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ORIGINAL RESEARCH

Spatiotemporal Anopheles Population Dynamics, Response to Climatic Conditions: The Case of Chabahar, South Baluchistan, Iran

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Abstract

BACKGROUND An understanding of the factors that affect the abundance of *Anopheline* species provides an opportunity to better understand the dynamics of malaria transmission in different regions. Chabahar, located south east of Iran, is the most malarious region in the country.

OBJECTIVE The main aim of this study was to quantify the spatiotemporal Anopheles population dynamics, response to climatic conditions in Chabahar.

METHODS Satellite-based and land-based climatic data were used as explanatory variables. Monthly caught mosquitoes in 6 village sites of Chabahar were used as dependent variable. The spatiotemporal associations were first investigated by inspection of scatter plots and single variable regression analysis. A multivariate linear regression model was developed to reveal the association between environmental variables and the monthly mosquito abundance at a 95% confidence level ($P \leq 0.5$).

FINDINGS Results indicated that Anopheles mosquitoes can be found all year in Chabahar with 2 significant seasonal peaks from March to June (primary peak) and September to November (secondary peak). Results of the present study showed that 0.77 of yearly mosquito abundance emerges in the thermal range of 24°C to 30°C and the humidity range of 0.70 to 0.80 in Chabahar.

CONCLUSION According to the developed multivariate linear model, 0.88 of temporal variance of mosquito abundance, nighttime land surface temperature, and relative humidity of 15 Universal Time Coordinated (18.30 Iran) are the main drivers of mosquito population dynamics in Chabahar.

KEY WORDS Anopheles mosquito, Chabahar, climatic factors, spatiotemporal association

INTRODUCTION

Malaria is transmitted by infected female Anopheles mosquito, and understanding mosquito ecology and population dynamics can inform how best to defeat malaria.[1] In 2013, an estimated 198 million cases of malaria occurred worldwide; of these, 90% were in Africa. The total number of deaths worldwide attributed to malaria was 584,000.[2] It is the most important parasitic disease in Iran, with 1373 confirmed cases in 2013. Of these cases, 18% were *Plasmodium falciparum*, and the remaining were *P. vivax*.[3] Climatic condition has been one of the main drivers of this disease governing the spatial extent and year-to-year

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variations.[4] The pathway from climate to malaria goes through the Anopheles mosquito and parasite.[5] Climate conditions affect larval development and parasite maturation within the infected mosquito.[6] Although it is well established that parasite development is influenced by temperature,[7-12] the vector's response to weather and climate is more complex.[8] Mosquito abundance in any area depends on temperature but also on the abundance of breeding sites (rainfall, evaporation, and vegetation cover),[10,13,14] drought and desiccation (air humidity, soil surface moisture, water body, irrigation systems),[15-17] and competition between mosquitoes.[18,19] The association between rainfall and malaria epidemics has been recognized for many decades,[20,21] but although increasing precipitation may increase vector populations in many circumstances by increasing available anophele breeding sites, excessive rains may have the opposite effect by flushing out small breeding sites, such as ditches or pools,[22] or by decreasing the temperature, which in regions of higher altitude can hinder malaria transmission.[23] Temperature also plays an important role in the variability of malaria transmission. The development rate of mosquito larvae and the malaria parasite within the mosquito host is highly regulated by temperature. It is also one of the factors that influences the survival rate of mosquitoes. Although each species of Anopheles has a different ecology, as a general rule, warmer temperatures mean that the mosquito develops more rapidly and feeds more frequently and earlier in its life cycle and that the plasmodium parasite within the mosquito develops and multiplies more rapidly.[24] Humidity affects the survival rate of the mosquito as well. Mosquitoes will generally not live long enough to complete their transmission cycle where relative humidity is constantly below 60%.[25,26] Malaria is a major health problem in southeast Iran. Despite more than 45 years of malaria-control campaigns, it remains prevalent in the southern and southeastern areas of country.[27,28] The southeastern areas of Iran, including the provinces of Sistan and Baluchestan, Hormozgan, and the tropical part of Kerman province, account for about 95% of all malaria cases in the country.[29] There are 31 *Anopheles* species in Iran, 8 of which are assumed to play a role as malaria vectors.[30] In southeast Iran, including Chabahar, Nikshahr, and Sarbaz, 6 anopheline mosquitoes including *An. culicifacies*, *An. stephensi, An. dthali, An. fluviatilis*, *An. superpictus*, and *An. pulcherrimusare* are known as the main malaria vectors.[31] The main purpose of this study was to evaluate the potential effects of climatic factors to control spatiotemporal dynamics of malaria vectors in Chabahar.

MATERIAL AND METHODS

Study Area. Chabahar was selected as the target district for the present study (Fig. 1). Chabahar is located in southern Sistan and Baluchistan province in Iran (southeast Iran) and is one of the most malarious areas in the country, with a >10-month transmission season. Chabahar is an area with substantial human migration originating mainly

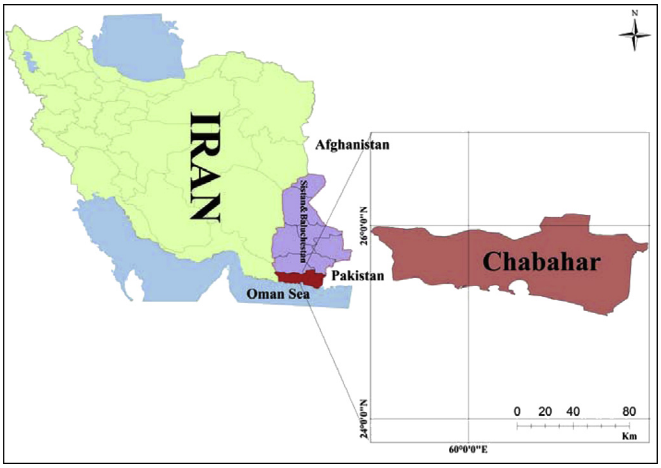

Figure 1. Chabahar is located in the south of Sistan and Baluchistan province of Iran (southeast Iran) and is one of the most malarious areas in the country.

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Table 1. **Environmental Data Used to Explain Spatiotemporal Dynamics of *Anopheles* Population in Response to Climate Conditions**

Data Type	Product	Description	Spatial Resolution	Temporal Resolution	Projection System	Re-projection	Time Duration	Format	Source
Remotely sensed data	MOD 13A3	Vegetation indexes	928 m	Monthly	Sinusoidal	GCS WGS84	1 Jan 08–31 Dec 13	HDF	MODIS website
	MOD 11A2	LST/ Emissivity	928 m	8 days	Sinusoidal	GCS WGS84	1 Jan 08–31 Dec 13	HDF	MODIS website
	TRMM-3B43	Accumulate monthly rainfall	1/4° (resampled to LST)	Monthly	-	GCS WGS84	1 Jan 08–31 Dec 13	NC	TRMM
Land-base synoptic station of Chabahar	Air temperature	Recorded at high 2 m from land surface	-	Monthly	-	GCS WGS84	1 Jan 08–31 Dec 13	Txt	IRIMO
	Relative humidity 15 UTC (18.30 IR)	%	-	Monthly	-	GCS WGS84	1 Jan 08–31 Dec 13	Txt	IRIMO
	Relative humidity 09 UTC (12.30 IR)	%	-	Monthly	-	GCS WGS84	1 Jan 08–31 Dec 13	Txt	IRIMO

MOD, MODIS; GCS, Geographical Coordinate System; HDF, Hierarchical Data Format; MODIS, Moderate Resolution Imaging Spectroradiometer; LST, land surface temperature; DLST, day-time LST; NLST, nighttime LST; TRMM, tropical rainfall measurement mission; NC, NetCDF (Network Common Data Format); IRIMO, Iran meteorological organization; UTC, Coordinated Universal Time; IR, Iran.

from Afghanistan and Pakistan. Malaria cases are reported during the whole year.

Environmental Data. In the present study, 2 types of environmental data were used (Table 1). Satellite-based data included day-time land surface temperature (DLST; °C), nighttime land surface temperature (NLST; °C), the enhanced vegetation index (EVI), monthly mean accumulated rainfall (mm), and land-based station data that included 09 UTC and 15 UTC relative humidity (RH; %, 12.30 Iran and 18.30 Iran, respectively), and monthly mean 2-m air temperature (°C) from January 2008 to December 2013 (6 years average).

Enhanced Vegetation Index. The EVI was designed to enhance the vegetation signal with improved sensitivity in high biomass regions and to improve vegetation monitoring through a decoupling of the canopy background signal and a reduction in atmosphere influences. The EVI was computed as follows:

$$EVI = G \times \frac{(NIR - RED)}{(NIR + C1 \times RED - C2 \times Blue + L)}$$

Where blue/red/near-infrared (NIR) is surface reflectance representing reflectance at the blue (0.45-0.52 μm), red (0.6-0.7 μm), and NIR (0.7-1.1 μm), wavelengths, respectively. L is the canopy background adjustment that addresses nonlinear, differential NIR and red radiant transfer through a canopy; and C1 and C2 are the coefficients of the aerosol resistance term, which uses the blue band to correct for aerosol influences in the red band. The coefficients adopted in the MODIS-EVI algorithm are; L = 1, C1 = 6, C2 = 7.5, and G (gain factor) = 2.5.

Land Surface Temperature. Land surface temperature (LST) is a good indicator of the energy balance at the earth's surface and the so-called greenhouse effect because it is one of the key parameters in the physics of land surface processes on a regional as well as a global scale.[32] LST combines the results of surface-atmosphere interactions and energy fluxes between the atmosphere and the ground.

TRMM Monthly Accumulated Rainfall. Tropical Rainfall Measurement Mission (TRMM) is a research satellite designed to improve understanding of the distribution and variability of precipitation within the tropics as part of the water cycle in the current climate system. We used 6 years (2008 to 2013) of average monthly accumulative rainfall (TRMM-3B43) for the study area.

Mosquito Collection. Six village sites along the Chabahar were selected for study (Fig. 2): Bavriran (25.556N, 60.279E), Gãnjãk (25.74N, 59.211E), Beris (25.136N, 61.190E), ChaharBidi (25.571N, 60.131E), Kacho (25.244N, 60.90E), and Rimdan-e-Delmora (25.427N, 61.44E), where the primary economic activities are fishing, gardening, small-scale agriculture of vegetables and

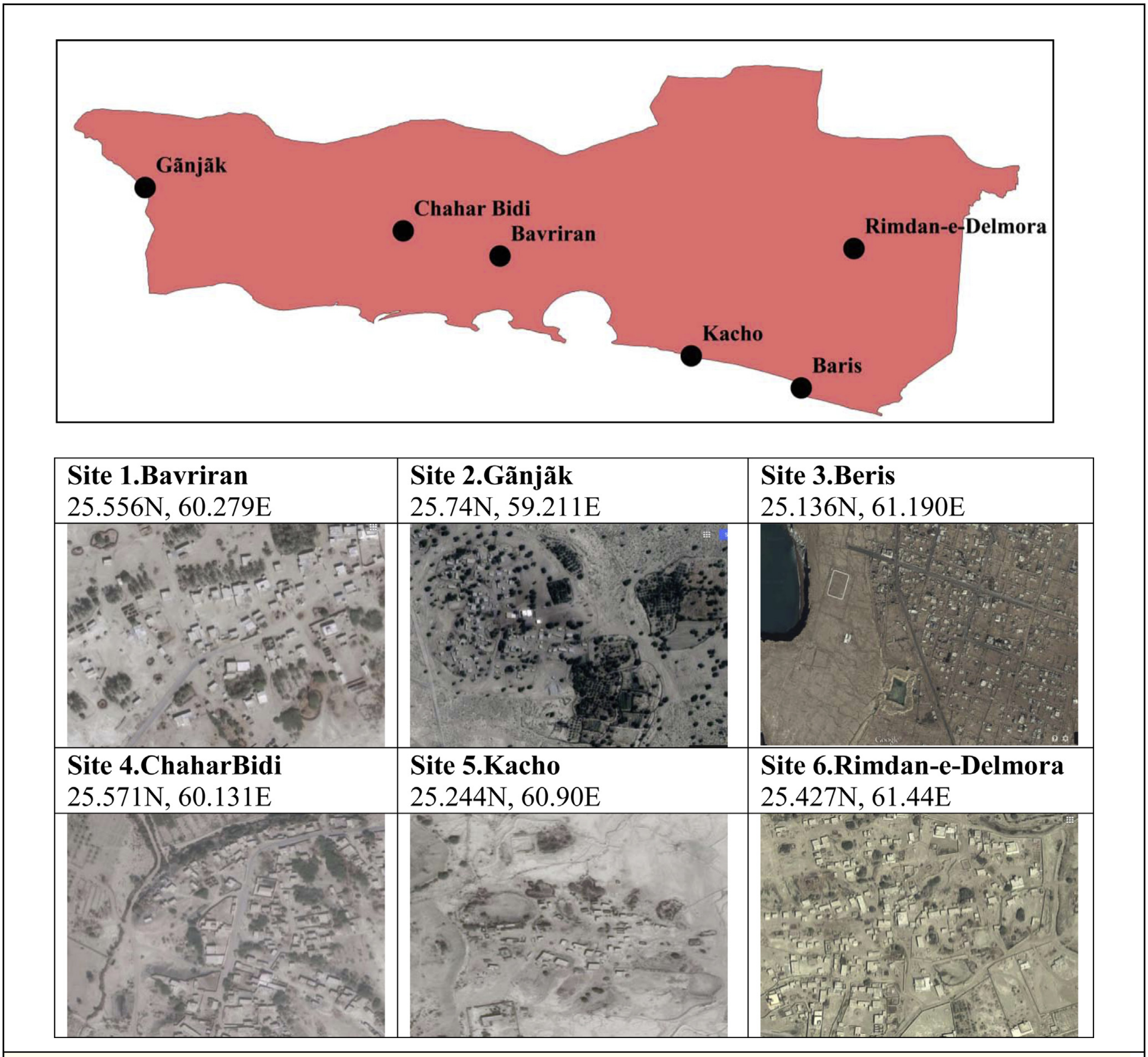

Figure 2. **Six rural sites, along the Chabahar, were selected for mosquito collection from January 1, 2008 to December 31, 2013.**

watermelon, and day labor at neighboring water buffalo and cattle farms.

All night landing catches of mosquitoes were made monthly in the village environment for 12 consecutive nights (2 successive nights in each site) from January to December 2013. Moon phases have been shown to affect the adult behavior of anophelines[33,34]; therefore, collections were centered around the new moon, when moonlight influence on catch was expected to be minimal. There were two 5-hour collection periods from 7 PM to 12 AM and 12 AM to 5 AM. Different collectors were used for each period, and collectors changed positions each night to prevent any bias. Mosquitoes were aspirated as they landed on one exposed leg of the collector and placed in unwaxed screened 0.5-L ice cream cartons modified as cages.

Statistical Analysis. We examined the spatiotemporal association between environmental variables and monthly anopheles abundance using Pearson product-moment correlation coefficient, which measures the direction and strength of association

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Table 2. Number of Monthly Caught *An.* Mosquitoes in 6 Villages of Chabahar

	Rimdan	Koucho	Baris	Gonjak	Charbidi	Bavriran	Total	%
Jan	39	47	51	32	43	32	244	34
Feb	54	50	43	35	61	42	285	4
Mar	107	97	107	75	86	96	568	8
Apr	141	161	148	97	102	103	752	10
May	185	178	161	130	143	128	925	13
Jun	194	162	160	145	175	155	991	14
Jul	96	101	75	72	69	72	485	6
Aug	70	60	70	62	55	32	349	4
Sep	152	163	132	87	85	64	683	9
Oct	178	158	168	129	128	105	866	12
Nov	110	112	132	79	61	78	572	8
Dec	60	81	31	25	50	39	286	4
Total	1386	1370	1278	968	1058	946	7006	1

between variables; 95% confidence level ($P \leq 0.5$) has been considered to determine the significance of correlation coefficients. The relationship between monthly anopheles abundance as an independent variable and each environmental explanatory variable were first investigated by inspection of scatter plots and by single variable regression analysis. Finally, multivariate regression models were developed to determine the association between environmental variables and the occurrence of anopheles in 95% level ($P \leq 0.5$).

RESULTS

The number of caught Anopheles mosquitoes in the 6 sites are presented in Table 2. As can be seen, the highest number of mosquitoes were caught in June and included 14% of all mosquitoes caught. Anopheles mosquitoes can be found all year round in Chabahar; however, their population reaches minimum level during December to February. A significant decrease can be seen in July and August, as well.

As seen in Figure 3, the temporal distribution of *An.* mosquitoes in Chabahar has a primary peak that commonly occurs from March to June. Of the total caught mosquitoes, 45% belong to this primary peak. Also a subsidiary peak occurs during the months of September, October, and November and includes 29% of all caught mosquitoes. So that 74% of caught mosquito's abundance related to March to June and September to November. Only 26% of mosquito's abundance belongs to other months (December to February and July to August).

The matrix of temporal association among climatic factors and monthly caught mosquitoes is presented in Table 3. As can be seen, NLST has the highest correlation with the monthly abundance of

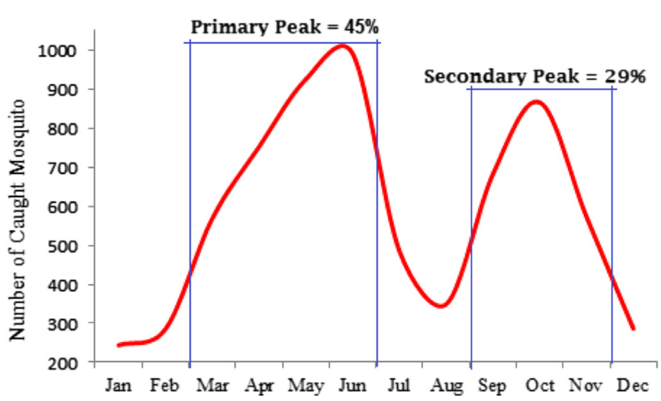

Figure 3. Total number of monthly caught mosquito in 6 village sites of Chabahar January 2012 to December 2012. Two significant seasonal peaks of mosquito abundance can be seen.

Table 3. Temporal Association Matrix Among Climatic Factors and Monthly Abundance of Caught Mosquito

Climatic Factors	Temporal Correlation	Sig
Air temperature at 2 m high	0.81	39×10^{-5}
DLST	0.71	20×10^{-4}
NLST	0.88	30×10^{-5}
09 UTC (12.30 IR) RH	0.64	92×10^{-4}
15 UTC (18.30 IR) RH	0.83	35×10^{-5}

DLST, day-time land surface temperature; IR, Iran; NLST, nighttime land surface temperature; RH, relative humidity; UTC, Coordinated Universal Time.

caught mosquitoes. Relative humidity of 15 UTC, daily air temperature at height of 2 meters from the land surface and DLST, and relative humidity of 09 UTC placed in the second to sixth positions, respectively.

The scatter-plot inspection of monthly caught mosquito versus each climatic factors are shown in Figure 4. A strong linear association can be seen in these figures. The coefficient of determination (R^2), which indicates how much of the variation of caught mosquitoes is explainable by any of the climatic factors in a univariate linear model, also is shown in these plots. Of the temporal variance of caught mosquitoes, 0.78 is explainable by NLST, whereas 09 UTC (12.30 Iran) RH could explain 0.42 of temporal variance of caught mosquito. This coefficient for the air temperature, DLST, and relative humidity at 15 UTC was 0.65, 0.50, and 0.69, respectively.

Monthly distribution of caught mosquitoes and climate factors has been visualized in Figure 5.

A contingency table (also referred to as cross tabulation or cross tab), which is a type of table in a matrix format that displays the frequency distribution of the variables and provides a basic picture of the interrelation among caught mosquito abundance and climatic factors, has been applied to find interactions between them (Table 4). As can be seen in Table 4, 77% of mosquito abundance occurred when the air temperature was between 24°C and 30°C, NLST was between 26°C and 35°C, DLST was between 32°C and 42°C, and RH of 09 UTC and 15 UTC were between 0.76 and 0.83 and 0.70 and 0.80, respectively. Out of the mentioned climatic ranges, only 23% of mosquitoes were observed. Eight percent of the number of caught mosquitoes occurred when NLST, DLST, and air temperature were >35°C, 42°C, and 32°C, respectively and RH was <0.70. But 15% of the of caught mosquitoes observed when NLST, DLST, and air temperature were <22°C, 25°C, and 20°C, respectively and RH of 09 and 15 URC were >0.70 and 0.75, respectively.

Chabahar, like other parts of Iran, has a Mediterranean climate pattern, which is characterized by warm to hot, dry summers and mild to cool, wet winters. In other words, temperature and

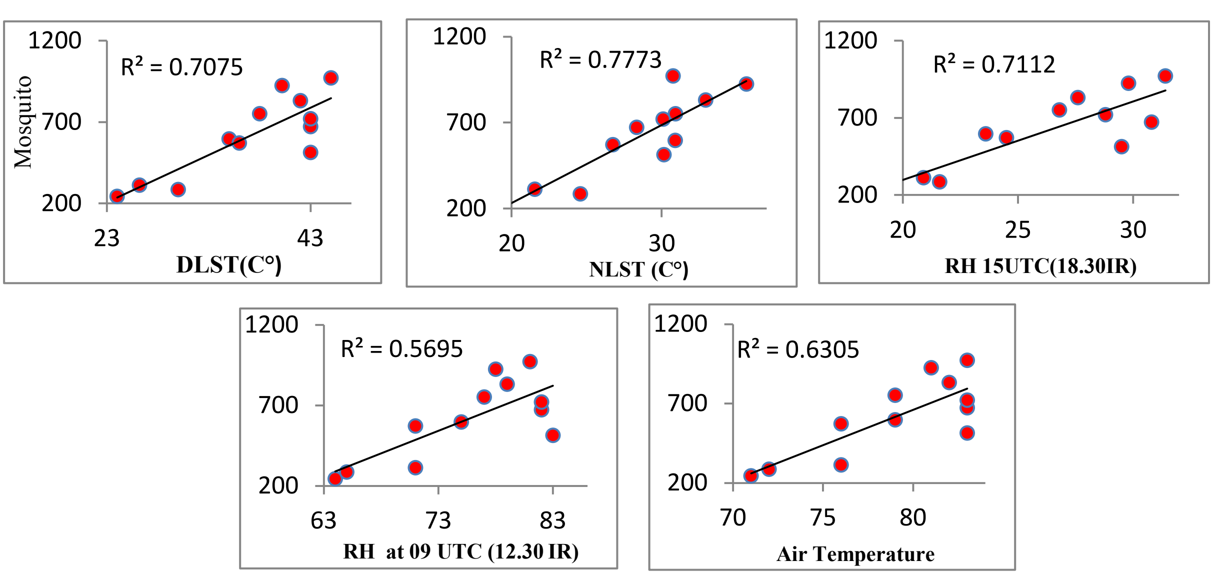

Figure 4. Scatter-plots inspection and single variable regression analysis of mosquito abundance versus 5 environmental factors.

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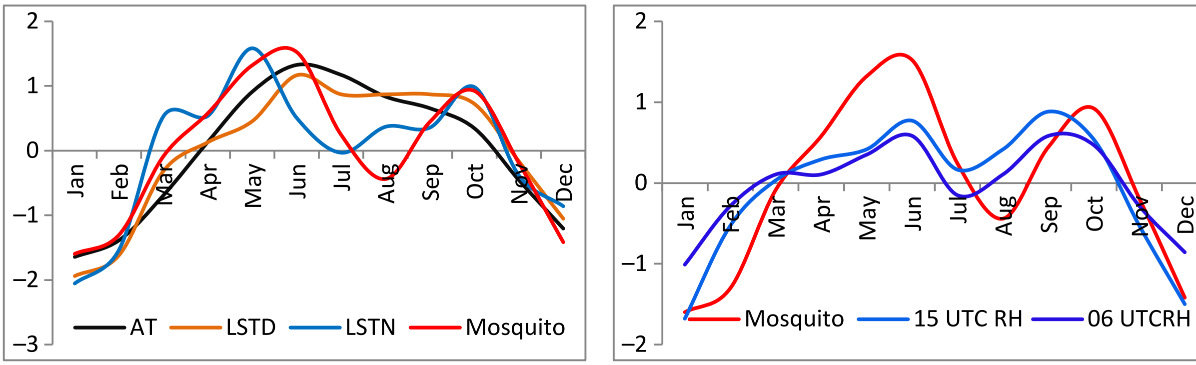

Figure 5. Monthly fluctuations of mosquito abundance and environmental factors. (Data have been standardized according normal distribution to being graphically comparable.)

precipitation in Chabahar have a reverse seasonal pattern. Thus, we use spatial correlation analysis to investigate the relationship between rainfall, vegetation cover, and *An*. mosquito abundance in 6 villages in Chabahr. The abundance of caught mosquitoes in any of the sites was compared with total annual precipitation and annual average of EVI. The results are presented in Figure 6. The highest number of mosquitoes were caught in Rymdan village site, which has the highest value of EVI.

The matrix of spatial association between 2 climatic factors (total annual rainfall, an EVI value of each village sites) and total caught mosquitoes in any site are presented in Table 5. As can be seen in this table, spatial distribution of *An*. mosquito is significantly associated with rainfall and EVI.

The scatter plot inspection of caught mosquitoes at each site, versus the rainfall and EVI of same site, is presented in Figure 7. According to fitted linear regression model, the annual rainfall could explain 65% of spatial variance of mosquito abundance across Chabahar, whereas 62% of spatial variance of mosquito abundance was explained by EVI in Chabahar.

Regarding a strong linear relationship among climatic factors and the spatiotemporal distribution of *An*. mosquito, a multivariate linear combination model was developed to predict the temporal distribution of the *An*. mosquito population in Chabahar using 5 climatic factors. The results are shown in Tables 6 and 7. As can be seen in Table 6, the coefficient of determination (R^2) of the developed model is 0.88, which indicates that 0.88 of variance of temporal distribution of caught mosquitos in Chabahar is explainable by this multivariate linear regression model.

According to the developed multivariate linear model shown in Table 7, NLST and RH 15 UTC have the highest standardized coefficients. So that these 2 climatic factors have the highest affect on the temporal distribution of *An*. mosquitoes in Chabahar.

Predicted mosquito abundance according to the developed climate-based linear model versus observed caught mosquito is shown in Figure 8 (left). A 0.88 linear association was observed between the model predicted mosquito abundance and the caught mosquito in Chabahar. Scatter plot inspection of model residuals or errors versus caught mosquitoes is shown in Figure 8 (right). Error

Table 4. Contingency Table of Mosquito Abundance in Various Ranges of Environmental Factors in Chabahar

Mosquito Abundance	RH 09 UTC (%)	RH 15 UTC (%)	DLST (°C)	AT 2 m (°C)	NLST (°C)
77% of annual abundance	76-83	70-80	32-42	24-30	26-35
15% of annual abundance	≥70	≥75	≤25	≤20	≤22
8% of annual abundance	65≥	70≥	≥42	≥33	≥35

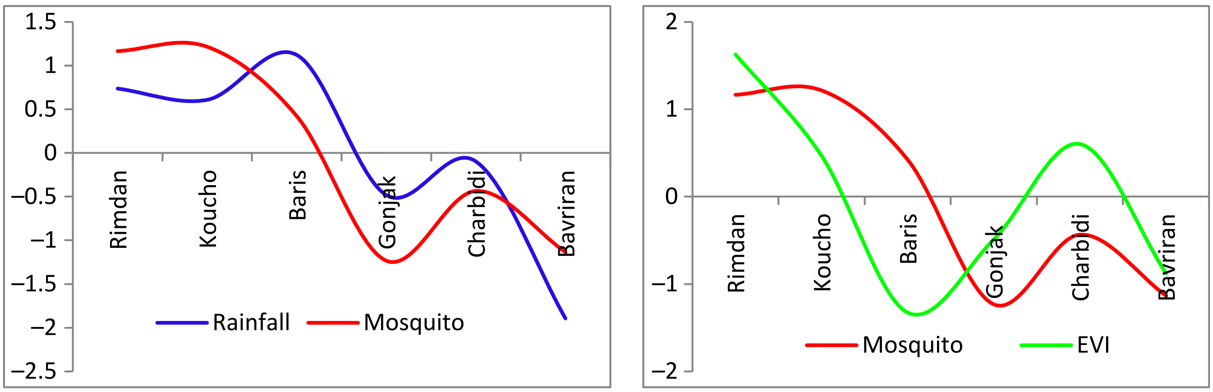

Figure 6. **Spatial fluctuations of mosquito abundance and environmental factors across 6 village site in Chabahar. (Data have been standardized according normal distribution to being graphically comparable.) EVI, enhanced vegetation index.**

Table 5. **Spatial Association Matrix Among Climatic Factors and Monthly Abundance of Caught Mosquito**

Climatic Factors	Spatial Correlation	Sig
TRMM annual Rainfall	0.66	0.018
EVI	0.61	0.021

EVI, enhanced vegetation index; TRMM, Tropical Rainfall Measurement Mission.

inspection detected no significant trend in residuals of models.

DISCUSSION

Malaria control in Chabahar, the most malarious region in Iran, is achieved mostly by drug treatment and insecticide-impregnated bed nets or treatment of mosquito resting sites with a long-lasting insecticide. However, these tools are increasingly failing because of the development of drug resistance in the parasites and insecticide resistance in the *An.* mosquito. For these reasons, new strategies of malaria control are required that target the vectors. Spatiotemporal distribution of *An.* mosquitoes strongly affected by climatic and ecologic condition. As shown in this study, monthly mosquito abundance in Chabahar, has 2 seasonal peaks: spring (March 15 to June) and early autumn (September to November). These peaks include 74% of *Anopheles* abundance. In July and August, which includes 8% of annual mosquito abundance, air temperature increases sharply and reaches >35°C in average. Relative humidity, which is the vital climatic factor of the surviving *An.* mosquito, was reduced as a result of increased air temperature, and desiccation lead to high mortality of the vectors. In the months discussed, intermittent irrigation of watermelon farms provided very attractive sites for breeding and egg laying. Of the irrigated farms, natural wetlands and temporary water bodies were mainly diminishing due to high temperature. Monsoon climatic patterns, the seasonal wind of the Indian Ocean, blowing from the southeast in summer, in some

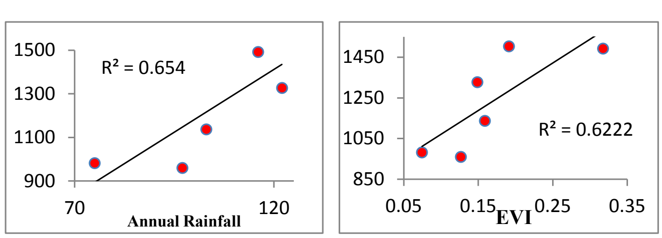

Figure 7. **Scatter plot inspection and single-variable regression analysis of mosquito abundance versus 2 environmental factors in Chabahar. EVI, enhanced vegetation index.**

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Table 6. Validation Statistics of Developed Linear Model

Regression Statistics	
Multiple R	0.94
R^2	0.88
Adjusted R^2	0.78
SE	111.8

Table 7. Climate-based Developed Linear Combination Predicting Temporal Distribution of *An*. Mosquitos in Chabahar

	Coefficients	Standard Coefficient (β)
Intercept	−3592.65	–
AT	44.58	0.49
DLST	−6.55	0.47
NLST	25.19	0.69
RH 15	−69.38	0.61
RH 09	98.91	0.42

AT, air temperature; DLST, day-time land surface temperature; NLST, nighttime land surface temperature; RH, relative humidity.

years bring heavy rains to Chabahar from July to September. Monsoon rains not only increase vector populations, providing temporal water body and anopheles breeding sites, but also moderating the air temperature in Chabahar during July and August increases the survival rate and longevity of *An*. mosquito. Monsoon rains can transfer the annual primary peak of vector abundance that is normally seen in May and June, to July through September. Shifting the primary peak forward 1 to 2 months due to monsoon rains strongly increases the malaria incidence in this area. Because the highest annual temperature is in July and August compared with other months, the sporogonic cycle length in the mosquito body decrease to 7 days. Shorter sporogonic cycle and high abundance of *An*. mosquito significantly increase malaria incidence in Chabahar. In the winter months (December to February) the low temperature decreases abundance of *An*. mosquito. Additionally, the sporogony cycle is prolonged >17 days, during which a large number of mosquitoes die. So despite of the higher abundance of malaria vectors in winter months (December to February) compared witth summer months (July and August), the malaria incidence rate is higher during the summer months in Chabahar. A 0.12 temporal variance of mosquito abundance was not explained by the developed linear model. Ignored factors such as mosquito emigration from Pakistan and northern region of Baluchestan to Chabahar, socioeconomic, and cultural factors that were not considered in this study may explain the remaining variance of temporal distribution of *An*. mosquito in Chabahar.

CONCLUSION

A seasonal pattern was observed in the abundance of anopheles in Chabahar with 2 peaks during the months of March to June and September to November. In this study, we developed a climate-based multivariate regression model to predict the monthly presence and abundance of anopheles

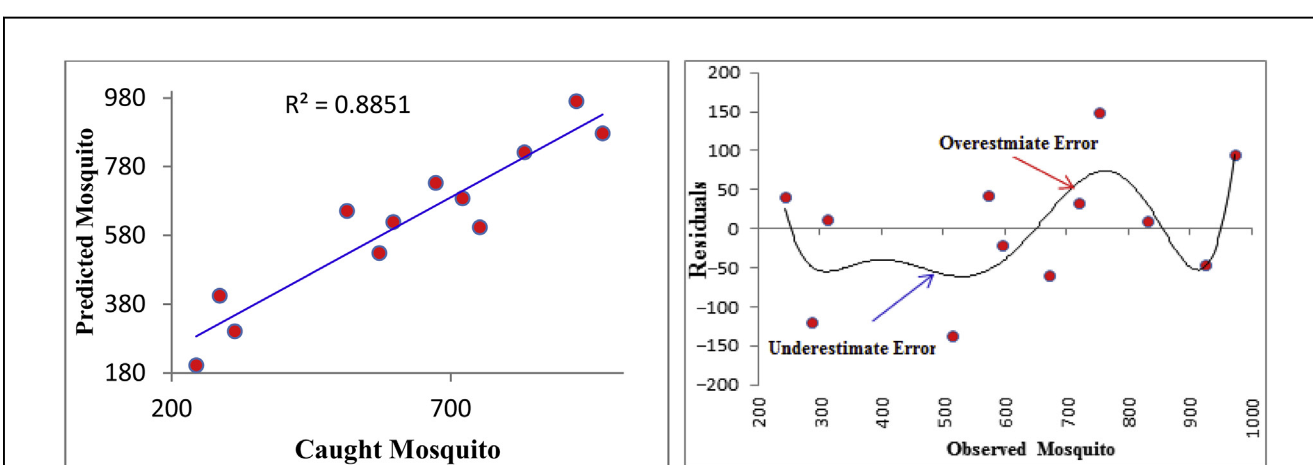

Figure 8. Predicted mosquito abundance versus caugh tmosquito abundance (left). Overestimated and underestimated errors can be seen in residuals of model but overall variance of residual is zero and no significant trends can be seen in residuals (right).

mosquitoes in Chabahar, the most malarious region in Iran. The developed multivariate model creates a flexible framework for exploring the effects of combined environmental variables on vector population dynamics. This combined model using 5 environmental factors explained the 0.88 of temporal fluctuation of monthly abundance of anopheles mosquito in Chabahar. According to this multivariate linear model, NLST and RH of 15 UTC (18.30 Iran) were found to be strong predictors of *Anopheles* abundance in Chabahar. The monsoon rainfalls that mainly occur from July to September, increase the uncertainty of this model by shifting the peak of mosquito abundance that is normally occur in May and June to July and August. Because the highest annual temperature is in July and August compared with other months, the sporogonic cycle length in mosquito body decreases to 7 days. An increase in mosquito abundance caused by monsoon rainfall in July and August, in addition to shorter sporogonic cycle in the hot months, leads to high ratio of malaria incidence in Chabahar in years that are associated with monsoon rainfall.

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