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Describing and analysing the association between meteorological variables and adult *Aedes aegypti* mosquitoes

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Abstract

The aim of this study was to describe the association between meteorological factors and the abundance of adult *Aedes aegypti* mosquitoes, over 5 year period, from 2006 to 2010 in Jeddah, Saudi Arabia. Daily meteorological data and the adult *Aedes* mosquito counts and identification were collected and retrieved from the Presidency of Meteorology and Environment (PME) and the laboratory of mosquitoes, which belongs to Jeddah Municipality. Different methods were used to verify the associations. Descriptive analysis provided a comparative view of adult *Aedes* mosquitoes and meteorological variables. Spearman correlation analysis was used to examine the association. The meteorological data were related to adult *Aedes* mosquito numbers on a weekly basis. The number of adult *Aedes* mosquitoes increased rapidly about two weeks after the week of rainfall, and sometimes after one week. Most of the meteorological variables associated negatively with the number of mosquitoes in most of the years of epidemic except 2007. In 2007, all meteorological variables considered in this study were positively correlated with the number of mosquitoes, and the most significant correlation was between the weekly averages of maximum relative humidity and the number of mosquitoes ($P = 0.49$). It was found that average weekly maximum temperature, average weekly minimum relative humidity and average weekly maximum relative humidity were not the main determinant factors in the abundance of adult *Aedes* mosquitoes, while rainfall and average weekly minimum temperature played determining roles in the abundance of adult *Aedes* mosquitoes. The study findings can help to improve current dengue fever surveillance system in Jeddah for more accurate forecasting. Every trap that is used to capture adult mosquitoes must have devices for measuring temperature and relative humidity to give a better understanding of the impact of climatic conditions on the adult mosquito abundance.

Key words: *Aedes aegypti*, Spearman correlation, temperature, relative humidity, rainfall.

Introduction

There is substantial evidence that climate variations impact on mosquito-borne diseases, including dengue fever [1]. Temperature, humidity and rainfall affect not only the *Aedes* mosquitoes' survival time and habitats, but also their replication, maturation and infective periods [2]. Most dengue fever cases are recorded in subtropical and tropical regions [3] because freezing temperatures and dry humidity destroy the larvae and eggs of *Aedes* mosquitoes outside these regions [4].

According to Wallis [5], "mosquitoes are critically dependent on climate for their survival and development. Also, climate circumscribes the distribution of mosquito-borne diseases such as dengue fever, while weather impacts the timing and intensity of outbreaks". In general, temperature ranges from 14-18ºC at the lower end and 35-40ºC at the upper end can lead to higher transmission occurrence [6]. Development increases in warmer temperatures, raising the odds of disease transmission, while the reproduction rates and replication of diseases are slower in cooler temperatures [6-9]. In general, high amounts of precipitation lead to increases in the number of breeding sites, and humidity is often overlooked as a factor in the life cycle of mosquitoes and in disease replication and transmission [10, 11]. Relative humidity is increased by rainfall, particularly following drought. Relative humidity strongly impacts flight and the subsequent host seeking behaviour of mosquitoes [11].

Limited studies have been conducted at county scale areas to study how meteorological variables might impact the magnitude of dengue epidemics. Bi *et al.* [12] have investigated the association between the outbreak of dengue fever and meteorological variables in the north of Queensland, Australia, and they found an association between those variables and the transmission of dengue fever [12]. Study of the development of predictive tools for pre-emptive dengue vector control showed that long-term meteorological factors have a significant relationship with abundance of adult *Aedes* mosquitoes; particularly when mean minimum temperature is lagged 6 months and mean daily temperature is lagged 4 months. Also, the prediction increase in abundance during the wet season [13]. Pontes *et al.* [14] found in their study in a Brazilian city that the vector population of dengue fever developed independently of rainfall. Al-Ghamdi *et al.* [15] studied the role of climatic factors on the seasonal abundance of *Aedes* mosquitoes in Jeddah, Saudi Arabia. They attempted to establish the relationship between *Aedes* mosquitoes, dengue fever cases, temperature and relative humidity and found that the role of relative humidity is well established compared to other climatic variables [15]. However, this study was based on limited data, covering a time span of one year only, and it did not use the rainfall data.

The present study aims to describe the relationships between relative humidity, temperature, rainfall and the abundance of adult *Aedes* mosquitoes over a five years period from 2006 to 2010 in Jeddah, Saudi Arabia. To date, this study is the first to describe this association on the basis of five years of weekly data in Jeddah. The previous studies were based on seasonal period and focused on two climatic variables (temperature and relative humidity). Worldwide, it is one of the few studies that investigates these relationships based on weekly data for each year of epidemic. Most of the previous studies used monthly or yearly meteorological data [1, 7, 12, 15- 17]. Different methods were used to achieve the main aim of this study, including descriptive analysis and Spearman correlation. Descriptive analysis provided a description of the time series characteristics of adult *Aedes* mosquitoes and meteorological variables, while Spearman correlation examined the association between them.

Materials and Methods

Study site: This study was conducted in Jeddah County, which is located in Makkah province in the western part of Saudi Arabia (Fig. 1a). The total area of Jeddah is around 1160 km², and it has a population of around 3.5 million. The average temperature in Jeddah is around 29ºC (84ºF). The highest monthly average of high temperatures in the study area is around 41ºC (106ºF) in June, and the lowest monthly average of low temperatures is 16ºC (61ºF) in January and February. The average rainfall in the study area is around 60 mm. The driest weather is between September and October, while the wettest weather is between December and January.

Entomological data: Daily mosquito samples are acquired by black hole traps and these samples are returned to the mosquito laboratory for filtering and sorting according to species, sex, dates of collections, coordinates and number of mosquitoes for each location. According to Aburas [18] black hole traps were considered the most efficient traps for the study area. From the mosquitoes that were collected only adult *Aedes aegypti* is vector for dengue fever and so were used in the analysis in this research. The adult *Aedes aegypti* mosquito counts and identification were provided by the laboratory of mosquito, which belongs to Jeddah Municipality. For the capture of mosquitoes, 504 black hole traps have been in operation since 2006. Theses traps were distributed geographically based on population density and different environmental factors (Fig. 1b) and capture mosquitoes by producing carbon dioxide.

Meteorological data: In Saudi Arabia, meteorological data including daily maximum temperature, daily minimum temperature, daily maximum relative humidity, daily minimum relative humidity and rainfall were retrieved from the Presidency of Meteorology and Environment (PME).

The collected data were entered into Excel files to remove the duplicate and redundant data, fill missing values and convert dates to weeks for each year of epidemic. The weekly averages of daily maximum temperature, daily minimum temperature, daily maximum relative humidity and daily minimum relative humidity were calculated and compared to the adult *Aedes* mosquito counts for each week from week 23 in 2006 to week 52 in 2010.

For rainfall, the situation was different. The rain usually falls during a small number of weeks in November, December or January. Therefore, most of the daily data for rainfall were recorded as 0 mm, but to illustrate the impact of rainfall on the abundance of mosquitoes even in a short period, we took into account each week that had rainfall data as well as the total number of mosquitoes for that week, two weeks before and two weeks after the rainfall event.

Data analysis: Descriptive analysis and Spearman correlation were used to verify the associations. Descriptive analysis provided a comparative view of adult *Aedes* mosquitoes and meteorological variables. Also, it was used to illustrate the different trends of the mosquitoes in each week of epidemic years.

Spearman correlation analysis (Equation 1) was performed because Pearson's correlation is based on the assumption that both X and Y as variables follow a normal distribution; therefore, it reflects only the degree of linear relationship between two variables. Given that the occurrence of mosquitoes may not be normally distributed and the relationship between meteorological variables and the mosquitoes may not be linear, it was appropriate to use.The calculation of the Spearman coefficient between two variables (X and Y) is as follows:

$$\rho = 1 - \frac{6\sum d_i^2}{n(n^2-1)}. \quad (1)$$

where $\sum d^2$ is the sum of squared differences between mosquito ranks and temperature or relative humidity ranks, and n is count of difference.

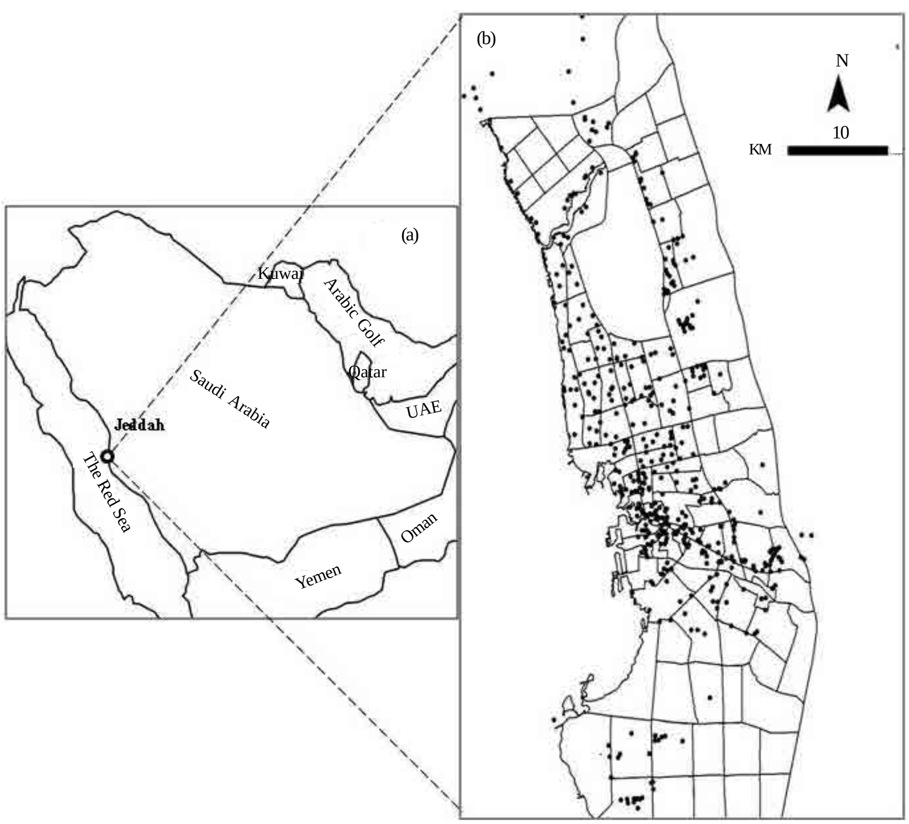

Figure 1. (a) The study site and (b) locations of black hole traps.

Results

Descriptive analysis of relative humidity, temperature and rainfall with adult Aedes mosquitoes: Over a five year period, the study showed no specific trends or patterns (Figs 2 and 3). The results were very variable for some years. In general, Fig. 2b shows an increase in the number of mosquitoes with increases in the average minimum and maximum weekly relative humidity, while Fig. 2c shows decreases in the number of mosquitoes with fluctuating average relative humidity. The number of mosquitoes was stable in 2009 while the relative humidity fluctuated (Fig. 2d). Similarly, no specific trends or patterns were noted between temperature and mosquito numbers over the study period. In 2007, the number of mosquitoes increased with increasing average minimum and maximum temperatures (Fig. 3b), while the number of mosquitoes decreased with increases in the weekly average temperature (Fig. 3c).

Fig. 4 shows that the number of adult *Aedes* mosquitoes increased rapidly about two weeks after the week of rainfall, and sometimes after one week. For instance, in 2008, the numbers of mosquitoes were around 45 in week 43 and week 44; and two weeks after the rainy week (week 45), the number of mosquitoes increased rapidly to reach around 180. In 2009, the mosquito number reached around 320 in week 50 as a result of rainfall in weeks 48 and 49. After week 7 of 2010 the number of mosquitoes increased rapidly (≈150) due to the rainfall in week 6. Week 52 was a rainy week in the study area, with average rainfall of around 55 mm, which led to an increase in the number of mosquitoes in weeks 1 and 2 of 2011.

Spearman correlation analysis: Table 1 shows that the weekly average maximum relative humidity, weekly average minimum relative humidity, weekly average maximum temperature and weekly average minimum temperature were negatively correlated with weekly mosquito numbers in 2006 and 2008. In 2007, all meteorological variables considered in this study were positively correlated with the number of mosquitoes, and the most significant correlation was between the weekly averages of maximum relative humidity and the number of mosquitoes ($P = 0.49$). In 2009, weekly averages of maximum relative humidity and weekly averages of minimum relative humidity showed very weak correlations with the weekly number of mosquitoes ($P = 0.16$, $P = 0.03$). In contrast, the weekly averages of maximum temperature and weekly averages of minimum temperature showed significant correlations with the number of mosquitoes. In 2010, the weekly averages of minimum and the weekly averages of maximum temperature were significantly negatively correlated with the number of mosquitoes ($P = -0.73$, $P = -0.58$). The weekly averages of minimum relative humidity were negatively correlated with the mosquito numbers ($P = -0.22$), while the weekly averages of maximum relative humidity were positively correlated with number of mosquitoes ($P = 0.14$).

Discussion

Increased risk of bites from adult *Aedes* mosquitoes in certain weeks was evaluated by considering meteorological variables. Descriptive analysis and Spearman correlation, used to relate weekly numbers of adult *Aedes* mosquitoes to various weekly meteorological data, indicated that relative humidity, temperature and rainfall had different impacts on the abundance of *Aedes* mosquitoes. In years such as 2007, the correlation coefficient of meteorological variables and mosquitoes was positive, which means that those variables and mosquitoes tended to increase or decrease together. In years such as 2008, the correlation coefficient of meteorological variables and mosquitoes was negative, which means that if one of those variables increased, the number of mosquitoes decreased, and vice versa. A reasonable assumption is that temperature and rainfall during the winter months directly influence the activities of *Aedes* mosquitoes, such as breeding rate. Rainfall was found to play a positive role in determining mosquito abundance. Average minimum temperatures ranging from ≈18ºC to 25ºC were generally negatively correlated with the abundance of adult *Aedes* mosquitoes.

Of the 4 variables used in this study, average minimum temperature showed the strongest correlations over the 5 years, while average minimum relative humidity showed the weakest correlations. However, for all the variables, there was no consistent pattern over the years. For average minimum temperature, 2007 gave a positive correlation, while all the other years gave negative correlations. On closer inspection we see that in 2007 the number of mosquitoes increased throughout the year, completely decoupled from temperature patterns and different to mosquito abundance patterns for the other years. The reason behind the increase of mosquito numbers was not related to the climatic variables, but as a result of the emergence of swamps due to the increase of sub-surface water level (personal observation). Swamps usually appeared in areas that had many housing constructions that had earthworks done and so formed environments for mosquitoes to breed (Fig. 5). In 2007, there were many more construction projects compared to other years, but the actions taken by the authorities such as drainage, piling and spraying these environments led to the eradication of eggs and larvae. This later reduced the number of adult mosquitoes.

Characterising the weekly distribution of *Aedes* mosquitoes provided insights into the important drivers of mosquito numbers, including rainfall and weekly average minimum temperature that impacted on weekly distributions. This study also confirmed that seasonal rainfall and weekly average minimum temperature had a strong influence on the abundance of *Aedes* mosquitoes and these mosquitoes responded quickly to variations in rainfall and minimum temperature.

Several studies have reported the impacts of meteorological factors on dengue fever vector [19-22]. For example, temperature and rainfall were reported to rise three and seven weeks, respectively, before entomological indices started to escalate [19]. Our study

Table 1. Spearman correlation coefficient between meteorological variables and adult *Aedes* mosquito numbers.

Meteorological Variable	Mosquitoes in 2006	Mosquitoes in 2007	Mosquitoes in 2008	Mosquitoes in 2009	Mosquitoes in 2010
Average Maximum Relative Humidity	-0.11	0.49	-0.03	0.16	0.14
Average Minimum Relative Humidity	-0.02	0.28	-0.02	0.03	-0.22
Average Maximum Temperature	-0.20	0.25	-0.43	-0.40	-0.58
Average Minimum Temperature	-0.34	0.33	-0.51	-0.50	-0.73

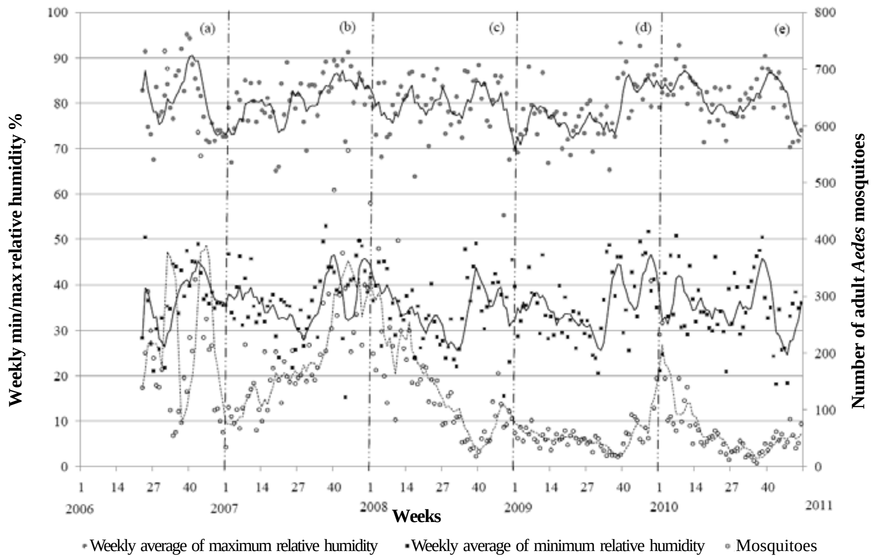

Figure 2. Annual weekly adult *Aedes* mosquito distributions compared to weekly averages of maximum and minimum relative humidity from 2006 to 2010.

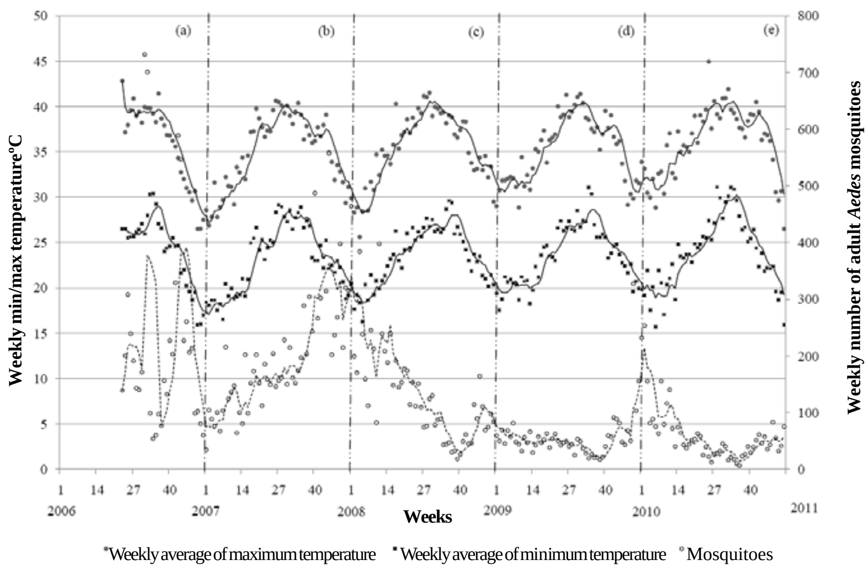

Figure 3. Annual weekly adult *Aedes* mosquito distributions compared to weekly averages of maximum and minimum temperature from 2006 to 2010.

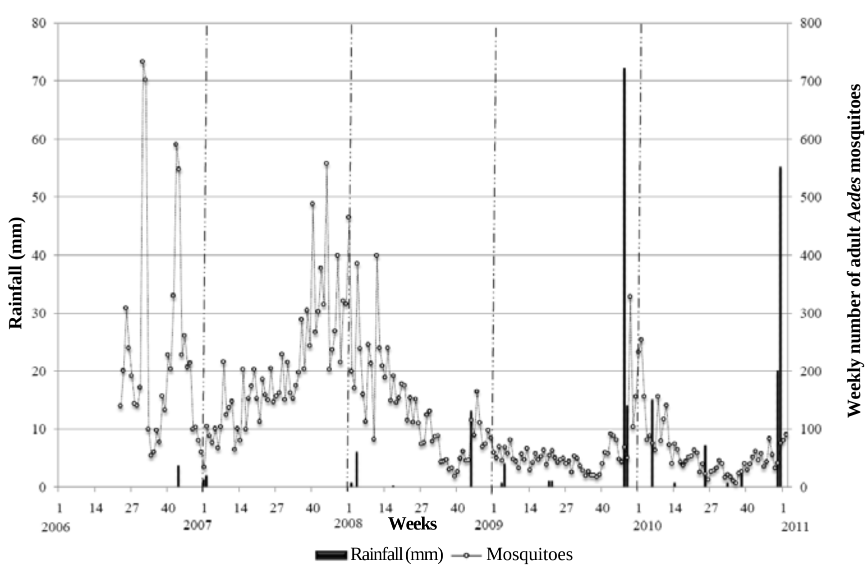

Figure 4. Impact of rainfall on mosquito abundance.

Figure 5. Housing constructions that had earthworks done and so formed environments for mosquitoes to breed (photos: H.Khormi).

showed a reverse trend. Usually, the mosquito numbers increased rapidly after two weeks of rainfall. Rainfall as a meteorological variable and the *Aedes* mosquito time series showed high correlation over short lag periods of around two weeks. Increase in the number of mosquitoes, especially after heavy rainfall, is due to the presence of swamps consisting of places for mosquitoes to lay eggs safely. In some weeks, rainfall was found negatively associated with adult *Aedes* mosquitoes. The plausible explanations might be the mosquito's eggs and larvae were washed away by heavy rainfall [23]. Numbers of adult mosquitoes especially after rains fluctuated due to the use of insecticide spraying in the air that leads to the death of adult mosquitoes while the eggs and larvae remain away from the danger of insecticides. This later leads to increases in the mosquitoes that transmit dengue. Also, some areas of the study site have limited access to the water supply, leading residents to use water storage containers [24] and ground level water storage yield. Many studies have shown that containers and tanks provide suitable places for larvae and pupae to live. Bisset *et al.* [25] found that the immature stages of *Aedes* were found in 70 containers and the pupae of this species were seen in 52 containers out of the total samples (≈1000) they used. They also found that 74.1% of the pupae that were collected in the ground level water storage tanks, and 19% were found in miscellaneous small containers.

The *Aedes* mosquito survival rate can increase at higher temperatures (not more than 38ºC) [20], and our study indicates the weekly temperatures and relative humidity that are suitable for survival of adult *Aedes* mosquitoes and transmission of dengue. Similar results have been presented by Githeko *et al.* [6], who found that temperature ranges from 14-18ºC at the lower end and 35-40ºC at the upper end could lead to higher dengue transmission.

Hales *et al.* [22] and Kuno [21] found that high relative humidity with high temperatures and heavy rainfall also positively affect the survival and breeding conditions of the mosquitoes, in agreement with the present findings. Rainfall created small puddles or swamps that serve as suitable breeding sites for mosquitoes, and increase humidity to suitable levels for enhancement of *Aedes* mosquito survival. Although some differences were noted between the results of previous studies and those of our study, overall, the studies indicated that rainfall and weekly average minimum temperature were the most significant meteorological variables that determined adult *Aedes* mosquito abundance. We found that the average weekly maximum temperature, average weekly minimum relative humidity and average weekly maximum relative humidity were not the main factors controlling the abundance of adult *Aedes* mosquitoes, in agreement with a study by Moore *et al.* [26]. They predicted *Aedes aegypti* abundance from climatological data and found that temperature was not a good indicator of abundance, while the amount of rainfall and the number of rainy days were useful predictors for *Aedes* mosquito numbers, especially for larval abundance.

Humidity is sometimes overlooked as a factor in the life cycle of mosquitoes and in disease replication and transmission. Koopman *et al.* [27] found a significant relationship between humidity and dengue infection in Mexico. Al-Ghamdi *et al.* [15] and Day and Curtis[11] found that relative humidity could be a determining factor in the seasonal abundance of *Aedes aegypti*. Our study shows an opposite trend to these findings, as we found only weak relationships between relative humidity and the abundance of the dengue vector in Jeddah. The main reason underlying these differences was that most of the previous studies were based on seasonal or yearly data and our study was based on weekly data, which is more reliable for describing associations. The variations in annual meteorological variables indicated that certain factors other than biological characteristics of adult *Aedes* mosquitoes determine dengue fever transmission. These other factors have a significant influence on dengue transmission and its vector and include human population factors such as abundance, social status, population immunity and economic status.

Conclusions

This study provides an indication that readily available meteorological variables (rainfall and minimum temperature) could be used to predict changes in the number of adult *Aedes* mosquitoes in Jeddah. The findings suggest that average weekly minimum temperature is the most significant factor to be associated with adult *Aedes* mosquito abundance in the shorter and longer term. Rainfall was a significant determinant of changes in the abundance of adult *Aedes* mosquitoes over a short period. Also, the results regarding the effect of temperature, relative humidity and rainfall on adult *Aedes* mosquito's reproductive aspects contribute towards an understanding of the population dynamics of this mosquito, particularly in summer and winter seasons. The greater concentration of adult *Aedes* mosquitoes in warm and rainy season is strongly influenced by the effects of minimum temperature and rainfall.

Githeko *et al.* [6] have suggested a temperature range of 14ºC to 40ºC as being conducive for *Aedes* mosquito transmission. The temperature range for Jeddah falls within this range, with the weekly average minimum temperature being above 15ºC throughout the year and the weekly average maximum temperature being below 40ºC for most of the year as well. This shows that the temperature range in Jeddah is suitable for *Aedes* mosquito survival throughout the year and so should not be a determining factor for mosquito presence or absence for this region. However, we find strong correlations between weekly average minimum temperature and mosquito abundance showing that the abundance increases with rising temperature. We would argue that for this region rainfall is the driving factor.

These findings can help in improving dengue fever surveillance system for more accurate forecasting. Decision makers who are responsible for the dengue fever control and prevention program should not depend on average weekly maximum temperature and weekly average relative humidity as determinants for dengue fever occurrences.

This research also shows the importance of multi-season data for determining correlations between climatological factors and mosquito abundance. For a number of variables tested we found that there were different patterns in different seasons, hence concluding relationships based on one season data can lead to damaging and ineffective management decisions.

To improve monitoring and forecasting, we suggest that every trap that is used to capture adult mosquitoes must have devices for measuring temperature and relative humidity to give a better understanding of the climatic conditions in the area. This can be used later to create temperature, relative humidity and rainfall surface layers for all of Jeddah districts and be used as parameters for modelling dengue incidences.

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