; 0: below university level)	+	0.64	0.48
MARRIAGE	The respondent's marriage situation	?	0.45	0.50
FAMILY	The respondent's family	?	4.76	1.70
INCOME	The respondent's income per month	+	65,021.20	22,017.90

Nevertheless, Cameron and James (1987a, b) suggested that the Probit model is preferred because the mean of WTP can be derived directly from the coefficient estimates. Therefore, we also use the Probit model to estimate the expenditure function. Based on these explanatory variables in Table 7, we can express the empirical model as in equation (7) below:

$$\begin{aligned} Y_{ij}^{*} = \beta_0 &+ \beta_{1j} SEX_{ij} + \beta_{2j} AGE_{ij} + \beta_{3j} AREA_{ij} + \beta_{4j} VALUE_{ij} \\ &+ \beta_{5j} EDUCATION_{ij} + \beta_{6j} MARRIAGE_{ij} + \beta_{7j} FAMILY_{ij} \\ &+ \beta_{8j} INCOME_{ij}, \end{aligned} \tag{7}$$

where Y_{ij}^{*} is the WTP of the ith respondent in the jth case, and $j = 1,2,3$ stand for case 1, case 2, and case 3, respectively. Meanwhile, β_0 is the intercept, and $\beta_{1j}, \beta_{2j}, \ldots, \beta_{8j}$ are the coefficients of the explanatory variables.

Additionally, to measure the goodness-of-fit of this empirical model, the Likelihood Ratio Test (LRT) and Correct Predicted Percentage are two important criteria. The formula for the likelihood ratio is

$$LR = -2 \ln \left(L_w / L_\Omega \right) = -2 \left(\ln L_w - \ln L_\Omega \right) \tag{8}$$

In equation (8), L_w is a restricted maximum likelihood value while L_Ω is an unrestricted maximum likelihood value. The likelihood ratio yields a chi-square distribution. The higher LR value means that it has a better explanatory ability. The other criterion, the correct predicted percentage, is also calculated based on the number of correct predicted samples divided by the total sample size. A higher correct predicted percentage means a higher validity.

The empirical results are presented in Table 8. In terms of the signs of these estimates, the results conform to what we expected in Table 7. The results reveal that income appears to have an important influence on WTP. Besides, the findings also indicate that area, education, and the value of respondents have positive effects on WTP. The results also suggest that sex, age, marriage, and family status are not significant variables. Furthermore, the last row in Table 8 shows that the percentages of correct prediction in these three cases are all larger than 80%, which suggests that the model is very reliable.

Finally, we can calculate the public's WTP for the three different cases from the above empirical results. In case 1, the public would pay NT$724 (i.e. US$22.6) per year to reduce the probability of dengue fever which increases by 12% due to climate change. Similarly, people would pay NT$3,223 and NT$5,114 (i.e. US$100.7 and US$159.8) per year in case 2 and case 3, respectively. There are two meanings attached to these figures. The first interpretation is that the economic damage from

Table 8 Estimation results of WTP

Variables	CASE 1 (12%)	CASE 2 (43%)	CASE 3 (87%)
CONSTANT	−0.4368097431	−1.398150796***	−2.045461727
	(0.3374)	(−0.0025)	(−4.432)
VALUE	0.0397016558	0.2859352675***	0.3563299046***
	(0.7075)	(0.0068)	(0.0006)
AREA	0.1642526164	0.4739137187***	0.3701673088**
	(0.3692)	(0.0049)	(0.0318)
SEX	−0.1194718211	−0.05116790835	0.1364254585
	(0.4122)	(0.7168)	(0.3214)
AGE	0.009250440388	−0.003665658752	0.01228497731
	(0.4570)	(0.7564)	(0.2706)
EDUCATION	0.5014530008***	0.5468118987***	0.5785807104***
	(0.0044)	(0.0012)	(0.0003)
MARRIAGE	0.09689773686	−0.007621732329	0.1693058049
	(0.6147)	(0.9675)	(0.3440)
FAMILY	0.007308905365	0.04235594854	−0.02953071617
	(0.8996)	(0.4741)	(0.5840)
INCOME	0.00001419358669***	0.00001175647226***	0.00001191260955**
	(0.0089)	(0.0186)	(0.0108)
α_j	−0.001717352408***	−0.0007917568634**	−0.0005421207807**
	(0.0055)	(0.0214)	(0.0077)
Log–likelihood	−231.1849	−271.5075	−301.1654
Chi-squared	77.75338	132.2803	164.3363
Percentage of correct prediction	83.44%	83.01%	81.32%

Numbers in parenthesis are *P*-values.

$\chi^2(0.01,8) = 20.09$.

α_j is the coefficient of T_j

*Significant at 10% level, **significant at 5% level; ***significant at 1% level dengue fever due to climate change ranges from NT$724 to NT$5,114 per year per person. Therefore, for the entire society, the total economic damage ranges from NT$16.6 to NT$117.6 billion (or US$0.52 to US$3.67 billion) per year. The second interpretation is that people in Taiwan would like to pay these amounts of taxes for government's actions to reduce such health risk.

The above estimation values could be justified by comparing with other WTP values for infectious diseases. For instance, in the case of food-borne diseases, Goldberg and Roosen (2007) found that an individual's WTP using CVM ranges from US$2.98 for a risk reduction of 40% for Campylobacteriosis or for a risk reduction of 40% for Salmonellosis to US$5.88 for a risk reduction of Salmonellosis of 80% and a risk reduction of Campylobacteriosis of 40%. Sauerborn et al. (2005) found that people was willing to pay US$3.78 for a vaccine against maternal malaria, and US$2.58 for a vaccine against childhood malaria. Jacobs et al. (2002) found that respondents would pay a median of dollars US$ 2,000 for risk-free prevention of hepatitis A symptoms. Meanwhile, a couple of studies estimated the WTP values for non-infectious diseases. Kleinman et al. (2002) found that respondents were willing to pay up to $181.66 to obtain a complete relief in a short period of time without side effects of Gastroesophageal Reflux. Johnson et al. (2006), respondents were willing to pay $1,510 over 3 years to participate in a lifestyle intervention program similar to the Diabetes Prevention Program. In addition, Yeung et al. (2005) found people are willing to pay US$44.99∼US$57.30 to prevent travel health problems. Our estimation values are within the middle ranges of these estimates.

These figures provide a basis for the government to measure the cost of medical treatment for dengue fever which is rising rapidly due to climate change. Furthermore, several policy implications can be drawn from this study. First, the government could use such a budget to develop a vaccine or drugs to treat the patients with dengue fever. Second, the authorities could take some actions, such as cleaning the breeding sites, killing mosquito populations, monitoring the epidemic situation, educating people, and so on in order to reduce the probability of people being infected by dengue fever.

5 Concluding comments

The scientific community has recognized that one of major impacts of climate change has to do with the spread of infectious diseases, especially vector-borne diseases, but so far little attention has been paid to the damage caused by these impacts. This paper provides an approach to estimating such economic impacts. First, we present an econometric approach to estimate the impact of climate change on a dengue fever epidemic. Our findings confirm that the transmission of dengue fever is strongly determined by climate change and these findings are in line with previous studies. In Taiwan, temperature, precipitation, population, and the density of the mosquito population are essential components of a dengue fever epidemic.

In our study, we also estimate the potential of the economic impacts of climate change on dengue fever in Taiwan using a non-market value CVM approach. We did not address and analyze any subjective risk perception of the respondents in this study. So the relatively simple version of CVM survey in our study is not able to address that the subjective risks for the dengue fever are different for the survey respondents and this will be the limit of our study. However, we did provide respondents the objective risk of death rate of the dengue fever and the probability of increase due to the climate change in this study. In applying this CVM approach to estimate the WTP for three different cases of dengue fever prevalence, we find that people in Taiwan would pay NT$724, NT$3,223, and NT$5,114 each year to reduce the increased likelihood of dengue fever occurring due to climate change by 12%, 43%, and 87%, respectively. These findings show that the respondents are concerned with the influence of climate change on a dengue fever epidemic. In other words, people in Taiwan are willing to pay significant money to avoid the increase in dengue fever cases brought about by climate change. The government's actions including reducing the Breteau index by killing the mosquito and educating people regarding disease prevention to reduce the chances of infection are therefore justified.

The mean climate change effects on the occurrence of infectious diseases as well as on the estimation of economic damage have been done on this study, however, the episodic effects of climate variability need to be explored in the near future. The economic impacts of climate variability may be difficult to quantify due to the uncertainty of these climate variability events. However, the possible consequences in terms of cost may enlarge the estimation of confidence level and the efforts to explore these estimating on the cost of diseases due to the episodic effects of climate variability could be fruitful areas of future studies.

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