Chapter 5

Climatic Variables and Malaria Transmission

Mercy Aparna Lingala

Research Coordinator, TB Association of India, 3, Red Cross Road, New Delhi-110001, India

Phone: +91 9654425774; Email: mercy_aparna@yahoo.co.in

Abstract

Malaria is one of the major vector-borne diseases caused by plasmodium spp. and transmitted to humans by anopheles mosquitoes. Malaria transmission is highly dependent on climatic variables such as temperature, rainfall and relative humidity. Malaria parasite *Plasmodium* completes its life cycle in two main hosts i.e., mosquito, humans and also in South-East Asian macaques (a natural host of *P. knowlesi*). It completes its sporogony in anopheles mosquitoes which are poikilothermic and requires ambient temperature to complete their life cycle. The duration of sporogony of the parasite inside the mosquito is highly influenced by the temperature. Moreover, malaria transmission is more in rainy season as the female anopheles mosquito lays eggs in water collection; therefore rainfall provides breeding places for mosquitoes which further increases the transmission intensity. Relative humidity has indirect effect on parasite development and survival of mosquito. The life cycles of parasite and the mosquito are completely dependent on temperature and relative humidity. The current chapter deals with the complex relation between the climatic variables and malaria transmission.

Keywords: Climatic Variables, Temperature, Rainfall, Relative Humidity, Plasmodium Parasite, Anopheles Mosquito

1. Introduction

Climate is defined as the long time pattern of weather components such as temperature, humidity, wind, and precipitation etc in a particular area over a period of time. These climatic components are also referred as meteorological variables. Change in climate can influence the human health either directly by extreme weather events such as heat waves, floods, cyclones or indirectly via changes in biological and ecological processes that influence the transmission of vector-borne diseases [1].

In vector-borne diseases, the abundance of vectors is affected by various physical factors such as temperature, rainfall, humidity etc. Moreover, circadian rhythm affects the feeding, resting, and oviposition which are restricted to optimum times, regardless of ambient temperature. Other factors such as forest ecosystem, temporary ground water pools with direct sunlight, vegetation near human settlement, agricultural practices, and human behaviour of the vector can also contribute to the disease burden. In addition, migration, urbanization, poor health infrastructure and other socio-economic contribute [2].

Of various vector-borne diseases, malaria is one of the major diseases and the link between climate and malaria distribution has long been established. Sustained transmission of malaria depends on favorable climatic factors for both mosquito and plasmodium parasite. Temperature, rainfall, and humidity are important, as well as the wind and the duration of daylight. The circadian rhythm affects other behaviors of the vector, such as feeding, resting, and oviposition which are restricted to optimum times, regardless of ambient temperature. Every single element that influences the climate and with it the entire ecosystem, is strongly altered by humans and their activities [3].

2. Malaria Statistics

Malaria continues to be the world's most widespread and serious vector-borne disease. In 2016, an estimated 216 million cases and 445000 deaths were occurred globally [4]. Most of these cases were from WHO regions of Africa (90%), followed by South-East Asia (7%) and the rest from Eastern Mediterranean region (2%) [4]. It is caused by *Plasmodium* parasite and transmitted by *Anopheles* mosquitoes.

3. Plasmodium Parasite

In order to understand the relation between malaria transmission and climatic variables, it is necessary to have brief knowledge of causative agent and its transmitter. As we know that malaria is caused by protozoan *Plasmodium* spp. and transmitted by female *Anopheles* mosquitoes. Of 250 species of plasmodia, five species i.e., *P. vivax, P. falciparum, P. malariae, P. ovale and P. knowlesi* infect humans [5]. *P. vivax* and *P. falciparum* are considered to be most widespread parasites. *P. falciparum* is most prevalent in African region (with 99% malaria cases), whereas *P. vivax* is predominant in Americas (64% cases) and 30% above cases, in South- East Asia and 40% in Eastern Mediterranean region [4]. Moreover, *P. knowlesi,* malaria of macaques (*Macaca fascicularis, M. nemestrina*) recognized as causative agent of human malaria from South East-Asian countries [6].

3.1. Life cycle of Plasmodium

Malaria parasite *Plasmodium* completes its life cycle in two hosts i.e., mosquito and humans **(Figure 1)**. Infection starts when female anopheles mosquito picks up plasmodium parasites in a blood meal taken from an infectious person and inoculates gametocytes into the healthy human host during another blood meal [7]. In the gut of mosquito, gametocytes develop into sporozoites and this process takes 7-20 days. Then the sporozoites moves to salivary glands of mosquito and inoculated into another human when it bite and suck another blood. Sporozoites, moves along bloodstream and infect liver cells, where they mature into shizonts and release merozoites upon rupture [In *P. vivax* and *P. ovale*, the merozoites remain dormant (hypnozoites) in the liver cells and can become active and releases into bloodstream causes relapse even after weeks or years]. The initial replication in the liver is also known as exo-erythrocytic shizogony [8]. The released merozoites in the blood infect red blood cells and multiplies into trophozoite (ring stage), mature into schizont, which rupture releasing merozoites. The cycle of merozoites to schizonts and back to merozoites is referred as erythrocytic schizogony [9]. In Red Blood Cell (RBC), some merozoites develop into male (micro) and female (macro) gametocytes. These micro and macro gametocytes are ingested by anopheles mosquito, during blood meal and multiplies inside the mosquito is known as sporogony (sexual cycle) [10]. Inside the mosquito stomach male and female gametocytes fuses and generate zygote which is subsequently develop into motile ookinetes which invade the midgut wall of the mosquito to develop as oocysts. The oocysts grow, divide and release sporozoites, which make their way to the salivary glands of the mosquito. When the mosquito loaded with sporozoites take another blood meal, inoculation of sporozoites into a new person's bloodstream, causing malaria infection in the human host [5,11].

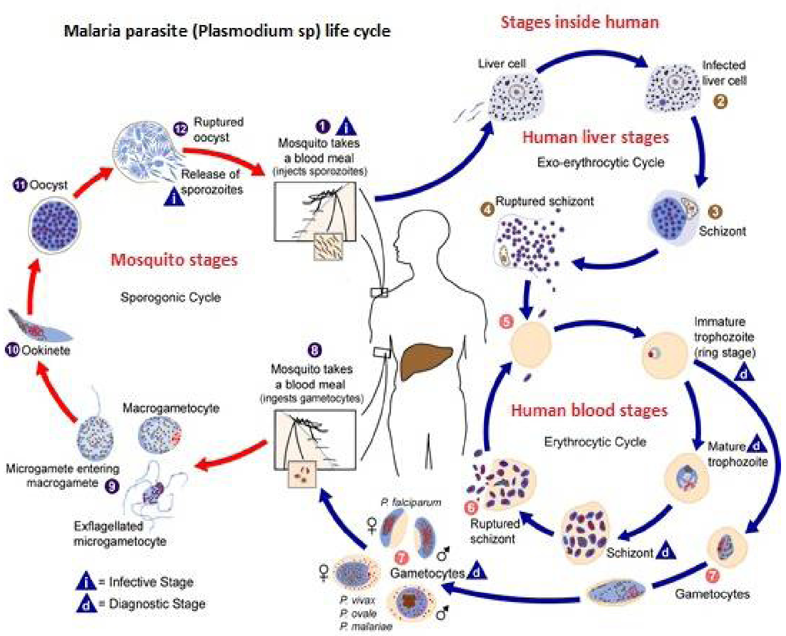

Figure 1: Life cycle of plasmodium parasite in two hosts i.e., humans and anopheles mosquito (Courtesy: Ref. 12)

Table 1: Identified dominant malaria vectors of different regions (Courtesy: Ref. 13-15)

Dominant malaria vectors in different regions			
Americas	Europe and Middle-east	Africa	Asia
An. freeborni *An. pseudopunctipennis* *An. quadrimaculatus* *An. albimanus* *An. albitarsis* *An. aquasalis* *An. darlingi* *An. marajoara* *An. nuneztovari*	*An. atroparvus* *An. labranchiae* *An. messeae* *An. sacharovi* *An. sergentii* *An. superpictus*	*An. arabiensis* *An. funestus* *An. gambiae* *An. melas* *An. merus* *An. moucheti* *An. nili*	*An. barbirostris, An. lesteri* *An. sinensis, An. aconitus* *An. annularis, An. balabacensis* *An. culicifacies, An. dirus* *An. farauti, An. flavirostris* *An. fluviatilis, An. koliensis* *An. leucosphyrus, An. maculatus group* *An. minimus, An. punctulatus* *An. stephensi, An. subpictus* *An. sundaicus, An. dthali,* *An. superpictus, An. sacharovi* *An. maculipennis, An. pulcherimus*
9	6	7	24
Grand total = 46			

4.1. Life Cycle of Anopheles

Anopheles mosquitoes are poikilothermic (change their body temperature according to the surroundings) and requires ambient temperature to complete their life cycle. Anopheles mosquitoes exploit different habitats for breeding. The female anopheles mosquito lays eggs in water collection; therefore breeding increases in the rainy season when water collects in bottles, tyres, broken water pipes, open tins/cans, open tanks, temporary water ponds formed due to rainfall, agricultural places, etc [16-18]. Female anopheles mosquito undergoes four stages in the life cycle: egg, larva, pupa, and adult **(Figure 2).** The first three stages are aquatic and adult female lays eggs directly on water and the eggs take two days to 3 weeks (in colder climates) to hatch. Larvae of mosquito have well developed head, thorax and segmented abdomen. They spend most of their time on feeding on algae, bacteria etc in the surface of micro layer. In pupa stage, head and thorax merged into cephalothorax with abdomen curving around underneath. After few days as pupa, the dorsal surface of the cephalothorax splits and the adult mosquito emerges. This complete cycle from egg to adult stages are strongly influenced by ambient temperature. The life cycle completes in five days in temperate conditions and 10-14 days in tropical conditions. The adult males feed on nectar or other sugar sources, whereas females on sugars for energy and blood meal for egg development. After taking blood meal, female mosquito rest for few days for digestion and egg development. This process depends on the temperature and takes 2-3 days in tropical conditions. Female lays fully developed eggs and resumes seeking host. The cycle repeats until the female dies. The life span of female mosquito is up to one month (or little longer) but in general mosquitoes do not live longer than 1-2 weeks where as males can survive about a week in nature [19,20].

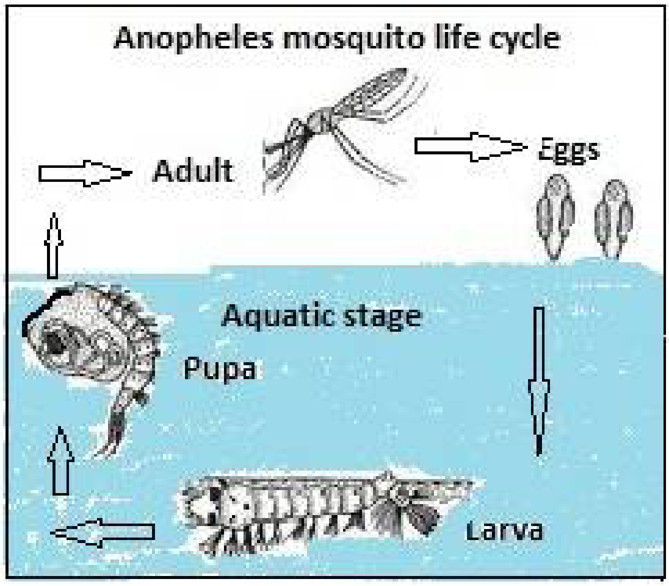

Figure 2: Life cycle of Anopheles mosquitoes

5. Parasite Inside the Vector

After ingested by the mosquito, the parasite undergoes development within the anopheles mosquito before infectious to humans. The time required for the development inside the mosquito is referred as the extrinsic incubation period (EIP/sporogony) which takes 10-21 days. This extrinsic incubation period is completely depends on the parasite species and temperature. Moreover, if the mosquito dies before the completion of extrinsic incubation, then it will not transmit plasmodia to humans [EIP is often longer than mosquito life expectancy] [19,20].

6. Transmission Intensity

The intensity of malaria disease depends on various factors such as vectorial capacity, entomological, entomological inoculation rate, urbanization, population migration change in the land use, agricultural practices, construction of dams/irrigation canals, resistance to insecticides etc [2,21,22,23]. Malaria transmission in human depends on vectorial capacity, longevity of the vector, the duration of the sporogony, interaction between the human and infected mosquito etc. Entomological parameters such as vector distribution rates, feeding behavior, biting rate also contribute in the disease transmission [24]. Moreover, malaria risk will be determined by the vectorial capacity which is further dependant on climatic variables [25].

7. Relation between Climatic Variables and Malaria Transmission

Apart from the above factors, environmental changes, climatic factors affect the biology and ecology of anopheles vectors, and their disease transmission. The complex relations between climatic factors and malaria transmission **(Figure 3)** have been widely reported across the world [26-28]. There are three main climatic factors that affect malaria transmission are temperature, rainfall (precipitation) and relative humidity [29]. The plasmodium parasite and their vector (anopheles mosquito)) are influenced by these factors. Temperature influences the life cycle of the parasite and mosquito; whereas rainfall provides breeding places for mosquitoes. The third climatic factor relative humidity has indirect effect on parasite development and on the survival capacity of anopheles mosquitoes [30]. Moreover, these climatic factors not only influence the malaria incidence but also constitute driving forces of malaria epidemics [31-33]. The affect of main climatic variables is described below.

7.1. Temperature

Temperature plays a fundamental role in parasite multiplication inside the mosquito. The temperature range for malaria transmission is between 15 to 40 °C and the number of days required for a mosquito to complete its life cycle depends on the temperature ranges and humidity [34]. Temperature directly influences the mosquito life cycle at different stages including biting rate, gonotrophic cycle (a physiological process of digestion of blood meal and development of ovaries) and survival probability. As the temperature increases, the rate of blood meal digestion also increases, which in turn accelerates ovaries development, egg laying and reduction of gonotrophic cycle. This will make the mosquito to feed more frequently on humans, thereby increasing the disease transmission intensity. The life cycle of mosquito from egg to adult takes 10 days at an optimum temperature of 28˚C. The duration gets prolonged at lower temperatures and reduced at high temperatures. The daily survival of the mosquito is dependent on the temperature, 90% of mosquitoes survives at temperatures 16˚C-36˚C [35]. Moreover the duration of parasite extrinsic incubation period (sporogony) also depends on temperature. Increased temperature leads to reduction in the duration gonotrophic and sporogony cycles which enhances the rate of transmission [36,37]. The average duration of EIP of plasmodium spp. is provided in the table **(Table. 2)**. Both gonotrophic and sporogony cycles are highly sensitive to temperature changes [38]. The minimum temperature required for main malaria parasites, *P. vivax* is 14.5–16.5˚C and *P. falciparum* is 16.5–19˚C for their development inside mosquito [27]. The optimum temperature for parasite development is about 20-30˚C [39]. The parasite completes its sporogony in five days temperature exceeds 30˚C [40]. However, the survival rate of mosquito decreases at 40˚C [41], *Anopheles culicifacies* a rural vector of India cannot survive more than 24 hrs [42].

An iconic study on degree day model was developed by Detinova et al., (1962) to define the EIP of *P. falciparum* inside the mosquito has been applied in numerous studies over the years. Moreover, numerous researchers across the world have been working on the relation between temperature and development of parasite inside the mosquito or mosquito population dynamics [31,44-46]. In all these models, variations are observed in EIP period and temperature and it could be depend upon mosquito species, mosquito condition, parasite strain, environmental fluctuations and specific vector-parasite combinations etc [47]. Small fluctuations in temperature can either lead to increased malaria incidence and at very high temperature can kill the mosquito, parasite. Moreover, the intensity of malaria transmission will vary spatially and temporally depending on environmental fluctuations and specific vector-parasite combinations.

Table 2: Number of days required for sporogony at different temperatures (Adapted from ref. 2 & 23)

Parasite	Duration of sporogony at 20°C	Duration of sporogony at 25°C	Duration of sporogony at 28°C
P. falciparum	22-23 days	12-14 days	9-10 days
P. vivax	16-17 days	9-10 days	8-10 days
P. malariae	30-35 days	23-24 days	14 days
P. ovale	_	15-16days	12-14 days
P. knowlesi	_	_	_

7.2. Rainfall

Rainfall is considered as a predominant factor for malaria transmission in arid and semi arid regions [48]. It is not only providing breeding places for mosquitoes to lay their eggs, but also modifies the effect of temperature which results in the increasing in the relative humidity which improves the mosquito survival rates [49]. But the relation between rainfall and mosquito abundance is best studied when temperature is not limiting factor. The first three stages of mosquito life cycle is aquatic phase which requires water for laying eggs, larval development and this water is provided through rainfall. Rainfall provides new breeding places and new water to existing ones [50,51]. The persistence of larval habitats and their development is highly depending on the frequency, duration and intensity of rainfall. Heavy rainfall during wet/monsoon season may flush away the vector breeding places [52]. Rainfall based malaria transmission is seasonal in arid, semi arid or high land regions. Several studies have reported increased risk of malaria following heavy rainfall [48, 53, 54]. Moreover, heavy rainfall in the highlands, arid and semi arid regions led to malaria outbreaks [55]. But the amount of rainfall and lag period (time between rainfall and malaria) varies from place to place. The lag period between *P. vivax* and *P. falciparum* was different based on the significant association between the climatic variables [31,32,48]. On contrary to this, there was no association between rainfall and malaria transmission observed in north eastern India [56,57].

7.3. Relative humidity

It is well known that relative humidity has indirect effect on parasite development and survival of mosquito [27]. There is a positive association was observed between rainfall and relative humidity. As the rainfall increases, relative humidity also increases. On the other hand, temperature has negative effect on humidity, as temperature increases humidity decreases. Relative humidity plays important role in arid, semi arid or dry zones. Relative humidity more than 60% along with the temperature between 20 to 30˚C favours plasmodium parasite development inside the anopheles mosquito [27]. Humidity levels between 55 to 80% are same for *P. vivax* and *P. falciparam* parasites. At the same humidity levels, *P. vivax* completes its sporogony in 15 to 20 days when the temperature ranges from 15 to 20˚C; the number of days decreases to 6 to 10 days when the temperature fluctuated between 25 to 30˚C. *P. falciparum* completes sporogony 20 to 30 days when the temperature ranges between 20 to 25˚C, 8 to 12 days between 30 to 35˚C temperature [34]. Though humidity is not main climatic factor, significant association between relative humidity and malaria incidence was reported [58]. A study from China, reported the significant association between the relative humidity and malaria cases [59]. Studies from India have reported the positive association between malaria incidence and relative humidity [48,60].

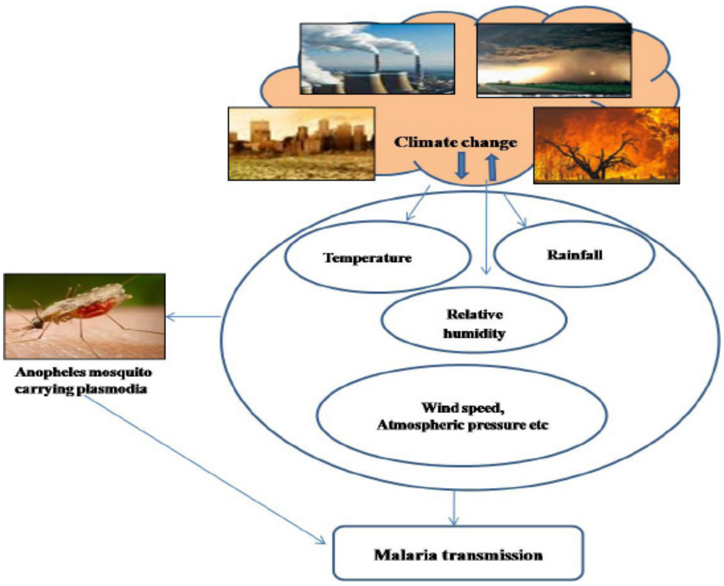

Figure 3: Climatic model of malaria transmission

8. Conclusion

Despite of widespread transmission, it is still difficult to predict future malaria intensity, particularly in the face of climate change. Because the parasites that cause malaria are so strongly tied to mosquitoes for transmission, malaria incidence will change as the climate changes. Though there are numerous studies and mathematical models based on temperature, rainfall and relative humidity to predict malaria transmission/epidemics, it is still unclear and debatable matter how the changes in transmission will occur [25,26,31]. To control the malaria transmission, strong vector control strategy, malaria control interventions, improved health care system and development of rainfall cutoff based prediction models for dry lands/semi arid regions will help to control the malaria disease in future.

9. References

1. Patz JA, Epstein PR, Burke TA, Balbus JM. Global climate change and emerging infectious diseases. Jama. 1996; 17: 275: 217-23.

2. Rossati A, Bargiacchi O, Kroumova V, Zaramella M, Caputo A, Garavelli PL. Climate, environment and transmission of malaria. Le infezioni in medicina: Rivistaperiodica di eziologia, epidemiologia, diagnostica, clinica e terapia delle patologie infettive. 2016; 24: 93-104.

3. Sheppard AD, Rund SS, George GF, Clark E, Acri DJ, Duffield GE. Light manipulation of mosquito behaviour: Acute and sustained photic suppression of biting activity in the Anopheles gambiae malaria mosquito. Parasites & vectors. 2017; 10: 255.

4. World Health Organization. World malaria report2017. http://apps.who.int/iris/bitstream/handle/10665/259492/9789241565523-eng.pdf?sequence=1 (Accessed on 1/07/2018).

5. Cox FE. History of the discovery of the malaria parasites and their vectors. Parasites & vectors. 2010; 3: 5 1-9.

6. Antinori S, Galimberti L, Milazzo L, Corbellino M. Biology of human malaria plasmodia including Plasmodium knowlesi. Mediterranean journal of hematology and infectious diseases. 2012; 4.

7. Billingsley PF, Hecker H. Blood digestion in the mosquito, Anopheles stephensi Liston (Diptera: Culicidae): activity and distribution of trypsin, aminopeptidase, and α-glucosidase in the midgut. Journal of Medical Entomology. 1991; 28: 865-71.

8. Stephens JWW. Black water Fever, A Historical Survey and Summary made over a Century. London: Hodder and Stoughton. 1937.

9. Scott HH: A History of Tropical Medicine London: Edward Arnold 1939; 1.

10. Russell PF: Man's Mastery of Malaria London: Oxford University Press. 1965.

11. Beier JC. Malaria parasite development in mosquitoes. Annual review of entomology. 1998; 43: 519-43.

12. Center for Disease Control (CDC), Biology. https://www.cdc.gov/malaria/about/biology/index.html (Accessed on 12/07/2018).

13. Sinka ME, Bangs MJ, Manguin S, Rubio-Palis Y, Chareonviriyaphap T, Coetzee M, et al. A global map of dominant malaria vectors. Parasites & vectors. 2012; 5: 69.

14. Hanafi-Bojd AA, Azari-Hamidian S, Hassan V, Zabihollah C. Spatio-temporal distribution of malaria vectors (Diptera: Culicidae) across different climatic zones of Iran. Asian Pacific Journal of Tropical Medicine. 2011 Jun 1; 4: 498-504.

15. Singh P, Lingala MA, Sarkar S, Dhiman RC. Mapping of Malaria Vectors at District Level in India: Changing Scenario and Identified Gaps. Vector-Borne and Zoonotic Diseases. 2017; 17: 91-8.

16. Bates M. The natural history of mosquitoes. The Natural History of Mosquitoes. 1949.

17. Keating J, Macintyre K, Mbogo CM, Githure JI, Beier JC. Characterization of potential larval habitats for Anopheles mosquitoes in relation to urban land-use in Malindi, Kenya. International Journal of Health Geographics. 2004; 3: 9.

18. Mattah PA, Futagbi G, Amekudzi LK, Mattah MM, de Souza DK, Kartey-Attipoe WD, et al. Diversity in breeding sites and distribution of Anopheles mosquitoes in selected urban areas of southern Ghana. Parasites & vectors. 2017;

10: 25.

19. Center for Disease Control (CDC), Anopheles mosquitoes, https://www.cdc.gov/malaria/about/biology/mosquitoes/index.html (Accessed on 12/07/2018).

20. Beier John C. The biology of mosquitoes, vol 1, Development, nutrition and reproduction. Science, 1993; 22; 1081.

21. Tyagi BK, Chaudhary RC, Yadav SP. Epidemic malaria in Thar desert, India. The Lancet. 1995; 346: 634-5.

22. Martens P, Hall L. Malaria on the move: human population movement and malaria transmission. Emerging infectious diseases. 2000; 6: 103.

23. Rubio-Palis Y, Bevilacqua M, Medina DA, Moreno JE, Cárdenas L, Sánchez V, Estrada Y et al. Malaria entomological risk factors in relation to land cover in the Lower Caura River Basin, Venezuela. Memórias do InstitutoOswaldo Cruz. 2013; 108: 220-8.

24. Shililu JI, Maier WA, Seitz HM, Orago AS. Seasonal density, sporozoite rates and entomological inoculation rates of Anopheles gambiae and Anopheles funestus in a high-altitude sugarcane growing zone in Western Kenya. Tropical medicine & international health: TM & IH. 1998; 3: 706-10.

25. Paaijmans KP, Read AF, Thomas MB. Understanding the link between malaria risk and climate. Proceedings of the National Academy of Sciences. 2009; 106: 13844-9.

26. Gething PW, Smith DL, Patil AP, Tatem AJ, Snow RW, Hay SI. Climate change and the global malaria recession. Nature. 2010; 465: 342-345.

27. Dhiman RC, Pahwa S, Dash AP. Climate change and malaria in India: Interplay between temperature and mosquitoes. In Regional Health Forum 2008; 12: 27-31.

28. Kim YM, Park JW, Cheong HK. Estimated effect of climatic variables on the transmission of Plasmodium vivax malaria in the Republic of Korea. Environmental health perspectives. 2012; 120: 1314.

29. Pampana E. A textbook of malaria eradication. 2nd edition. 1969.

30. Dale P, Sipe N, Anto S, Hutajulu B, Ndoen E, Papayungan M, Saikhu A, et al. Malaria in Indonesia: a summary of recent research into its environmental relationships. Southeast Asian Journal of Tropical Medicine & Public Health. 2005; 36: 1-3.

31. Craig MH, Snow RW, le Sueur D. A climate-based distribution model of malaria transmission in sub-Saharan Africa. Parasitology Today. 1999; 15: 105-11.

32. Githeko AK, Ndegwa W. Predicting malaria epidemics in the Kenyan highlands using climate data: a tool for decision makers. Global change and human health. 2001; 2: 54-63.

33. Zhou G, Minakawa N, Githeko AK, Yan G. Association between climate variability and malaria epidemics in the East African highlands. Proceedings of the National Academy of Sciences. 2004; 101: 2375-80.

34. Bhattacharya S, Sharma C, Dhiman RC, Mitra AP. Climate change and malaria in India. Current Science-Bangalore. 2006; 90: 369.

35. Alemu A, Abebe G, Tsegaye W, Golassa L. Climatic variables and malaria transmission dynamics in Jimma town, South West Ethiopia. Parasites & vectors. 2011; 4: 30.

36. Molineaux L. The epidemiology of human malaria as an explanation of its distribution, including some implications for its control. Malaria Principles and practice of malariology. 1988; 2: 913-98.

37. Detinova, TS, Bertram, DS, World Health Organization. Age-grouping methods in Diptera of medical importance,

with special reference to some vectors of malaria. 1962.

38. Lindsay SW, Birley MH. Climate change and malaria transmission.Annals of Tropical Medicine & Parasitology. 1996; 90: 573-88.

39. Bruce-Chwatt, LJ, Essential malariology. William Heinemann Medical Books Ltd. pp. 1985; 129-168.

40. Teklehaimanot HD, Lipsitch M, Teklehaimanot A, Schwartz J. Weather-based prediction of Plasmodium falciparum malaria in epidemic-prone regions of Ethiopia I. Patterns of lagged weather effects reflect biological mechanisms. Malaria journal. 2004; 3: 41.

41. Ijumba JN, Lindsay SW. Impact of irrigation on malaria in Africa: paddies paradox. Medical and veterinary entomology. 2001; 15: 1-1.

42. Rajindar P. On the Bionomics of Anopheles culicifacies Giles. Part I. Longevity under controlled conditions of temperature and humidity. Journal of the Malaria Institute of India. 1943; 5: 77-85.

43. Paaijmans KP, Blanford S, Bell AS, Blanford JI, Read AF, Thomas MB. Influence of climate on malaria transmission depends on daily temperature variation. Proceedings of the National Academy of Sciences. 2010; 107: 15135-9.

44. Pascual M, Ahumada JA, Chaves LF, Rodo X, Bouma M. Malaria resurgence in the East African highlands: temperature trends revisited. Proceedings of the National Academy of Sciences. 2006; 103: 5829-34.

45. Blanford JI, Blanford S, Crane RG, Mann ME, Paaijmans KP, Schreiber KV, Thomas MB. Implications of temperature variation for malaria parasite development across Africa. Scientific reports. 2013; 3: 1300.

46. Mordecai EA, Paaijmans KP, Johnson LR, Balzer C, Ben-Horin T, de Moor E, McNally A, et al. Optimal temperature for malaria transmission is dramatically lower than previously predicted. Ecology letters. 2013; 16: 22-30.

47. Ohm JR, Baldini F, Barreaux P, Lefevre T, Lynch PA, Suh E, Whitehead SA, et al. Rethinking the extrinsic incubation period of malaria parasites. Parasites & vectors. 2018; 11: 178.

48. Lingala MA. Effect of meteorological variables on Plasmodium vivax and Plasmodium falciparum malaria in outbreak prone districts of Rajasthan, India. Journal of infection and public health. 2017; 10: 875-80.

49. Reiter P. Climate change and mosquito-borne disease. Environmental health perspectives. 2001; 109: 141.

50. Gimnig JE, Ombok M, Kamau L, Hawley WA. Characteristics of larval anopheline (Diptera: Culicidae) habitats in Western Kenya. Journal of medical entomology. 2001; 38: 282-8.

51. Koenraadt CJ, Githeko AK, Takken W. The effects of rainfall and evapotranspiration on the temporal dynamics of Anopheles gambiaess and Anopheles arabiensis in a Kenyan village. Acta tropica. 2004 Apr 1; 90: 141-53.

52. Jepson WF, Moutia A, Courtois C. The malaria problem in Mauritius: the bionomics of Mauritian anophelines. Bulletin of entomological research. 1947; 38: 177-208.

53. Kilian AH, Langi P, Talisuna A, Kabagambe G. Rainfall pattern, El Niño and malaria in Uganda. Transactions of the Royal Society of Tropical Medicine and Hygiene. 1999; 93: 22-3.

54. Bi P, Tong S, Donald K, Parton KA, Ni J. Climatic variables and transmission of malaria: a 12-year data analysis in Shuchen County, China. Public health reports. 2003; 118: 65.

55. Akhtar R, McMichael AJ. Rainfall and malaria outbreaks in western Rajasthan. The Lancet. 1996; 348: 1457-8.

56. Dev V, Dash AP. Rainfall and malaria transmission in north–eastern India. Annals of Tropical Medicine & Parasitology. 2007; 101: 457-9.

57. Wardrop NA, Barnett AG, Atkinson JA, Clements AC. Plasmodium vivax malaria incidence over time and its

association with temperature and rainfall in four counties of Yunnan Province, China. Malaria journal. 2013; 12: 452.

58. Bouma MJ, Dye C, Van der Kaay HJ. Falciparum malaria and climate change in the northwest frontier province of Pakistan. The American journal of tropical medicine and hygiene. 1996; 55: 131-7.

59. Li T, Yang Z, Wang M. Temperature, relative humidity and sunshine may be the effective predictors for occurrence of malaria in Guangzhou, southern China, 2006–2012. Parasites & vectors. 2013; 6: 155.

60. Kumar V, Mangal A, Panesar S, Yadav G, Talwar R, Raut D, Singh S. Forecasting malaria cases using climatic factors in Delhi, India: a time series analysis. Malaria research and treatment. 2014; 1-6.

Citation of this book chapter: Lingala MA, Climatic variables and malaria transmission, Chapter 5, in Vector-borne diseases and treatment. 2018; Vol 2: 1-12.