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Faculteit Bedrijfseconomische Wetenschappen

master in de toegepaste economische wetenschappen

Masterthesis

The effect of climate change on malaria distribution: A systematic literature review of empirical studies

Muhammet Oruç

Scriptie ingediend tot het behalen van de graad van master in de toegepaste economische wetenschappen, afstudeerrichting beleidsmanagement

PROMOTOR :
Prof. dr. Stephan BRUNS

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COVID-19

This master thesis was written during the COVID-19 crisis in 2020-2021. This global health crisis might have had an impact on the (writing) process, the research activities and the research results that are at the basis of this thesis.

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Muhammet Hasan Oruç
Diepenbeek, Augustus 2021

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1 Introduction

The correlation between anthropogenic environmental disturbance and atmospheric carbon dioxide and consequently global average surface temperature is widely accepted to be positive (Derraik, 2007). While the causality between the recent dramatic increase in carbon dioxide and global average temperatures and the anthropogenic environmental footprint cannot be deducted, the ramifications of an increase in global average temperatures can be felt by wildlife, livestock, and many other habitants of the Earth. One of the ramifications induced by climactic variability is the transitioning of certain regions to sustainable habitats for vector-borne disease, more specifically mosquitos carrying the plasmodium parasite. The plasmodium parasite, responsible for malaria infections, poses a significant health and economic threat to African countries in particular. While a great many studies have analyzed, modelled, and researched the effects of climate change on malaria distribution, this thesis intents to execute a concise and effective systematic literature review of the empirical studies conform the ROSES reporting standards for systematic evidence synthesis. The motivation behind this thesis is due to the urgent need for a better understanding of this topic, paving the way for new research and preventing the resurgence, introduction, or prevalence of malaria in certain regions.

For many economies industrialization seemed to be a key determinant in economic development. Although the effects on individual households have been positive, the implications on nature are overlooked. The positive effects revolved around improved food production, infrastructure and many more, while not accounting for the external costs and the implications on nature. The deterioration of nature has many long-term effects (Wadanambi, 2020). The realized benefits are now dwindling and taking a turning point. The climatic stress experienced due to increased temperatures and untimely rains is affecting farmers in major regions. The yield of agricultural production could experience a global decline, where developing countries will be impacted the most due to the disparity between developing and developed countries (Rosenzweig, 1994). In addition, low-income groups are assumed to be impacted significantly more due to the inelastic nature of demand for basic necessities like food. Furthermore, the proportional increase of spending on food may lead to an increase in inequality due to a decrease in disposable income (Nelson, 2014). The effects of climate change on humans have far reaching direct and indirect implications.

Besides humans, the ramifications of climate variability on the animal kingdom are also considerable. Climate change can impact the variability and persistence of species. The ability to adapt seems to vary considerably depending on the species, with a persistent and constant lag behind the phenotypical optimum (Radchuk, 2019). The spatial and temporal heterogeneity of climate change will pave the way to novel climatic environments (Kingsolver, 2011).

This may force animals to either adapt by changing their behavior, biological structure, or a combination of both. These adaptations are not limited to finding a phenotypical optimum, these novel climatic environments could lead to temporal or permanent relocations of animals. These migrations could lead to a redistribution of certain animals over a certain number of regions. One subcategory of animals, namely insects, are an essential component of our ecosystem. The Earth´s entomofauna is experiencing a dramatic decline that could impact the rest of the world (van der Sluijs, 2020). The relation between invertebrate animals and the ecosystem functioning is a given (Harvey, 2020). This relation, given the decline of the Earth´s entomofauna, could be an indication for serious consequences. The atmospheric temperature is predicted to increase even further in the near future. However, some insects may benefit from the increased temperatures. There is a causality between higher temperatures and increased reproductivity rate among some insects (Adamo, 2012).

One particular class of Insectia, with order Diptera, is the mosquito from the animal kingdom. A small increase in temperature could be translated in a disproportional increase in the mosquito population (Pascual, 2006). Mosquitos are classified as the deadliest animals to humans in the world, infecting millions of people annually due to being a vector that transmits mosquito-borne diseases (Tolle, 2009). These mosquito-borne diseases consist of parasites or viruses. One group of parasites in particular stands out, the Plasmodium group. The Plasmodium group is a member of the Pyhlum Apicomplexa, these are a group of parasitic eukaryotes. The genus plasmodium contains five species that infects humans with malaria: P. ovale, P. malariae, P. vivax, P. knowlesi, P. falciparum (Caminade, 2014). The Plasmodium group is responsible for millions of malaria infections each year, resulting in more than 400 000 deaths annually (Tolle, 2009). Malaria is one of the most prevalent vector-borne diseases (Martens, 1995). The life cycle of vectors and the reproduction rate of parasites are all susceptible to climate variability (Semenza, 2018). The main variables used in empirical studies that were seen as enablers of malaria are temperature, precipitation, presence of water indexes and humidity (Gage, 2008; Brugueras, 2020). Climate change seems to be beneficial to these organisms, where global temperatures are expected to increase by 1.7–4.4°C and an increase in precipitation of about 5 percent by the end of the 21st century (Jung, 2016). It seems that climate variability circumscribes the distribution of mosquitos, and consequently the distribution of malaria, while weather affects the intensity and timing of local outbreaks (Epstein, 1998).

This may indicate that the short-term effects vary from the long-term effects, where long-term effects are situated around global average temperature increase and an introduction of novel climatic environments, whereas the short-term is more focused on local temperature increases, humidity, and local water indexes. The far-reaching effects of climate change are, including but not limited to; heavy precipitation, biodiversity loss, increasing spread of pests and pathogens, id est malaria (Martens, 1995; Haensler, 2013; Jung, 2016; Radchuk, 2019). The interplay between climate change, mosquito distribution and development, and parasitical development and indirectly distribution could produce potential threats on a global scale. While the prevalence of malaria is restricted to tropic and subtropic regions (Martens, 1995), the climatic variability could potentially alter other regions to be more accessible to vectors that carry malaria. The effects of climate change on the prevalence and distribution of malaria vectors needs to be put in a spatial context, where changes in regions, due to climate change, are a central part. These changes in specific regions may lead to the introduction of malaria in Europe (Semenza, 2018; Brugueras, 2020)

Since malaria poses a great economic and health threat to African countries in particular. It is imperative to analyze the current empirical literature regarding the relation between malaria distribution and climate change for policy makers and anyone affected by this. This thesis will have a spatial limitation, namely Africa. This is due to the fact that the overwhelming majority of malaria-cases are recorded in African regions. The distribution of malaria is twofold; ecological factors and socioeconomic factors (Cella, 2019). The ecological factors are related to climactic variability, while the socioeconomic factors comprise the anthropogenic local capacity to deploy countermeasures against malaria and the general health care systems in effect (Caminade, 2014). Since methods to control mosquito populations are of anthropogenic origin, these will not be evaluated.

This master´s thesis has two objectives. The first one is to review articles with the intention to understand the current literature, particularly how climate change has been conceptualized and operationalized in connection to malaria distribution. The second one consists of discussing the main factors of climate variability that have been found to contribute to malaria transmission based on the empirical finding presented in the reviewed studies.

2. Methodology

2.1 The research question and method of choice

The research question and method of choice

The introduction of this thesis started with the notion that climate change leads to an increase in global average surface temperature. The implications of climate change, however, are not limited to an increase in global average surface temperatures. The far-reaching effects of climate change are, including but not limited to; heavy precipitation, biodiversity loss, increasing spread of pests and pathogens, id est malaria (Martens, 1995; Haensler, 2013; Jung, 2016; Radchuk, 2019). The spatial and temporal heterogeneity of climate change will pave the way to novel climatic environments (Kingsolver, 2011).

The variability in precipitation, humidity and temperature could favor some animals, for example the mosquito. A small increase in temperature for example could be translated in a disproportional increase in the mosquito population (Pascual, 2006). Mosquitos are, due to being a vector for vector-borne diseases, one of the deadliest animals to humans in the world, infecting millions annually (Tolle, 2009). These mosquito-borne diseases consist of parasites or viruses. One group of parasites is the Plasmodium group. The Plasmodium group is responsible for millions of malaria infections each year (Lüthi, 2015). Malaria is one of the most prevalent vector-borne diseases, killing many people each year (Lüthi, 2015). Africa, compare to the rest of the world, is disproportionately and negatively affected by malaria, posing a great economic and health threat. It is imperative to analyze the current empirical literature regarding the relation between malaria distribution and climate change for policy makers and anyone affected by this. For adequate policy interventions to be applied, governments and organizations need to be aware of the current spatial distribution of malaria.

For these reasons the following research questions was formulated; Effects of climate change on malaria distribution: A systematic literature review of empirical studies. To accurately present this information, all variables will be discussed in detail. We broke down climate change into four major topics to study the effect of these factors on malaria distribution. The four major topics are temperature, precipitation, geographical features, and large-scale climate phenomena such as La Niña, El Niño, and the Indian Ocean Dipole. After the variables are explored in depth, the distribution of malaria will be discussed.

Before researching the effects of climate change on malaria distribution, a careful assessment of the available methods needs to be executed before providing a synthesis of the existent literature on the chosen topic and to answer the formulated specific research question. The choice of method has a profound impact on the structure of this thesis. Reliable synthesis of the increasingly growing amount of evidence is essential for the process of evidence-informed decision-making in environmental policy, practice, and research. The methods for systematic evidence synthesis, including systematic reviews, are becoming an industry standard for cataloguing, collating and synthesising documented evidence (Haddaway, 2018). Furthermore, most journals have started changing their policy in accepting review papers, giving systematic reviews a priority (Pae, 2015). With the use of predefined eligibility criteria, empirical evidence is collated to answer a specific question (Haidich, 2010). The systematic review aims to provide a comprehensive, unbiased synthesis of many relevant studies (Aromataris, 2014). A systematic review collects these relevant studs following rigorous, objective, and transparent processes (James, 2016). The explicit and exhaustive reporting of the methods used in the synthesis is also a defining characteristic of a systematic review (Aromataris, 2014). Conducting the synthesis through transparent and reproductible processes allows for the maximizing of objectivity and minimizing bias throughout the review, thus providing more reliable findings from which conclusions can be drawn (Haidich, 2010; Haddaway, 2018). While it may have many of the characteristics of a traditional literature review, summarizing knowledge from a body of literature, it differentiates itself by attempting to collate all of the relevant evidence relevant to a question and to focus research reporting data, rather than concepts or theory (Aromataris, 2014). As Haidich et al., (2010) noted, the characteristics of a systematic review are a clearly stated set of objectives with predefined eligibility criteria for studies; an explicit, reproducible methodology; a systematic search that attempts to identify all studies that meet the eligibility criteria; an assessment of the validity of the findings of the included studies (for instance, through the assessment of risk of bias); and a systematic presentation and synthesis of the findings from the studies used. Systematic reviews ideally, just as is the case for this thesis, aim to answer specific questions, rather than general summaries of the literature on a topic of interest. A systematic review does not create new knowledge but synthesizes the existing knowledge (Aromataris, 2014).

A systematic review, if done correctly, minimizes bias and tries to answer a specific question, in this case a question relating to environmental sciences, adhering to a rigorous, objective, and transparent processes. The methods used are reported exhaustively and explicitly, proving reproducibility and transparency. Given the methodological and procedural needs of this thesis, a systematic review will be conducted. In addition, the systematic literature review of this thesis will be executed conform the ROSES reporting standards for systematic evidence synthesis. We opted for ROSES reporting standards due to several reasons. First of all, ROSES has been adapted specifically for systematic reviews in the field of conservation and environmental management (Haddaway, 2018). In addition, ROSES reporting standards aim to increase and maintain high standards in the conduct of systematic reviews through increased transparency, and to facilitate the quality assurance (Haddaway, 2018). Finally, ROSES provides detailed and precise instructions with examples for all stages of the review process (Haddaway, 2018). Given these arguments, ROSES reporting standards are, in this specific case, a great way to conduct our systematic literature review.

There are, however, many alternative methods that could have been used for this synthesis. The first option was the traditional literature review, also known as a narrative review. The purpose of a traditional literature review is the examination of recent or current literature, to identify the previous accomplishment, allowing for consolidation, for building on previous work, for summation, for avoiding duplication and for identifying omissions or gaps (Booth, 2009). A literature review works by qualitatively summarizing evidence on a topic using informal or subjective methods to collect and interpret studies (Kysh, 2013). The ultimate end goal is to provide a broad summary or overview of the topic related to the research question (Kysh, 2013; Pae, 2015). A major problem with this method, according to Booth et al., (2009), is that traditional literature reviews lack an explicit intent in maximizing the scope or analyze the data collected. This means that the lack of explicit protocols for conducting the search or analyzing the data may lead to selection bias (Pae, 2015).

The conclusion they may reach are therefore open to bias from the potential omitting of critical parts of the literature (Booth, 2009). Traditional reviews, while very useful in describing an issue and its underlying concepts and theories, are difficult to reproduce if there is no explicitly stated methodology (Aromataris, 2014). Another drawback traditional literature reviews have, is heavy reliance on the knowledge and experience of the author, rather than an exhaustive presentation of the topic. This leads to reviews being based on selectively chosen evidence, resulting in potential risks for bias and systematic errors (Aromataris, 2014). Additionally, most journals have started changing their policy in accepting review papers to provide the best evidence for all basic and clinical questions and further hypothesis. Systematic reviews are given a priority, while narrative reviews are excluded (Pae, 2015).

While traditional literature reviews are useful, they have major drawbacks. Given that this thesis aims to conduct a thorough analysis for the purpose of understanding the current literature and to discuss the main factors of climate variability and to answer the research question, a traditional literature review is not the ideal method for the purposes of this thesis.

Another option was to conduct a scoping review. As defined by Booth et al., (2009), this type of review provides a preliminary assessment of the potential size and scope of available research literature, aiming to identify the nature and the extent of the research evidence.

There are four purposes of a scoping review. The first purpose is to provide a quick overview of a field of research, examining the extent of the research done on a particular topic or area. The quantity of data generated, however, can be considerable. This leads to making a trade-off between providing a detailed analysis and appraisal of a smaller number of studies or to cover all available materials. The second purpose is to use a scoping review to determine the feasibility, relevance, and/or costs of conducting a full systematic review. A major point of criticism of a scoping review is the disregard for the quality of the included studies (Arksey, 2005). Moreover, a scoping review can be used to inform policymakers as to whether a systematic review is needed (Booth, 2009). The third purpose of a scoping review is to provide a focused synthesis, with potentially more speed. However, as stated above, there needs to be some type of trade-off between providing a detailed analysis or to cover all available material. The fourth and final purpose of a scoping review is for drawing conclusions and identifying gaps in the existing literature (Arksey, 2005). Additionally, a scoping review can be used to clarify concepts or to investigate research conduct (Munn, 2018).

Scoping reviews cannot be regarded as the final output because limitations in their rigour mean a risk for potential bias due to inattention to quality assessment (Arksey, 2005; Booth, 2009). According to Booth et al., 2009, their findings alone cannot be used to recommend policymakers, which is what this thesis aims to do. Given that this thesis aims to answer a specific research question, perform quality appraisals in assessing the relevance of the included research articles and to inform policymakers about the effects of climate change on the distribution of malaria, it is evident that this method is not suitable for this thesis.

Another method would be a Meta-analyses. As defined by Booth et al., (2009), a meta-analysis is a technique that statistically combines the results of quantitative studies to provide a more previse effect of the studies. Since this thesis narrows the included articles down to empirical studies, at first glance this method may seem appropriate. Haidich et al., (2010) define a meta-analysis as a quantitative, formal, epidemiological study design used to systematically assess the results of previous research to derive conclusions about that body of research.

Stegenga et al., (2011) argues that a meta-analysis should only be considered when a group of studies is sufficiently homogeneous in terms of outcomes, interventions, and participants. A meta-analysis is only meaningful when the data from multiple studies is generated from a single kind of causal relationship (Stegenga, 2011). However, if there are methodological, statistical, or clinical heterogeneities, Stegenga et al., (2011) advise the use of a qualitative approach, similar to a systematic review. This is due to the multiple studies measuring multiple causal relations. Heterogeneity refers to primary studies not estimating the same population effect. There are, according to Nelson et al., (2009), two basic causes of heterogeneity, factual and methodological causes. Factual heterogeneity refers to real differences in effects between studies, while methodological heterogeneities refer to heterogeneities arising from the use of different study designs and methods. An important choice that should be considered when using meta-analysis is the degree of discordance that the analyst is willing to accept. The degree of discordance means the degree at which evidence from different studies disagree or contradict each other (Stegenga, 2011). This means that there is a certain level of expertise needed to perform certain personal judgements. This allows for biases and could explain why multiple meta-analysis reach different conclusions regarding the same hypothesis (Stegenga, 2011).

The notion that a meta-analysis can be used as a standalone type of review is not unanimously accepted. A meta-analysis is seen as a subset of quantitative synthesis tools for combining studies with numerical data in an aggregative manner (Haddaway, 2018). Haidich et al, (2010) believe that meta-analysis are a subset of a systematic review.

There is also a growing community who believe that meta-analysis is not a standalone type of review, but rather a subset of quantitative synthesis tools for combining studies with numerical data aggregatively (and in fact separate from other quantitative synthesis methods, such as meta-regression. This is an important point, since meta-analyses alone are subject to the same biases as traditional literature reviews (Haddaway, 2018). The statistical nature of a meta-analysis, based on personal expertise for judgement, with the notion that a group of studies should be adequately homogenous and the objective to derive conclusions on a body of research, rather than a specific research question, disallows the use of this method for this thesis. Furthermore, the synthesis of a meta-analysis is graphical and tabular with narrative commentary, in contrast to the objective of this thesis, being narrative with tabular accompaniment (Booth, 2009).

Compared to previous alternatives, a systematic map provides documentation on the methods used in the mapping process in a transparent and objective manner, rendering reproducibility of the study possible. The documentation follows the same basic format as a systematic review, a rigorous, objective, and transparent process to capture all evidence related to the topic (James, 2016). This process avoids potential pitfalls of traditional literature reviews. Miake-Lye et al., (2016) define a systematic map as a systematic search of a broad field to identify gaps in knowledge and/or future research needs that presents results in a user-friendly format, often visual figures or graphs, or a searchable database. The main objective of a systematic map is to collate and catalogue a body of evidence, describing the state of the knowledge for a particular topic or question (James, 2016). Additionally, a systematic map can be used to identify gaps in the research literature (Booth, 2009).

A systematic map, however, does not aim to answer a specific question, which is the case for a systematic review (James, 2016; Cooper, 2026). Contrary to a systematic review, a systematic map collates, describes, and catalogues evidence. This enables a better comprehension of the concepts, the identification of evidence for policy-relevant questions, knowledge gaps, and knowledge clusters (James, 2016). While a systematic map is a great method, due to its rigorous, objective, and transparent processes, it does not cover the needs of this thesis. This thesis aims to answer a specific question with the use of similar rigorous, objective, and transparent processes to capture relevant evidence relating to the effects of climate change on the distribution of malaria.

2.1 The review protocol

Given the nature of the formulated research question, the author opted to perform the review according to the Collaboration for Environmental Evidence (CEE) guide-lines for systematic review and evidence synthesis in environmental management, where the ROSES reporting standards for systematic evidence synthesis will be used (Haddaway et al., 2018). ROSES aims to ensure that researchers provide all relevant methodological information in their review, enabling peer-reviewers to critique the validity and reliability of the review.

The systematic literature review comprises three main subcategories namely identification, screening, and eligibility. To ensure the quality of this review, the research papers were identified through well-known databases after which they were screened based on a select number of criteria designed specifically to establish a set of research papers relevant to this review. After identifying a range of articles, they were reviewed on eligibility. The screening and eligibility were both determined by the predefined inclusion and exclusion criteria. The selected research papers were also subject to quality appraisal, where the internal and external validity, together with any potential bias, were reviewed. This procedure consists of the authors explaining their applied strategy to ensure the quality of the articles reviewed. The last step consists of the discussion regarding the data extraction and the analyses and validation of the extracted data.

2.2 Search strategy

As discussed in the previous section, the systematic literature strategy will comprise three main subcategories, namely identification, screening, and eligibility. In the following sections each subcategory will be explained in detail.

2.2.1 Identification

Identification is the first of three subcategories of the systematic literature review. The searching process was conducted through query strings. These query strings were developed with the purpose of finding the greatest number of relevant papers, where the use of Boolean operators, truncation and wild cards were an essential part of the query strings.

First of all, the essential words were "Malaria" and "Distribution" with the use of the AND Boolean. These keywords had to be included in either the title, abstract, keywords and/or topic. After the essential keywords were determined, the author opted to, through the use of the OR Boolean, to include keyword variants of climate change, malaria and several determinants that could impact larval development, mosquito survivability or climate change effects. With the AND Boolean the essential keywords were linked to one or more of the other keywords. This way the author ensured that the search results were relevant to this review. Since the advanced search option varied slightly between databases, the query strings were also slightly modified to match the required formats of the different databases. The constructed query strings were used across three different databases namely Scopus, Web of Science and PubMed. Additionally, the references of the selected papers were examined for potential articles.

Table 1 Performed search string on each database, with the received results.

The search string

Database	Search string	Results
Web of Science	TS=(("Climate change" OR "climate varia*" OR "temperature var*" OR temperature increases OR "environment*" OR "climat* effects" OR "climactic factors" ecology) AND ("Vector borne disease*" OR "Vector transmission" OR "malaria transmission" OR "* falciparum" OR "*plasmodium" OR "mosquito-borne infectious disease" OR "plasmodium ovale" OR "Plasmodium malariae" OR "Plasmodium vivax" OR "Plasmodium knowlesi" OR "Plasmodium falciparum" OR "female mosquito*") AND ("distribution" OR "spatial distribution" OR "geographical distribution") AND ("Malaria") AND ("rainfall" OR "meteo*" OR "environment" OR "humidity" OR "percipation" OR "vector*" OR "altitude"))	294
Scopus	TITLE-ABS-KEY((("Climate change" OR "climate varia*" OR "temperature var*" OR temperature increases OR "environment*" OR "climat* effects" OR "climactic factors" ecology) AND ("Vector borne disease*" OR	21

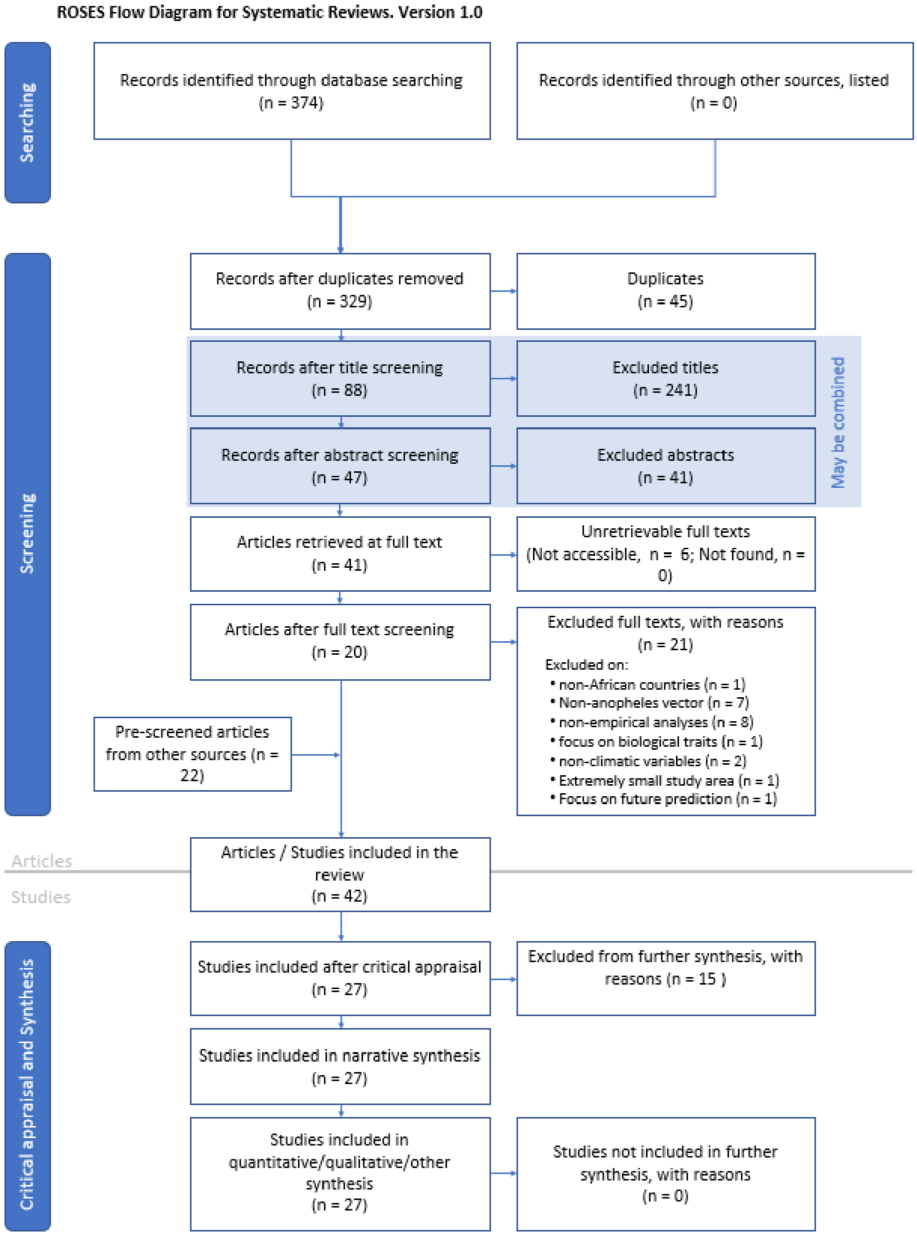
	"Vector transmission" OR "malaria transmission" OR "* falciparum" OR "*plasmodium" OR "mosquito-borne infectious disease" OR "plasmodium ovale" OR "Plasmodium malariae" OR "Plasmodium vivax" OR "Plasmodium knowlesi" OR "Plasmodium falciparum" OR "female mosquito*") AND ("distribution" OR "spatial distribution" OR "geographical distribution") AND ("Malaria") AND ("rainfall" OR "meteo*" OR "environment" OR "humidity" OR "percipation" OR "vector*" OR "altitude")))	
PubMed	(("Climate change" OR "climate varia*" OR "temperature var*" OR temperature increases OR "environment*" OR "climat* effects" OR "climactic factors" ecology) AND ("Vector borne disease*" OR "Vector transmission" OR "malaria transmission" OR "* falciparum" OR "*plasmodium" OR "mosquito-borne infectious disease" OR "plasmodium ovale" OR "Plasmodium malariae" OR "Plasmodium vivax" OR "Plasmodium knowlesi" OR "Plasmodium falciparum" OR "female mosquito*") AND ("distribution" OR "spatial distribution" OR "geographical distribution") AND ("Malaria") AND ("rainfall" OR "meteo*" OR "environment" OR "humidity" OR "percipation" OR "vector*" OR "altitude"))	59
Examination of references	/	17

2.2.2 Screening and eligibility

After the identification process, two additional processes have to be applied before finding the articles that will be included in this review namely the screening process and the eligibility process. The screening process was done prior to the eligibility process in accordance with a set of inclusion and exclusion criteria. All three databases possessed different sorting functions, giving the author a wide array of tools to impose some of the criteria on the results. Given that the searching process started in March 2021, it seemed appropriate to limit the search to 2020. In addition, only articles after 2010 were eligible. On top of the restriction on publication year, studies other than original research articles and electronically inaccessible articles where both excluded from this review. Furthermore, to avoid misinterpretation only articles published in English were chosen for this review. Given that the majority of malaria cases happen in Africa due to mosquito bites from the genus Anopheles, Africa will be region of interest and the Anopheles genus will be the vector of interest. Given that the research question is a systematic literature review of empirical studies, all non-empirical studies were also excluded.

After the screening process, the selected articles will be subjected to the eligibility process. In this process the articles were manually examined to check for consistency with the predetermined criteria. The manual examination consisted of three stages. Before the first stage could begin, all duplicates had to be removed. The first stage was to read the titles of all articles. This way the author could filter out titles that did not correspond with the topics of this review. Then the abstracts of the remaining articles needed to be studied. Lastly, the selected articles were explored and read in full to assess for eligibility for this review. The author proceeded to check for additional articles in the reference section of a sample of the selected articles. The articles from the reference section of the selected articles were also subjected to the same criteria. Below is the ROSES Flow Diagram, providing a clear picture of the steps that were taken.

Figure 1 ROSES Flow Diagram for Systematic Reviews



3. Results

3.1 Identified studies

The primary search in March 16, 2021 yielded a total of 374 results from three databases before correcting for duplicates and the application of inclusion and exclusion criteria. The articles found through the examination of references yielded an additional 17 results, resulting in a total of 391 results.

Before subjected the selected articles through the eligibility process, 45 duplicates were removed. The title of all the articles was read, enabling us to filter out 241 titles. After reading the abstracts, we filtered out an additional 41 titles. The first two steps ensured that all articles that did not correspond with topics of this review were filtered out. Lastly, the selected articles were explored and read in full to assess for eligibility for this review. The end result consisted of 20 articles.

The articles from the reference section of a sample of the selected articles were also subjected to the same criteria, yielding another 6 papers. Overall, there were 27 articles included in this review. The inclusion of 27 articles translates to the exclusion of 353 articles in total due to focus being on vectors other than the Anopheles vector, conducted in non-African countries, non-empirical analyses, not electronically accessible, focus on biological traits, focus on the effects of non-climatic variables, too small of a study area.

After the methodology a number of academic papers were deemed appropriate in presenting the effects of climate change on the distribution of malaria. To accurately present this information, all variables will be discussed in detail. After analyzing the academic papers at hand, the mayor topics that will be explored are temperature and precipitation, vegetation indices and landcover and El Niño/La Niña and different oscillators. After the variables are explored in dept, the distribution of malaria will be discussed separately.

3.2 Temperature

Before explaining the effect of climate change on malaria distribution, the factors relevant for malaria distribution that are also linked to climate change need to be discussed in the context of the current literature. The first factor to be discussed is one of the most prevalent among all studies, namely temperature.

Since the late 19th century, average global surface temperatures have increased around 0.5–0.6◦C, which is expected to increase further, additionally, there is a significant spatial heterogeneity in anticipated changes, with the greatest temperature increase going to occur at sub-Saharan Africa (Agusto, 2015). While climate change has multifaceted effects on malaria transmission over significant parts of Africa, not all of Africa is affected by climatically induced malaria transmission due to malaria transmission being limited in certain African highlands and desert fringes because of temperature and rainfall limiting mosquito abundance.

Diouf et al. (2020) analyzed the general trend of temperature for the period of 1979-2009 in West Africa and concluded that the warmest areas are located over the northern part of West Africa, bordering the Sahara Desert. The temperatures showed a bimodal evolution, with peaks in April and May. The authors noted that the average monthly temperatures increased over the years. The prevalence of malaria is limited in the northern part of West Africa, in contrast to the southern part of West Africa, where malaria is endemic. (Diouf, 2020)

Temperature seems to be influencing malaria significantly. Zacarias et al., (2010) argues that malaria incidence is positively correlated with temperature and rainfall in Maputo, capital of

Mozambique. However, the correlation between temperature and malaria incidence seems to be more pronounced for the winter period (Zacarias, 2010). Temperature, as a cofactor to other climatic variables, determines the survival rate of the plasmodium parasite and the Anopheles mosquitoes. The Anopheles mosquitoes and the Plasmodium parasites both need temperatures above 16◦C and below 32◦C for their development and survival. The optimal temperature for malaria transmission is, according to Adeola et al., (2019), at 25◦C, while transmission decreases at temperatures above 28◦C. Even though malaria transmission is triggered by precipitation, the length of the aquatic stage of the mosquito life cycle is principally determined by temperature (Adeola, 2019).

The lowest malaria incidence rate in South Africa is observed during the cold and dry season (June to August), conversely, the warm and wet season (December to February) enable the highest malaria incidence rate (Ikeda, 2017). The study also suggests a strong association between temperature and high incidence of malaria on the condition that precipitation was also higher than normal. Wet and warm environments pose as ideal breeding grounds for mosquitos (Ikeda, 2017). It is important to note that when ambient temperatures reach certain extreme heights, it can impact mosquito abundance negatively (Ikeda, 2017).

The implications of climate change even affect larval development. Paaijmans et al., (2010) showed that adding the projected increase of 3,2◦C in temperature to the current air temperatures significantly shortens larval development period, leading to an increase in population growth rates. When the dynamics of air and water temperature are considered, the magnitude of the decrease in larval development period and the increase in mosquito population rate is limited. Instead of reducing the larval development rate by 7,7-7,8 days in the highland and 3,6 days in the lowland areas, the predicted reduction is actually 1,5-3,1 days in the highland and 1,4-1,8 days in lowland. This translates to less extreme mosquito population growth rates, namely 5-9% in the highland and 4-5% in the lowland areas rather than 17% and 9%, respectively. However, this still shows the underlying trend, an increase in temperature has implications on larval development rate (Paaijmans, 2010). Additionally, an increase in temperature allows for female adult Anopheles mosquitoes to feed more frequently, since their digestion system benefits from the increased heat and allows for faster digestion and shortening the juvenile incubation period (Agusto, 2015). Moreover, the malaria parasite matures inside mosquitos within 19 days at 22◦C, but decrease to eight days at 30◦C, while the lifespan of a mosquito is about 21 days, the range of 30◦C to 32◦C decreases the lifespan of mosquitos. Extreme temperatures greater than 34◦C, however, decrease survival rates of mosquitos, parasites, and consequently transmission rates (Agusto, 2015). According to Kulkarni et al. (2016), temperatures ranging from 30°C and 35°C have been shown to decrease the survival rates of mosquitos, however, it seems that some mosquito species adapt better than other mosquito species. When looked at the survival rates of the Anopheles arabiensis and the Anopheles gambiae, the Anopheles arabiensis seemed to adapt better than the Anopheles gambiae when temperatures ranged between 30°C and 35°C (Davies, 2016). This temperature range is also supported by Kulkarni et al. (2016) and they added that a decline in survival rate was predicted for all temperatures after 35°C. An increase in temperature seemed especially beneficial for the Anopheles arabiensis. One explanation is that an increase in temperatures leads to an increase in development rate, and consequently increases the demand for more nutrients with a faster working metabolism. These requirements can be very demanding in the development process leading to insufficient mass being accumulated for eclosion. When they emerge sooner under higher temperatures, they are less vulnerable to predators, pathogens, excess rainfall flushing their habitat or their habitat drying up in exchange for a reduction in their fitness for survival and longevity. This also leads to a greater population growth rate among mosquitos (Davies, 2016).

Temperature is not limited to influencing population growth rates among mosquitos but also biting rates (Shapiro, 2017). The analyses on the interplay between the biting rate per human per day in south Africa and temperature yielded a strong seasonal pattern, where the biting rate per human per day seemed to be temperature dependent. (Abiodun, 2017) During the summer period the biting rate was much higher compared to the winter period, where temperatures were low (Abiodun, 2017). The availability of adult population is very dependent on ambient temperature, where adult mosquitoes persist at temperatures suitable for aquatic mosquitos. When temperatures get extremely high, mosquito population abundance seems to be decreasing, which has been demonstrated multiple times (Abiodun, 2017). According to Kakmeni et al. (2018), regions in Africa where temperatures are about 25◦C experience the highest R0 values, in this study the range was from R0 of 0 to an R0 of 9 where 25◦C corresponded with an R0 of 9. In the present context, the basic reproduction number R0 is used as a tool in evaluating and predicting risk zones for malaria transmission. High values of R0 (> 1) correspond to malaria risk zones. While the role of rainfall as a provider of suitable breeding habitats is not undermined in this study, temperature is regarded as a critical driver that affects mosquito biology and parasite life cycle. More specifically Kakmeni et al., (2018) argues that temperature affects transmission intensity, including mosquito development rate, biting rate, and survival of the parasite within the mosquito, vector competence, adult mortality rate, eggs laid per adult female per day, and egg-to-adult survival probability.

Rising temperatures lead to warmer climates, these climates could increase larval development rate, enhance vector survivorship and reproductive fitness, increase biting rate and feeding frequency, and parasite sporogonic development rate, in previously cooler highlands (Kweka, 2016; Shapiro, 2017). Adeola et al., (2017) found that December was the hottest month of the year with a temperature of 26.6 °C, at the same time was the highest amount of rainfall recorded with an average of 153,33 mm per month for the months November, December, and January for the period 1998 to 2017 in Limpopo, South Africa. The analyses of the authors revealed a strong association between high malaria cases and years above normal rainfall. The increase in temperature allows for an increase in transmissions due to shortening the time interval between blood meals and consequently allowing for mosquito abundance. At 16°C larval development may take more than 45 days leading to reduction of mosquitos, for context the coldest month was in July, sitting at 18.1°C. Furthermore, temperatures ranging from 20 °C to 30 °C allow for a reduction in incubation period of the malaria parasites. The study concluded that the correlation coefficient of the mean minimum temperature had the highest correlation with malaria cases. Additionally, combining total monthly rainfall and monthly mean minimum temperature, with a two-month lagged effect, lead to being the most significant climatic variable in predicting malaria transmission in Limpopo, South Africa (Adeola, 2017).

Komen et al. (2015) concur with the findings of Diouf et al. (2005) for South Africa and argue that a positive unidirectional linear relation with malaria cases and temperature exists. Additionally, it also provides evidence that rainfall is also positively associated with the number of malaria cases. Here the authors argue that the unidirectional causality from rainfall to malaria cases does not increase malaria cases significantly and that an increase in temperature is consistent with an increase in malaria cases. Increasing temperatures, however, do not intrinsically and immediately translate to an increase in malaria cases. There is a certain lag period involved, meaning that after a certain amount of time the increase in heat will lead to an increase in malaria cases. The minimum and maximum temperature lag times are argued to be between 1–2 and 2–5 months, respectively. This is due to the fact that an increase in temperature generally accelerates vector life cycles and decreases the incubation period of the parasite, this acceleration is capped at a certain temperature and very high temperatures could lead to a hindrance in the completion of the mosquito life cycle, making the occurrence of transmission not possible (Komen, 2015).

Zacarias et al., (2010) formulated a space-time model where the regression coefficients indicate that values of minimum temperature between 17°C and 21.1°C, maximum temperature of 28 to 35°C, and the presence of relative humidity in the range 54.5% to 83% are positively associated with malaria incidence risk. Furthermore, an increase of 1°C in maximum temperature leads to a disproportionate increase in malaria incidence risk, whereas an increase of 1% of relative humidity leads to a different possible outcomes. The high level of humidity is generally a consequent of high levels of rainfall in combination with high temperatures, leading to suitable conditions and breeding sites for mosquito population and parasite development (Zacarias, 2011). The interplay between temperature and rain was studied by Amadi et al., (2018). The authors provided evidence that low minimum temperatures were coincided with high rainfall. This was observed in the highland and riverine zones. Climate warming may make certain areas previously too cool for vector populations now more suitable, leading to an increase in vector population in higher altitudes.

Since mosquitoes are dependent on temperature and precipitation, Parham et al. (2010) calculated the Probability of local seasonal extinction for mosquitoes across Tanzania, East Africa, for the month April. Incorporating simpler population models within climate-driven transmission models allowed for quantifying the impact of climate on Anopheles population dynamics, where mosquito fadeout probabilities may be used as a very approximate indicator of malaria fadeout probabilities. The results for Tanzania showed that a decrease in temperature, combined with an extremely high average rainfall could reduce the prevalence of malaria in most of Tanzania. The authors argue that although the global distribution of malaria will change as climatic variables change, the impact will not always be for the worse. However, it is clear that an increase in temperature increases the probability of mosquito emergence, and as a consequence the emergence of malaria, in regions that are currently not endemic. The results for the predicted changes in R0 across Tanzania in 2080 for the month April show an increase in R0, assuming that the peak transmission windows stay beneath 32-33◦C. Additionally, they predict endemicity in previously unsuitable areas for transmission. These areas are the districts bordering the Democratic Republic of Congo, Malawi, Mozambique, and all coastal regions. These predictions are limited to the month April, the following months should experience an increase in temperature and a decrease in rainfall, potentially leading to overestimating the effects on a yearly because of reduced vector abundance due to reduced rain fall. Leedale et al. (2016) analyzed the effects of climate scenarios on simulated temperature changes for 2020, 2050, and 2080. It is evident that the greatest warming occurs over the border regions north and south of East Africa. There are large uncertainties regarding precipitation changes and temperature changes over the Congo rainforest area in the Democratic Republic of Congo and northern South Sudan. Generally, the majority of the East African region is expected to increase in temperature by at least 3◦C by the 2080s, which in turn will impact malaria transmission considerably. Generally, there are large uncertainties in predicting the change in precipitation, while temperature is expected to increase (Abrha, 2018).

Lastly, the results of Yamana et al. (2013) for West Africa predict an increase between 2°C to 6°C for the period 2080–2099. The predicted change in rainfall was less clear, where the sign and magnitude varied quite significantly ranging from a decline of 400% to an increase of 260%. The authors noted that the current climate in the northern part of West Africa is drier and warmer than optimal for malaria transmission, to maximize vectorial capacity, the climate needs to be wetter and temperatures need to decrease. Additionally, Yamana et al. (2013) discussed the interplay of temperature and precipitation. They argue that an increase in precipitation would lead to less warming due to a wetter climate leading to more evaporative cooling and decreasing some of the warming caused by greenhouse gases. Alternatively, a decrease in precipitation is associated with an increase in temperatures. Lastly, Yamana et al. (2013) state that the number of days an average mosquito will be infective is maximized at 28°C. Underlining the multifaceted effects of temperature on mosquito and malaria prevalence. However, not every study regarded temperature as the most important variable. Kulkarni et al. (2016) argued that the impact of temperature was of relative minor importance in Tanzania, East-Africa. Arguing that elevation and vegetation indices are far more useful in predicting mosquito habitat suitability.

The table below shows the characteristics of the articles included in the review regarding temperature. Additionally, it also show whether they assume a positive (+), negative (-) or no (NA) association between temperature and malaria prevalence.

Table 2 Characteristics of the articles included in the review regarding temperature.

Author	year	Title	analytical approach	Location	Association
Kulkarni et al.	2016	10 Years of Environmental Change on the Slopes of Mount Kilimanjaro and its Associated Shift in Malaria Vector Distributions.	Models consisted of Entomological and vector occurrence data	East	+
Diouf et al.	2020	Climate Variability and Malaria over West Africa	The Liverpool Malaria Model	West	+
Komen et al.	2015	Long-Run Relative Importance of Temperature as the Main Driver to Malaria Transmission in Limpopo Province, South Africa: A Simple Econometric Approach.	Spatio-temporal method, Correlation analysis and econometric methods are applied	South	+
Zacarias et al.	2010	Mapping malaria incidence distribution that accounts for environmental factors in Maputo Province – Mozambique.	Parameter estimation and infe rence, using MCMC simulation techniques based on Poisson variation	East	+
Amadi et al.	2018	Mapping potential Anopheles gambiae s.l. larval distribution using remotely	Negative binomial regression	East	+

		sensed climatic and environmental variables in Baringo, Kenya.			
Abiodun et al.	2017	Modelling and analyzing the impact of temperature and rainfall on mosquito population dynamics over Kwazulu-Natal, South Africa.	Climate-based, ordinary-differential-equation model	South	+
Parham et al.	2010	Modelling the Effects of Weather and Climate Change on Malaria Transmission.	dynamic process-based mathematical models	East	+
Yamana et al.	2013	Projected Impacts of Climate Change on Environmental Suitability for Malaria Transmission in West Africa	coupled a detailed mechanistic hydrology and entomology model with climate projections from general circulation models (GCMs)	West	+
Leedale et al.	2016	Projecting malaria hazard from climate change in eastern Africa using large ensembles to estimate uncertainty.	climate- driven malaria projections	East	+
Paaijmans et al.	2010	Relevant microclimate for determining the development rate of malaria mosquitoes and possible implications of climate change.	temperature-dependent development model for Anopheles gambiae immatures	East	+
Kakmeni et al.	2018	Spatial panorama of malaria prevalence in Africa under climate change and interventions scenarios	dynamical mathematical netw ork model	General	+
Kweka et al.	2016	Effect of deforestation and land use changes on mosquito productivity and development in Western Kenya Highlands: implication for malaria risk.	one-way analysis of variance (ANOVA)	East	+
Zacarias et al.	2011	Spatial and temporal patterns of malaria incidence in Mozambique.	A Bayesian model with interaction terms	East	+
Adeola et al.	2019	Rainfall Trends and Malaria Occurrences in Limpopo Province, South Africa	Annual and seasonal trends, as well as cross-correlation analyses, were performed on time series of monthly total rainfall and monthly malaria cases	South	+
Ikeda et al.	2017	Seasonally lagged effects of climatic factors on malaria incidence in South Africa.	Composite analysis	South	+
Agusto et al.	2015	Qualitative assessment of the role of temperature variations on malaria transmission dynamics.	mechanistic deterministic mod el for assessing the impact of t emperature variability on mala ria transmission dynamics	Gen	+
Adeola et al.	2017	Climatic Variables and Malaria Morbidity in Mutale Local Municipality, South Africa: A 19-Year Data Analysis.	Time series analysis	South	+
Davies et al.	2016	Effect of stable and fluctuating temperatures on the life history traits of Anopheles arabiensis and An. quadriannulatus under conditions of inter- and intra-specific competition.	Parametric ANOVAs	Laborato ry	+
Shapiro et al.	2017	Quantifying the effects of temperature on mosquito and parasite traits that determine the transmission potential of human malaria.	Laboratory	Laborato ry	+

3.3 Precipitation

Following temperature, the second factor relevant for malaria distribution that is also linked to climate change is precipitation, being the second most prevalent among all studies.

When looked at precipitation data for all of African over the period of 1901-1995, it indicates that precipitation levels are not uniformly distributed and contains variability across the African continent.

Precipitation appears to be increasing in East Africa but decreasing in the western and northern part of the continent (Kakmeni, 2018).

Diouf et al. (2020) analyzed the seasonality in temperature and rainfall in West Africa and concluded that it is evident that the boreal summer (Boreal climate, a climate characterized by long winters and short, cool to mild summers) comprised by the months July, August and September provides the highest mm in rainfall. The authors noted that West Africa experienced several unexpected variabilities in rainfall. The drought during the 1970s–1980s lead to a decrease in malaria cases, in comparison to the wet period of the 1950s-1960s. This is in line with the expected seasonality in the number of malaria incidents. The malaria season occurs between September to November, with a clear peak in October. After heavy rains and monsoon rains malaria transmission can continue until the start of the dry season depending on the available temporary ponds. The duration of the temporary ponds is determined by the presence of an unusual wet year, if this is the case then the ponds can be present for a longer than usual duration and may facilitate a sustainable breeding ground for mosquitos.

Besides heavy rains and monsoon rains, temperature, following a rainy season, seems to also have an influence on the survival rate of mosquitos in East Africa by influencing the size of the parasite's reservoir. This could lead to an increase in malaria incidence rates after it has rained. The positive association of malaria incidence and rainfall seems to be evident (Zacarias, 2010). The interplay between precipitation and temperature is pronounced and there seems to be a dependability between the aforementioned variables in enabling mosquito breeding habitats and consequently malaria incidence rates. When looked at the mean temperature values and the mean rainfall values for the coastal region of Dar Es Salaam and the central region of Singida in East Africa, it is evident that there is a strong seasonal heterogeneity across Tanzania, especially in the mean rainfall values (Parham, 2010). Parham et al., (2010) argue that the impact of rainfall is more pronounced than the impact of mean temperature values. Furthermore, water temperatures are generally higher than ambient air temperatures, with mean water temperatures in Kenya, East Africa, exceeding mean air temperatures by 4.5 to 5.8°C. In the lowlands the difference is less pronounced but still present around 3.7-4.3°C (Paaijmans, 2010).

In sub Saharan Africa mosquito breeding sites are determined by the availability of rainfall, this increases the amount of available breeding sites and productivity with respect to ambient temperature. Suitable breeding habitats for mosquitos due to rainfall, therefore, enhance malaria transmission. However, excess rainfall may lead to the flushing out of breeding sites (Agusto, 2015). Rainfall not only enables potential breeding habitats for mosquitos, influencing malaria prevalence, it also influences the aquatic stage of the mosquitos' life cycle. The implications of rain are multitudinous; the laying of mosquito eggs, the development to larvae, and the development into adults all require aquatic breeding sites. Additionally, rainfall increases relative humidity to sustain the longevity of the adult mosquitos. The optimal scenario for the survival of the Anopheles mosquito and the plasmodium parasite is a temperature between 20°C and 30°C, a humidity above 65%, and adequate amount of rainfall (cumulative average of around 400 mm) (Adeola, 2017). Abrha et al., (2018) concur on the importance of temperature, rainfall, and humidity in determining the distribution and burden of disease.

There is, however, a negative but significant association between rainfall and malaria cases at lag 0 and 1-month potentially due to the flushing out of breeding sites due to high rainfall (Adeola, 2017). The lag time is a timeframe where the vector-parasite-host cycle can be developed and completed (Adeola, 2019). Over southern Mozambique in East Africa there also is a positive correlation between precipitation and malaria incidence rate anomalies but at a three-month lag. When temperatures drop in the austral winter season (below 18°C) in Southern Africa, it has been reported that the Anopheles arabiensis can feed, lay eggs, and enter diapause during winter (Ikeda, 2017).

The aquatic stage dynamics influence the number of adult mosquitos greatly because there is a strong seasonal variability present, where the mosquito density is minimal throughout the winter period starting from June all the way to August, limiting adult mosquito activity to a 6-month period (Abiodun, 2017). Abiodun et al. (2017) analyzed the puddle dynamics in South Africa, the results showed that the puddle increases and decreases along with rainfall, affecting population dynamics of juvenile mosquitos. According to Smith et al., (2020), local water bodies also affect mosquito development. While the flowing water in large river channels not providing a larval habitat for mosquitos may sound counterintuitive, the smaller water bodies in adjacent bankside and floodplain areas can be highly sustainable as a breeding ground for mosquitos and consequently increase malaria incidence rates.

Adeola et al. (2019) analyzed the annual variability around the mean values of rainfall and looked for a certain trend in Limpopo, South Africa for the period 1998-2017. The results showed a decrease in rainfall by about 170 mm, depicting drier conditions. Drier conditions lead to malaria cases exhibiting negative trends because of the positive correlation between malaria and rainfall. Overall, high malaria cases seem to be preceded by early rainfall in the winter months of June, July, and August leading to an abundance of mosquito population in the spring months of September, October and November and a transmission peak in the summer months December, January, and February. Furthermore, after a significant rainfall malaria prevalence seems to be persistent even after a few months, indicating that there is an averaged lagged time of one to two months between rainfall and malaria incidence rates. A significant rainfall can increase malaria transmission after a month and keep having significant impacts in the consequent months up to the fifth consecutive month, after which there is a negative relationship between lagged months and malaria prevalence. As stated earlier the lag time is a timeframe where the vector-parasite-host cycle can be developed and completed (Adeola, 2019). The development of the female Anopheles mosquito from egg to larva to pupa to adult and to parasite takes between 5–14 day. The second stage is the development of the plasmodium parasite (gametocyte to sporozoites), which takes about 10–18 days. The final stage consists of the incubation period in the human host from infection to malaria symptoms, which takes around 14 days. This explains why malaria prevalence is persistent after a significant rainfall and stays persistent even after several months (Adeola, 2019).

Precipitation also impacts the general wetness and vegetation of an area, also affection malaria transmission. The topographic wetness, commonly used to quantify topographic control on hydrological processes, showed low values for the riverine zones in Kenya, East Africa, in contrast to the lowland zones. Both the lowland zones and the riverine zones had slopes <7%. The slope impacts a variety of hydrological processes. In this study the areas of hydrological processes affected were area drainage, water velocity and accumulation. Additionally, high topographic wetness values coincided with low minimum temperatures, thus resulting in unsustainable climates for malaria incidence. Since topographic values coincide with low minimum temperatures, combined with larval development being dependent on the presence of water, topographic wetness has impact on the occurrence and duration of larval habitats, potentially enabling high mosquito productivity (Amadi, 2018). The results of Amadi et al. (2018) showed that rainfall, slope, and vegetation health had significant influences on the Anopheles gambiae larvae distribution in East Africa.

The predicted suitability for the Anopheles Arabiensis in East Africa increases with wet season vegetation index but reaches a peak after which suitability declines. It is also noted that vegetation indices decline in lower altitudes in the wet and dry season. This decline insinuates a trend towards lower precipitation. At mid to high altitudes the dry season vegetation indices declined, however, the wet season vegetation indices increased. Given the presence of the Anopheles Arabiensis at higher elevations, this suggests that vector reproduction in highland areas may not be limited by precipitation in the same way as lower altitudes. The annual rainfall in Tanzania, East Africa, is typically >1200mm, compared to the 800-900mm in lowland areas (Kulkarni, 2016).

The table below shows the characteristics of the articles included in the review regarding precipitation. Additionally, it also show whether they assume a positive (+), negative (-) or no (NA) association between precipitation and malaria prevalence.

Table 3 Characteristics of the articles included in the review regarding precipitation.

Author	year	Title	analytical approach	Location	Association
Kulkarni et al.	2016	10 Years of Environmental Change on the Slopes of Mount Kilimanjaro and its Associated Shift in Malaria Vector Distributions.	Models consisted of Entomological and vector occurrence data	East	+
Diouf et al.	2020	Climate Variability and Malaria over West Africa	The Liverpool Malaria Model	West	+
Smith et al.	2020	Incorporating hydrology into climate suitability models changes projections of malaria transmission in Africa	Spatio-temporal method, Correlation analysis and econometric methods are applied	West	+
Zacarias et al.	2010	Mapping malaria incidence distribution that accounts for environmental factors in Maputo Province – Mozambique.	Parameter estimation and infe rence, using MCMC simulation techniques based on Poisson variation	East	+
Amadi et al.	2018	Mapping potential Anopheles gambiae s.l. larval distribution using remotely sensed climatic and environmental variables in Baringo, Kenya.	Negative binomial regression	East	+
Abiodun et al.	2017	Modelling and analyzing the impact of temperature and rainfall on mosquito population dynamics over Kwazulu-Natal, South Africa.	Climate-based, ordinary-differential-equation model	South	+
Parham et al.	2010	Modelling the Effects of Weather and Climate Change on Malaria Transmission.	dynamic process-based mathematical models	East	+
Paaijmans et al.	2010	Relevant microclimate for determining the development rate of malaria mosquitoes and possible implications of climate change.	temperature-dependent development model for Anopheles gambiae immatures	East	+
Adeola et al.	2019	Rainfall Trends and Malaria Occurrences in Limpopo Province, South Africa	Annual and seasonal trends, as well as cross-correlation analyses, were performed on	South	+

			time series of monthly total rainfall and monthly malaria cases		
Ikeda et al.	2017	Seasonally lagged effects of climatic factors on malaria incidence in South Africa.	Composite analysis	South	+
Agusto et al.	2015	Qualitative assessment of the role of temperature variations on malaria transmission dynamics.	mechanistic deterministic mod el for assessing the impact of t emperature variability on mala ria transmission dynamics	Gen	+
Adeola et al.	2017	Climatic Variables and Malaria Morbidity in Mutale Local Municipality, South Africa: A 19-Year Data Analysis.	Time series analysis	South	+
Abrha et al.	2018	Climate change impact on coffee and the pollinator bee suitable area interaction in Raya Azebo, Ethiopia.	general circulation models	East	+

3.4 Geographical features

While the main focus seems to be set on climatic variables like temperature and rainfall, the geographical features of a region present valuable information in finding the effects of climate change on malaria distribution. The geographical features of an area could have certain characteristics limiting or enabling mosquito development and malaria prevalence.

According to Kulkarni et al., (2016) elevation is deemed the primary predictor of Anopheles arabiensis distribution. When looked at data ranging from 2004-2014 in Tanzania, East Africa, it was notable that the predicted suitability in combination with the mosquito density declined when altitude increased in 2004. It should be noted that mosquito density declined exponentially and not linearly. In 2014, 10 years after the initial study, the predicted area suitable for Anopheles arabiensis declined. Lowland areas experienced a decline in mosquito density, while highland areas experienced an increase in mosquito density. This finding is also supported by Chaves et al., (2012). The spatial distribution of mosquitos, and consequently malaria, in response to climatic variability experiences heterogeneities. Areas of below 1600 meters above sea level began a decrease in mosquito density in western Kenya highland, East Africa, in the late 1980s. In contrast, altitudes above 1600 meters above sea level have experienced an increase in malaria transmission intensity in the 1980s and 1990s (Chaves, 2012). Ermert et al., (2012) project that in North Africa malaria is to become stable above 1600 meters and below 2000 meters above sea level, which confirms the findings of Kulkarni et al., (2016) and Chaves et al., (2012). In addition, zones above 2000 meters above sea level are projected to transform into epidemic-prone areas (Ermert, 2012).

Adeola et al., (2019) argues that the interaction between topography and climatic conditions poses an important part in investigating the spatial variability of rainfall. In the Soutpansberg Mountain, which is located in South Africa and peaks at 1747 meters above sea level, the orographic effect is known to be causing an increase in rainfall in the eastern region, influencing malaria transmission.
Furthermore, Kulkarni et al., (2016) noted a decrease in wetness at low altitudes and an increase in temperature at high altitudes. Additionally, a shift in land cover was realized; woody savannas in the highlands increased in land area and grasslands increased in land area at all altitudes. At higher altitudes mixed and deciduous forest lost land area. These were not used as cropland, since there was no discernable increase in cropland land area, the occurrence of natural or anthropogenic

deforestation seems plausible. Deforestation has been linked with an increase in temperatures and in creating sustainable habitats for Anopheles mosquitos and consequently for malaria development. The mosquito of interest is the Anopheles arabiensis, which is known to be well adapted to deforested high land areas. The increase in temperature in the highlands due to deforestation and the decrease in wetness in the lowlands could explain the increase in mosquito density at the highlands over a period of 10 years (Kulkarni, 2016). In determining the spatial distribution of malaria, land cover seems to be an important factor. Different land cover types have different soil water input capacities. This means that depending on the vegetation, mosquito abundance and malaria transmission rates may vary (Amadi, 2018).

Kweka et al., (2016) analyzed the Effect of Deforestation and Land Use Changes on Mosquito Productivity and Development in Western Kenya Highlands for the period of 2003 to 2012. Their results indicate that deforestation in Africa is linked to altered malaria transmission dynamics. Deforestation can originate from anthropogenic actions or be a natural occurrence but whatever the cause, the implications are significant in the tropical regions of Africa. The changes in land cover and land use may impact the temperature and the relative humidity of mosquito sites in the highlands. When looked at the differences in temperature between cultivated and natural swamps in southwestern highlands of Uganda, East Africa, the cultivated swamps were significantly warmer than the natural swamps. These implications decrease the median survival rate of the Anopheles gambiae in East Africa but these mosquitos do present an enhanced reproductive fitness. This is due to faster bloodmeal digestion and the feeding of blood. While the survival rate experiences a decline, the population growth rate could experience an increase within a short time, given that adequate breeding sites are present. Moreover, deforestation can increase larval productivity, accelerate larval development time, and increase larval pupation rate as well as adult emergence rate (Kweka, 2016).

The results of Kweka et al., (2016) indicated that deforested areas experienced an increase in indoor and outdoor temperature in deforested areas in the western Kenya highlands compared to forested areas. The outdoor temperature was 0,4°C higher during dry and rainy seasons in the deforested areas compared to the forested areas, while indoor average temperature was 1,2°C higher in the deforested areas compared to the forested areas during dry season. In addition to the increase in temperatures, humidity rates also experienced change due to deforestation. However, these effects fluctuated substantially. The effects of deforestation, be it from anthropogenic origins or from natural causes, negatively influenced the mosquitoes' gonotrophic cycle, shortening the duration from 4.6 days to 2.9 days. The gonotrophic cycle refers to the period starting from the taking of a blood meal by a mosquito until oviposition. This decrease could mean an increase in biting rate from once every five days to once every three days, enhancing malaria transmission rates greatly. Furthermore, these changes also reduced the sporogonic development time of malaria. This translates to shorter parasitic development times and hence higher malaria incidence rates and malaria transmissions. These findings mean that the Anopheles arabiensis has better survival rates in deforested areas and are capable of laying more eggs, leading to an increase in population size. Thus, land cover changes are crucial in understanding the increases in the rate of malaria vectors in Western Kenya highlands (Kweka, 2016).

The NDVI is a dimensionless index that describes the difference between visible and near-infrared reflectance of vegetation cover and can be used to estimate the density of green on an area of land (Malahlela, 2018). High NVDI areas seemed to correspond with cropland and forest areas. One explanation could be the presence of irrigation activities inflating surface moisture content(Amadi, 2018). Amadi et al., (2018) reported that croplands and wetlands in East Africa exhibit high Anopheles gambiae abundance, suggesting that irrigation activities enable year-round mosquito habitats in the lowlands. In addition, De Souza et al., (2010) found a negative association between slope and larval distribution in Ghana, West Africa. Accordingly, Area slope and topographic wetness are often seen as predictors of mosquito breeding sites, further explaining the mosquito breeding sites present at irrigation sites in lowland areas. Additionally, vegetation index NDVI is known to be a surrogate for rainfall, enabling mosquito breeding habitats. Malahlela et al., (2018) argues there is a correlation between malaria and vegetation, due to vegetation being correlated with rainfall and temperature. While it is evident that water bodies serve as potential habitats for mosquitos, leading to mosquito abundance, the size, compactness, depth, and temperature of said water bodies that will serve as a breeding habitat differ depending on the preference of the different Anopheles species (Amadi, 2018).

Malaria probability exhibits variability depending on the vegetation, a high probability of malaria distribution is associated with high ground cover, comprising of moist, riparian vegetation (meaning plants and trees along the water margins and banks) (Ricotta, 2014). This means that green vegetation environments serve as refuges for malaria vectors, where the Anopheles arabiensis is the most prominent in South Africa. Besides, the abundance of healthy vegetation enables resting sites for mosquitos, thereby increasing the intensity of foci for malaria (Malahlela, 2018). Another foci for year-round malaria transmission are complex and large river networks. The Nile in particular extents to the far north coast of Africa, resulting in many suitable breeding habitats for mosquitos and historical observations of malaria outbreaks. The Niger and Senegal rivers in Mali and Senegal, and Webi Juba and Webi Shabeelie rivers in Somalia similarly extend beyond the geographical ranges predicted to be climatically suitable for malaria by all rainfall thresholds but are still seen as breeding grounds for mosquitos leading to malaria transmissions (Smith, 2020). This could mean that environmental and climatic variability may explain the variation in malaria incidence rates across different regions (Adeola, 2019).

The table below shows the characteristics of the articles included in the review regarding geographical features. Additionally, it also show whether they assume a positive (+), negative (-) or no (NA) association between geographical features and malaria prevalence.

Table 4 Characteristics of the articles included in the review regarding geographical features.

Author	year	Title	analytical approach	Location	Association
Kulkarni et al.	2016	10 Years of Environmental Change on the Slopes of Mount Kilimanjaro and its Associated Shift in Malaria Vector Distributions.	Models consisted of Entomological and vector occurrence data	East	+
Malahlela et al.	2018	Evaluating Efficacy of Landsat-Derived Environmental Covariates for Predicting Malaria Distribution in Rural Villages of Vhembe District, South Africa	stepwise logistic regression model	South	+

Smith et al.	2020	Incorporating hydrology into climate suitability models changes projections of malaria transmission in Africa	Spatio-temporal method, Correlation analysis and econometric methods are applied	West	+
Ermert et al.	2012	The Impact of Regional Climate Change on Malaria Risk due to Greenhouse Forcing and Land-Use Changes in Tropical Africa	Liverpool Malaria Model (LMM)	Gen	+
Amadi et al.	2018	Mapping potential Anopheles gambiae s.l. larval distribution using remotely sensed climatic and environmental variables in Baringo, Kenya.	Negative binomial regression	East	+
Kweka et al.	2016	Effect of deforestation and land use changes on mosquito productivity and development in Western Kenya Highlands: implication for malaria risk.	one-way analysis of variance (ANOVA)	East	+
Chaves et al.	2012	Regime shifts and heterogeneous trends in malaria time series from Western Kenya Highlands.	Time series analysis	East	+
Adeola et al.	2019	Rainfall Trends and Malaria Occurrences in Limpopo Province, South Africa	Annual and seasonal trends, as well as cross-correlation analyses, were performed on time series of monthly total rainfall and monthly malaria cases	South	+
De Souza et al.	2010	Environmental factors associated with the distribution of Anopheles gambiae s.s. in Ghana; an important vector of lymphatic filariasis and malaria.	remote-sensed satellite data		
Ricotta et al.	2014				

3.5 Large-scale climate phenomena

Seasonal to interannual variations in malaria incidence rates are associated with large-scale climate phenomena, such as the El Niño Southern Oscillation, La Niña, Indian Ocean (subtropical) Dipole and sea surface temperature variabilities (Agusto, 2015; Kulkarni, 2016; Ikeda, 2017; Malahlela, 2018). As an example, the large malaria epidemic in Uganda, East Africa, was due to a decline in malaria control activities during the late 1970s, in combination with heavy rainfall associated with El Niño 1997–1998 (Kulkarni, 2016). Additionally, Agusto et al., (2015) also found a relationship between years of high malaria cases and La Niña events, as well as tropical cyclones from the Mozambique Channel.

Malahlela et al., (2018) argues that there is evidence that suggest that rainfall anomalies during the summer months are usually affected by the occurrences of El Niño and La Niña. Generally, El Niño years are signified by below average malaria incidences, contrary to the above average malaria incidences during the La Niña years (Malahlela, 2018). Given that northeastern parts of South Africa are on average drier due to below average rainfall associated with El Niño events, compared to La Niña years, where rainfall is higher than average, a slower rate of malaria transmission is expected during the El Niño years (Malahlela, 2018). Furthermore, climate variations in the southern Indian Ocean also seem to influence rainfall variability over South Africa. Moreover, wetter than normal austral summers are also associated with La Niña patterns (Ikeda, 2017).

Ikeda et al., (2017) analyzed the Seasonally lagged effects of climatic factors on malaria incidence in South Africa for the period 1998-2014 and claims that there are statistically significant associations between seasonal malaria incidence rate anomalies in Limpopo, South Africa, and regional and remote climate factors. Regional climate factors consist of factors, like rainfall, in neighboring countries (e.g., Mozambique) that affect malaria incidence rate in Limpopo, whereas remote climate factors consist of Indian Ocean Subtropical Dipole (IOSD) La Niña and El Niño patterns. Additionally, wetter conditions were observed in Southeastern Mozambique in September at a two-months lag due to La Niña patterns. Six months before the pre-peak season (defined as the months September to November) higher than average precipitation was seen over Limpopo, Southern Zimbabwe and Mozambique with winds blowing from the Mozambique Channel and the Indian Ocean and lower than average mean temperatures. These climate factors coincided with La Niña patterns. La Niña patterns are associated with wetter than normal austral summers in South Africa. La Niña and the Indian Ocean Subtropical Dipole show significant correlations with malaria incidence rates. In the peak malaria season Limpopo, Mozambique and other neighboring countries experiences higher than normal rainfall in the dry winter months. This wet dry winter season may have created mosquito breeding habitats for the Anopheles arabiensis, which is one of the primary malaria vectors in South Africa. Ikeda et al., (2017) show that there are seasonal lagged effects of climatic factors from local regions and neighboring countries, that affect the timing and severity of malaria outbreaks in Limpopo. La Niña conditions from July may explain the wetter conditions in the southern coast of Mozambique in September. Although the wetness did not increase in September, rainfall did increase. This led to an increase in malaria cases in Mozambique and Limpopo, due to mosquitos needing sufficient support during their early aquatic life stages. In general, high malaria incidence rates during the peak and pre-peak seasons were preceded by positive IOSD patterns and La Niña patterns, respectively. The results of Agusto et al., (2015) show that malaria incidences during the period of January 1998 to May 2017 in the northeastern parts of South Africa, Limpopo were associated with tropical storms after a period of two to three months. Furthermore, years with rainfall above normal seem to be associated with positive sea surface temperature anomalies, La Niña conditions in the Pacific Ocean as well as tropical cyclones from the Mozambique Channel. This means that remote climatic factors play an important role in determining the prevalence of malaria cases (Agusto, 2015).

La Niña patterns and tropical cyclones from the Mozambique Channel can onset early rainfall. The early rainfall and also temperature exhibit a significant relationship with malaria occurrence at a time lag of two months (Agusto, 2015). Furthermore, relationship could be on a longer timescale. It may be possible that malaria transmission of the following year could be affected as well (Agusto, 2015). According to Agusto et al., (2015), the two-month lagged effect is realistic in the context of the malaria cycle, which consists of three components. The first component being the growth of the Anopheles female mosquito from egg to adult to parasite transmission. The second component being the development of the Plasmodium parasites, enabling the parasite to infect humans. The last component consists of the incubation period in the human host from infection to malaria symptoms. Given that malaria occurrence can be expected to be to be at a peak at about one and a half to two months after the onset of rain, the two-month lagged effect seems to be plausible. This two-month lagged effect is proven to be present at Limpopo, Mozambique, Zimbabwe, and Ethiopia (Adeola, 2017; Ikeda, 2017).

The periods of high rainfall, potentially caused by La Niña, in combination with adequate temperature and high humidity could benefit saturated soil moisture content causing water bodies to persist longer, therefore enabling the persistence of larval habitats (Agusto, 2015). While mosquito breeding sites are caused by tropical cyclones from the Mozambique Channel and La Niña patterns, these are also associated with flooding that could wash away mosquito breeding sites. However, after the flood, new water bodies may be created, leading to new mosquito breeding habitats. When climatic and environmental factors allow conditions favorable to larval development, in combination with the aforementioned newly created water bodies, mosquito vector populations could experience an increase in size, potentially leading to higher malaria cases, withing a few weeks (Agusto, 2015). Agusto et al., (2015) note that habitat preference of the local vector species is an important determinant.

The Indian Ocean Dipole is another mode of climate variability that significantly influences regional rainfall patterns and malaria incidence rates, particular in the eastern side of the African continent. The dominance of the Indian Ocean Dipole is particularly prevalent in Kenya, exerting significant influence on malaria incidence rates (Malahlela, 2018). Rainfall generally increases the availability and productivity of mosquito habitats and enhances malaria transmission, given adequate temperatures not negatively influencing mosquito survival rates (Agusto, 2015). In addition, the Indian Ocean subtropical Dipole, according to Ikeda et al., (2017), directly affects southwestern Africa by modifying the moisture transported to that region.

Malahlela et al., (2018) focused on the months September to February, encompassing the spring and summer months, in Vhembe, a district in South Africa, for the period 1998-2013. These months are signified by the highest malaria cases. In addition, Malahlela et al., (2018) analyzed the global anomalies of SST, sea level pressure (SLP) and surface wind in relation to Vhembe. The authors found that the placement of the meridional dipole pattern in the southwestern Indian Ocean was different to other studies. The meridional dipole was also connected indirectly to the subtropical high. The subtropical high, also known as the Mascarene high, is a high-pressure zone in the South Indian Ocean with positive trends observed with sea surface temperature (Malahlela, 2018). (VIDYA; Global warming hiatus contributed weakening of the Mascarene High in the Southern Indian Ocean) The western side of the Mascarene High, near Madagascar, seems to experience an increase in intensification during positive dipole years, this means that the sea surface temperature of the Indian Ocean becomes warm south of Madagascar and cold east of Madagascar. This southwestern intensification of the Mascarene High leads to higher moisture convergence and above normal rainfall over Vhembe, Zimbabwe, and Mozambique. The implications of a higher moisture level and above normal rainfall, given a warm climate, was explained in the previous chapters.

Malahlela et al., (2018) observed a shift in malaria incidence rates after 2006 in Vhembe, South Africa. The decadal shift seen in malaria incidence was analyzed in relation to the decadal climate by analyzing climate patterns. The sea surface temperature anomalies changed to a warmer phase east of Madagascar, adjacent to the coasts of southern Africa. The dipole years were after 2006 negative, meaning that warm sea surface temperatures prevail east of Madagascar and cold sea surface temperatures prevail south of Madagascar, leading to a reduction in the amount of rainfall experienced over northeastern parts of South Africa, including Vhembe, and adjacent regions of

Madagascar after 2006. The change in sea surface temperature anomalies were associated with moisture divergence over these regions and moisture convergence over the warm waters Madagascar. However, there were still regional rainfall variations on year-to-year time scales. South Africa, for example, experienced in the period of 2008-2011 above normal rainfall. Generally, the decadal rainfall shift over southern Africa is associated with decadal sea surface temperature anomalies over the southwestern Indian Ocean near Madagascar. This means that prior to 2006, northeastern part of South Africa experienced more rainfall compared to the period after 2006. In essence, mosquitos thrive in the wet and humid climate conditions. An above normal increase in rainfall could lead to an increase in population growth, leading to higher malaria transmissions. This explains the reduction in malaria prevalence in Vhembe, showing the importance of climatic factors in addition to the non-climatic factors (Malahlela, 2018).

Large-scale climate phenomena influence various climatic variables, such as temperature, precipitation, wind, and moisture. These climatic variables in turn influence the vegetation. All these effects in turn add to increased malaria transmission, favorable breeding habitats and higher malaria incidence rates. Additionally, the climate of neighboring countries, potentially caused by Large-scale climate phenomena, also impacted the malaria incidence rates (Ikeda, 2017).

The table below shows the characteristics of the articles included in the review regarding large-scale climate phenomena. Additionally, it also show whether they assume a positive (+), negative (-) or no (NA) association between large-scale climate phenomena and malaria prevalence.

Table 5 Characteristics of the articles included in the review regarding large-scale climate phenomena.

Author	year	Title	analytical approach	Location	Association
Kulkarni et al.	2016	10 Years of Environmental Change on the Slopes of Mount Kilimanjaro and its Associated Shift in Malaria Vector Distributions.	Models consisted of Entomological and vector occurrence data	East	+
Malahlela et al.	2018	Evaluating Efficacy of Landsat-Derived Environmental Covariates for Predicting Malaria Distribution in Rural Villages of Vhembe District, South Africa	stepwise logistic regression model	South	+
Ikeda et al.	2017	Seasonally lagged effects of climatic factors on malaria incidence in South Africa.	Composite analysis	South	+
Agusto et al.	2015	Qualitative assessment of the role of temperature variations on malaria transmission dynamics.	mechanistic deterministic mod el for assessing the impact of t emperature variability on mala ria transmission dynamics	Gen	+
Abrha et al.	2018	Climate change impact on coffee and the pollinator bee suitable area interaction in Raya Azebo, Ethiopia.	general circulation models	East	+

3.6 The distribution of malaria

The effects of temperature, precipitation, geographical features, and large-scale climate phenomena on the prevalence of mosquito and larval development, and consequently on malaria incidence rates have been discussed. In this final chapter of the Results section, the effects of climatic variables on the distribution of malaria in the Africa continent will be discussed. This chapter will start off by discussing the distribution of malaria in East Africa. After which, the distribution of malaria in West Africa will be explored in detail, followed by the distribution of malaria in South Africa. At the end of this chapter, Central Africa will be explored. This enables the exploration of the distribution of malaria in Africa due to climatic effects to be more systematic and provides a clearer view of the present situation of the African continent.

The overwhelming majority of malaria burden is currently concentrated in Sub-Saharan Africa, where temperatures are expected to increase greater than the global average (Agusto, 2015). Kakmeni et al., (2018) looked at the precipitation data for all African countries over the period of 1901-1995. It indicates a nonuniform distribution in precipitation levels, where precipitation seems to be increasing in East Africa and decreasing in North and West Africa. In addition, the dry conditions in the horn of Africa also restrict malaria transmission (Ermert, 2012). This insinuates a variability in malaria prevalence in relation to climatic variables, such as precipitation. Climate plays a great role in the distribution of malaria prevalence, rendering previously unsuitable high-altitude habitats into sustainable habitats for mosquito populations. For instance, high altitude areas in Tanzania used to exhibit a low abundance of Anopheles arabiensis, however, the increase in temperature in the highlands due to deforestation and the decrease in wetness in the lowlands lead to an increase in mosquito density at the highlands over a period of 10 years (Kulkarni, 2016).

The prevalence of malaria in Tanzania, East Africa, is dependent on a series of climatic variables. Kulkarni et al., (2016) deems elevation as the primary predictor of Anopheles arabiensis distribution. When Kulkarni et al., (2016) studied the shift in Malaria vector distribution for the period of 2004-2014 in Tanzania, East Africa, it was apparent that suitability and mosquito density declined when altitude increased in 2004. Ten years after the initial study, this trend was still visible. Mosquito density experienced a decline in lowland areas, in contrast to highland areas where an increase in mosquito density was noted. In addition, a shift in land cover was noted. At high altitudes an increase in woody savannas, and grasslands was noted, while forests decreased in size. The decrease in forest land area, leading to higher temperatures, in combination with a decrease in wetness at low altitudes rendered the higher altitudes more favorable for mosquito development. The prevalence of the Anopheles arabiensis experienced a substantial decrease in range over the 10-year study period, with a net contraction of 325 km2 in predicted species range at lower altitudes (<900 m). In comparison, the prevalence of the Anopheles arabiensis experienced an increase in predicted range at higher elevations. The increase in predicted range at mid altitudes (901–1,000 m) was 219 km2 and 194 km2 at high altitudes (1,001–2,000 m) (Kulkarni, 2016). According to Parham et al., (2010), temperatures are expected to increase further, potentially increasing malaria incidence rates in Tanzania. In addition, the mean water temperatures of aquatic habitats in deforested areas in East Africa exhibit mean water temperatures that are 4.8–6.1°C higher than in forested areas. In addition, deforested areas cause an increase in humidity rate. The Anopheles arabiensis in the western Kenyan highlands experienced an increase in larval-to-adult survivorship by 65-82% due to an increase in mean water temperature and humidity rate. Additionally, larval development times in breeding sites located in farmlands were significantly shorter than natural swamps in the western Kenyan highlands. However, it should be noted that while the reproductive fitness increased, the mean survival rate decreased (Kweka, 2016). However, not all highlands are associated with increases in mosquito populations. The central highlands in Madagascar, similar to the highlands in eastern Africa, are characterized by very low malaria transmissions (Kakmeni, 2018). In addition, large-scale climate phenomena are also proven to be associated with the prevalence of malaria in Kenya (Malahlela, 2018). Flowing water in large rivers may not provide suitable larval habitats for African vector mosquitos, the smaller water bodies in adjacent bankside and floodplain areas can be highly productive. For instance, the Webi Juba and Webi Shabeelie rivers in Somalia are observed foci of malaria transmission, highlighting the importance of water bodies for mosquito development and the presence of malaria in Somalia (Smith, 2020).

Amadi et al., (2018) analyzed the relationship between climatic and environmental conditions and mosquito abundance, and focused on modelling the Anopheles gambiae distribution in Baringo County, in Kenya from December 2015 to December 2016. The impact of precipitation on the general wetness and vegetation is apparent in the central part of Baringo County. The central of Baringo County part is characterized by high precipitation and high topographic wetness but also exhibits low temperatures, rendering an unsustainable climate for mosquito development and leading to low malaria incidence. The lowland and riverine zones had, with slopes smaller than 7%, the highest Anopheles species density. The slope influences hydrological processes, these processes consist of area drainage, water velocity and water accumulation. In the western Kenyan highlands, the distribution of malaria exhibits high spatial variability. Sites of relative low altitude, below 1600 meters above sea level, malaria trends began to decrease in the late 1980s. Conversely, at higher altitudes, above 1600 meters above sea level, malaria transmission experienced an increase in intensity and variability in the 1980s and 1990s (Chaves, 2012).

West Africa is seen as a malaria endemic region (Kakmeni, 2018). The distribution of malaria in West Africa is, however, not uniformly distributed. There is a high incidence rate of malaria in southern West Africa. The southern part of West Africa consists of wetter parts and higher precipitation. Norther West Africa, however, has lower malaria incidence rates due to low precipitation and high temperatures, compared to southern West Africa. When wet conditions occur, the warm temperatures over the northern part of West Africa allow for a higher malaria incidence rate (Diouf, 2020). The northern part of West Africa consists of the Republic of The Gambia, Guinea-Bissau, Mauritania, Mali, Niger, and Senegal. Currently, these countries are drier and warmer than optimal for malaria transmission. An increase in precipitation in the northern part of West Africa would lead to more evaporative cooling. Conversely, a decrease in precipitation is associated by greater warming due to greenhouse gasses. The northern part of West Africa is associated with low mean annual rainfall, high temperatures (above optimal malaria transmission temperatures) and low malaria incidence rates. High temperatures and low precipitation limit the range of mosquitos, unable to develop and sustain growth here. Consequently, this leads to low prevalence in malaria incidences (Yamana, 2013; Diouf, 2020). According to Yamana et al., (2013), southern Mali and Burkina Faso do exhibit a high prevalence of malaria incidences. Southern part of the Mali and Burkina Faso have, compared to other northern parts of West Africa, temperatures optimal for mosquito development and average rainfall. In addition, the Niger and Senegal rivers in Mali and Senegal are also foci for malaria transmission (Smith, 2020).

The southern part of West Africa consists of Liberia, Sierra Leone Guinea, Côte d'Ivoire, Ghana, Togo, Benin, and Nigeria. These regions are signified by medium to high rainfall, ranging from 1000 mm/year to values above 2000 mm/year. Compared to northern West Africa, these regions exhibit high malaria prevalence due to temperature and precipitation enabling mosquito development (Yamana, 2013; Diouf, 2020). It should be noted that the Jos Plateau exhibits low transmission rates and shorter and delayed malaria seasons due to less-than-optimal temperatures for malaria transmission (Ermert, 2012). There are heterogeneities in the spatial variability of malaria prevalence. Malaria is, for example, more prevalent in Liberia compared to northern Guinea (Yamana, 2013; Diouf, 2020).

South Africa, similarly to central Angola (neighboring country), is presented as mostly malaria free, but the northeastern provinces and Maputo, capital of Mozambique, continue experiencing seasonal outbreaks threatening public health safety (Ikeda, 2017; Kakmeni, 2018).

Malaria is majorly endemic in three provinces, namely Limpopo, Mpumalanga, and KwaZulu-Natal. Occasionally there are few major outbreaks in Northern Cape and North-West provinces along the Orange and Molopo Rivers due to breeding habitats being present and enabling mosquito survivability. The prevalence of malaria in the provinces Limpopo, Mpumalanga, and KwaZulu-Natal is determined by climatic variables. The main climatic variables that are correlated against malaria incidences are temperature and precipitation. Temperatures shorten the incubation period of the parasite, shorten the larval development rate and to increase mosquito density. Precipitation on the other hand influences the aquatic stage of the mosquitos' life cycle and increases relative humidity to sustain the longevity of the adult mosquito. Consequently, optimal levels for mosquito survival and transmission are temperatures between 20 °C and 30 °C, relative humidity above 65 percent and cumulative average rainfall of about 400mm (Agusto, 2015). Malaria incidence is at its highest in January and at its lowest in the austral winter months, namely June, July, and August. In addition, large-scale climate phenomena also significantly impact the prevalence of malaria in these regions (Agusto, 2015; Adeola, 2019).

Besides large-scale climate phenomena and local climatic variables, warm temperatures and high precipitation in neighboring countries also influence the prevalence of malaria. Malaria in Limpopo is influenced by the prevalence of high precipitation and warm temperatures in neighboring countries like Mozambique (Agusto, 2015). Additionally, areas with a high likelihood of malaria occurrences are located in green vegetation environments, providing mosquito resting sites and refuges (Davies, 2016; Adeola, 2017).

In Limpopo years of high malaria cases seems to be preceded by early rainfall in the austral winter months. The early rainfall leads to an abundance of mosquito population in the months September, October, and November, highlighting the correlation between rainfall and malaria cases over the five districts of Limpopo. Malaria incidence rates are not uniformly distributed over Limpopo. Some districts experience higher malaria incidence rates than other districts. The Soutpansberg Mountain, located in the Vhembe district, is associated with an orographic effect causing the eastern region to receive more rainfall, influencing malaria transmissions. In addition, the Mopani and Vhembe districts also receive the most rainfall, with much of that rain being in the summer period, namely

December, January, and February (Adeola, 2019). Consequently, these two districts have had the highest malaria cases for the period of 1998-2017. The other three districts, namely Waterberg, Capricorn, and Sekhukhune, have very low malaria cases (Komen, 2015; Adeola, 2019).

In the low altitude areas of the northern and eastern parts of KwaZulu-Natal and Mpumalanga malaria is endemic. This is caused by rainfall patterns influenced by large-scale climate phenomena such as La Niña, El Niño, and the Indian Ocean Dipole (Malahlela, 2018). Furhtermore, large-scale climate phenomena such as La Niña cause convergence and above normal rainfall in Mozambique and Zimbabwe, influencing malaria prevalence (Malahlela, 2018). The distribution of malaria in Maputo, Mozambique, is similar to Limpopo, not uniformly distributed. The high malaria risk districts in 2001 were Moamba and Magude, compared to the low malaria risk zones Marracuene, Matutuine and Namaacha. Boane and Manhiça were categorized as medium risk zones.

Similar to West Africa, Central Africa can be seen as malaria endemic (Kakmeni, 2018; Ermert, 2012). The Democratic Republic of the Congo exhibits high risk of malaria, similar to that of Republic of the Congo, Central African Republic, Cameroon and Gabon (Kakmeni, 2018; Ermert, 2012). In addition, the Congo Basin in the Democratic Republic of the Congo has year-round malaria transmission (Ermert, 2012). Additionally, southwest of Cameroon is characterized by a high rate at which people are bitten by mosquitos and a strong year-to-year variability. However, the western part of Cameroon exhibits low malaria transmissions (Kakmeni, 2018). Mountainous areas also influence malaria distribution. The Adamawa Plateau leads to lower transmission, shorter and delayed malaria seasons, and diminished infection rates due to projected temperatures ≤ 20°C (Ermert, 2012).

The table below shows the characteristics of the articles included in the review regarding distribution. Additionally, it also show whether they assume a positive (+), negative (-) or no (NA) association between distribution of mosquitos and malaria prevalence.

Table 6 Characteristics of the articles included in the review regarding the distribution of malaria in Africa.

Author	year	Title	analytical approach	Location	Association
Kulkarni et al.	2016	10 Years of Environmental Change on the Slopes of Mount Kilimanjaro and its Associated Shift in Malaria Vector Distributions.	Models consisted of Entomological and vector occurrence data	East	+
Diouf et al.	2020	Climate Variability and Malaria over West Africa	The Liverpool Malaria Model	West	+
Chaves et al.	2012	Regime shifts and heterogeneous trends in malaria time series from Western Kenya Highlands.	Time series analysis	East	+
Zacarias et al.	2010	Mapping malaria incidence distribution that accounts for environmental factors in Maputo Province – Mozambique.	Parameter estimation and infe rence, using MCMC simulation techniques based on Poisson variation	East	+
Amadi et al.	2018	Mapping potential Anopheles gambiae s.l. larval distribution using remotely sensed climatic and environmental variables in Baringo, Kenya.	Negative binomial regression	East	+
Malahlela et al.	2018	Evaluating Efficacy of Landsat-Derived Environmental Covariates for Predicting Malaria Distribution in Rural Villages of Vhembe District, South Africa	stepwise logistic regression model	South	+

Yamana et al.	2013	Projected Impacts of Climate Change on Environmental Suitability for Malaria Transmission in West Africa	coupled a detailed mechanistic hydrology and entomology model with climate projections from general circulation models (GCMs)	West	+
Smith et al.	2020	Incorporating hydrology into climate suitability models changes projections of malaria transmission in Africa	Spatio-temporal method, Correlation analysis and econometric methods are applied	West	+
Kakmeni et al.	2018	Spatial panorama of malaria prevalence in Africa under climate change and interventions scenarios	dynamical mathematical netw ork model	General	+
Kweka et al.	2016	Effect of deforestation and land use changes on mosquito productivity and development in Western Kenya Highlands: implication for malaria risk.	one-way analysis of variance (ANOVA)	East	+
Ermert et al.	2012	The Impact of Regional Climate Change on Malaria Risk due to Greenhouse Forcing and Land-Use Changes in Tropical Africa	Liverpool Malaria Model (LMM)	Gen	+
Adeola et al.	2019	Rainfall Trends and Malaria Occurrences in Limpopo Province, South Africa	Annual and seasonal trends, as well as cross-correlation analyses, were performed on time series of monthly total rainfall and monthly malaria cases	South	+
Ikeda et al.	2017	Seasonally lagged effects of climatic factors on malaria incidence in South Africa.	Composite analysis	South	+
Agusto et al.	2015	Qualitative assessment of the role of temperature variations on malaria transmission dynamics.	mechanistic deterministic mod el for assessing the impact of t emperature variability on mala ria transmission dynamics	Gen	+
Adeola et al.	2017	Climatic Variables and Malaria Morbidity in Mutale Local Municipality, South Africa: A 19-Year Data Analysis.	Time series analysis	South	+
Davies et al.	2016	Effect of stable and fluctuating temperatures on the life history traits of Anopheles arabiensis and An. quadriannulatus under conditions of inter- and intra-specific competition.	Parametric ANOVAs	Lab	+
Komen et al.	2015	Long-Run Relative Importance of Temperature as the Main Driver to Malaria Transmission in Limpopo Province, South Africa: A Simple Econometric Approach.	Spatio-temporal method, Correlation analysis and econometric methods are applied	South	+

4. Discussion

Since the late 19th century, average global surface temperatures have increased by about 0.5◦C – 0.6◦C and due to tropical warming and this trend is expected to continue (Thomson, 2005). The overwhelming majority of malaria burden is currently concentrated in Sub-Saharan Africa, where temperatures are expected to increase greater than the global average (Thomson, 2005; Kakmeni, 2018). Millions of malaria infections each year are caused by the plasmodium group (Lüthi, 2015). This poses a significant health and economic thread.

Given that malaria poses a great economic and health threat to African countries in particular, it was imperative to analyse the current empirical literature regarding the relation between malaria distribution and climate change for policy makers and anyone affected by this. The objective of this master´s thesis was twofold. The first one was to review articles with the intention to understand the current literature, particularly how climate change has been conceptualized and operationalized in connection to malaria distribution. The second one consisted of discussing the main factors of climate variability that have been found to contribute to malaria transmission based on the empirical finding presented in the reviewed studies. Before the synthesis on the effects of climate change on malaria distribution could begin, a careful assessment of the available methods needed to be executed. Ultimately, we opted for a systematic literature review of the empirical studies, conducted conform the ROSES reporting standards for systematic evidence synthesis. With the use of predefined eligibility criteria, articles were found and analysed.

empirical evidence was collected to provide an answer to the initial question of this synthesis, what are the effects of climate change on the distribution of malaria. We followed a rigorous, objective, and transparent process to capture all relevant evidence relating to our research question. The methodology was reported explicitly to allow transparency and reproduction, minimizing bias, and maximizing objectivity. We broke down climate change into five points and studied the effects of these factors on malaria distribution. The four topics that were explored consisted of temperature, precipitation, geographical features, and large-scale climate phenomena. After exploring each variable in depth, the distribution of malaria was discussed. In the discussion we will summarize and discuss the findings of our systematic literature review separately for each variable, followed by related literature as to compare our finding, which will also be done separately for each variable. Finally, we will answer our research question.

4.1 Temperature

Climatically induced malaria is not present in all of the African continent due to malaria transmission being limited by climatic and regional variables (Ermert, 2012). For instance, the warmest areas are located over the northern part of West Africa, bordering the Sahara Desert (Diouf, 2020). These parts are signified by low malaria transmissions, potentially due to extreme temperatures and low precipitation. While an increase in temperature generally seems to induce higher malaria prevalence, this is not always the case. The Anopheles mosquitoes and the Plasmodium parasites both need certain temperatures to survive. (Ikeda, 2017) When this criteria is not met, the Anopheles species cannot survive, let alone increase in population. According to Adeola et al., (2019), Anopheles mosquitoes and the Plasmodium parasites both need temperatures above 16◦C and below 32◦C. According to Agusto et al., (2015) the optimal scenario for the Anopheles mosquito is between 20°C and 30°C. (Kakmeni, 2018) and (Adeola, 2019) argued that the optimal temperature for malaria transmission was 25◦C. Temperatures greater than 34◦C, however, have a negative effect on the survival rates of mosquitos. (Agusto, 2015) (Parham, 2010). Furthermore, the temperature range differs from one mosquito to another. For instance, the Anopheles arabiensis and Anopheles gambiae differed in survival rates; the survival rate of Anopheles arabiensis was higher than Anopheles gambiae when temperatures got between 30°C and 35°C (Davies, 2016). This temperature range is also supported by Kulkarni et al. (2016).

Temperature has multiple effects on mosquito development. An increase in temperature, up to a certain range, influences population growth. Paaijmans et al. (2010) showed that adding the projected increase of 3,2°C in temperature to the current air temperatures in Kenya significantly shortens larval development period, leading to an increase in population growth rates. According to (Agusto, 2015), an increase in temperature benefits the digestive system of mosquitos, allowing for faster digestion and shortening juvenile incubation period. Moreover, an increase in temperatures also translates to an increase in biting rates. During the summer period in Kwazulu- Natal the biting rate is much higher compared to the winter period, where temperatures are low (Abiodun, 2017).

The implications of temperature variability on mosquito and malaria prevalence are significant. Many studies in this synthesis have reported that mosquito and malaria prevalence is at its highest during the summer period, whereas the winter period is associated with the lowest values of mosquito and malaria prevalence. Additionally, the effects of temperature on transmission intensity are multifaceted, affecting transmission intensity, mosquito development rate, biting rate, survival of the parasite within the mosquito, adult mortality rate, eggs laid per adult female per day and egg-to-adult survival probability (Alfrane, 2012; Kakmeni, 2018). Increasing temperatures, however, do not intrinsically and immediately translate to an increase in mosquito populations and malaria incidence rates. There is a certain lag period involved, meaning that after a certain amount of time, the increase in heat will lead to an increase in malaria cases. This is due to the fact that an increase in temperature generally accelerates vector life cycles and decreases the incubation period of the parasite, this acceleration is capped at a certain temperature and very high temperatures could lead to a hindrance in the completion of the mosquito life cycle, making the occurrence of transmission not possible. (Komen, 2015; Ikeda, 2017).

It is clear that temperature is significantly associated with mosquito populations survivability and growth, and the prevalence of malaria. It is important to also note what future predictions are. Leedale et al. (2016) indicate that the majority of East Africa will experience an increase in temperature by at least 3 degrees Celsius by the 2080s, impacting malaria transmissions considerably. However, the authors noted that that there are large uncertainties regarding precipitation changes in the Democratic Republic of Congo and northern South Sudan. Yamana et al. (2013) predicted an increase between 2 and 6°C for the period 2080–2099 for West Africa. This could be counteracted by an increase in precipitation, leading to less warming due to more evaporative cooling. Alternatively, a decrease in precipitation is associated with an increase in temperatures.

It is clear that an increase in temperature increases the probability of mosquito emergence, and consequently the emergence of malaria, in regions that are currently not endemic. For instance, Parham et al., (2010) project increases in temperature in Tanzania. This translates to a guaranteed endemicity in previously unsuitable areas for transmission. These areas are the districts bordering the Democratic Republic of Congo, Malawi, Mozambique, and all coastal regions.

The main focus of this thesis has been the African continent but it is important to discuss the effects of temperature on the prevalence of mosquitos and malaria in other continents.

To illustrate the importance of temperature in the distribution of malaria, rising global temperatures are expected to shift the geographic range of malaria. Warmer conditions in Europe due to increased global average surface temperatures could enable large parts of Southern and South-Eastern

European areas as regions of high transmission stability in 2100 (Fischer, 2020). Additionally, Laneri et al. (2019) found a positive correlation between malaria prevalence and temperature in Salta, Argentina, where the effects of temperature are more pronounced above 25°C . Shapiro et al., (2017) showed that biting rate, adult mortality rate, parasite development rate, and vector competence are temperature sensitive with a temperature optimum for transmission of 26°C. These findings agree with our systematic literature study regarding the interplay between temperature and mosquito development, and, consequently malaria. Although the malariogenic potential is limited to mostly the African continent, the reintroduction of malaria into parts of Australia, the United States, and Southern Europe is still a risk to be considered due to imported cases of malaria, increases in global mean temperature and the availability of breeding sites of several Anopheles species (Martens, 1995). This means that malaria may only be temporarily limited to mostly the African continent. While future climatic predictions are not part of the objectives of this thesis, it helps in determining the importance of temperature in the prevalence of malaria.

The impact of temperature, one of the discussed climatic variables, is significant on the prevalence of malaria. In addition, temperature proves to be a critical variable in determining the distribution of malaria with multifaceted effects. Extreme temperatures hinder mosquito growth and malaria incidence rates, while other temperatures enable sustainable habitats for mosquito growth and malaria incidence rates. It should be noted that temperature alone may not be enough to increase population rates, as mosquitos are dependent on water.

4.2 Precipitation

Following temperature, another one of the factors relevant for malaria distribution that is also linked to climate change is precipitation. Precipitation is the second most prevalent among all studies.

When looked at precipitation data for all of African over the period of 1901-1995, it indicates that precipitation levels are not uniformly distributed and contains variability across the African continent. Precipitation in East Africa appears to be increasing, in contrast to the western and northern part of the continent, where it seems to be decreasing (Kakmeni, 2018). The heterogeneity in precipitation levels across Africa insinuates that some regions may be affected differently in the context of malaria prevalence in relation to climate variability.

Diouf et al. (2020) analyzed the seasonality in temperature and rainfall in West Africa and concluded that it is evident that the boreal summer comprised by the months July, August and September provided the highest mm in rainfall. Depending on the availability of temporary ponds, malaria transmission can continue after heavy rains and monsoon rains until the start of the dry season. The implications of precipitation on malaria prevalence in West Africa is significant and can lead to many months suitable for malaria transmission, indicating the prevalence of a lagged time. (Zacarias, 2010) Adeola et al. (2019)

Besides heavy rains and monsoon rains, temperature, following a rainy season, seems to also have an influence on the survival rate of mosquitos in East Africa by influencing the size of the parasite's reservoir.(Zacarias, 2010) There is a significant interplay between temperature and precipitation. This interplay allows for mosquito breeding habitats and malaria transmissions. Mosquitos and plasmodium parasites both need ideal temperatures and precipitation values to survive. Additionally, water temperatures are generally higher than ambient air temperatures (Paaijmans, 2010). An increase in ambient temperature also influences water temperatures, highlighting the interplay between ambient temperature and water temperature.

The presence of heavy precipitation does not immediately translate to an increase in transmission rates, there is a certain lag time before malaria transmissions increase. At 0-month and 1-month lag malaria transmissions are negatively correlated with rainfall. (Adeola, 2017) Mosquito habitats are potentially flushed out by heavy rains, decreasing mosquito populations and malaria incidences. However, after a certain time, there is a multitude of new water bodies. These new water bodies serve as excellent new habitats for mosquitos, given that temperature values are within the optimal ranges. Water bodies are associated with mosquito development (Smith, 2020). For instance, over southern Mozambique in East Africa, bordering South Africa, there is a positive correlation between precipitation and malaria incidence rate anomalies at a three-month lag (Ikeda, 2017). While water bodies are present due to rainfall, the amount of rainfall also determines the size of these water bodies, affecting population dynamics of juvenile mosquitos (Abiodun, 2017)

The implications of rain are multitudinous; the laying of mosquito eggs, the development to larvae, and the development into adults, all require aquatic breeding sites. Additionally, rainfall increases relative humidity to sustain the longevity of the adult mosquitos. The optimal scenario for the survival of the Anopheles mosquito and the plasmodium parasite is a temperature between 20 °C and 30 °C, a humidity above 65%, and adequate amount of rainfall (cumulative average of around 400 mm) (Agusto, 2015). Precipitation is not limited in affecting only mosquito population abundance and malaria incidence rates. Precipitation also impacts the general wetness and vegetation of an area, also affection malaria transmission (Amadi, 2018). For instance, the lowland areas in Tanzania typically have lower precipitation values compared to the highland areas, this in turn affects the vegetation indices, and, consequently malaria prevalence (Kulkarni, 2016).

It is imperative to analyze the results in light of related literature to determine if the results are valid for other parts of the world. Firstly it is important to make a distinction between the effects of temperature and precipitation. Temperature is a regulator of malaria transmission, since it directly affects the survival rate and the development of the mosquito, which was already discussed quite extensively. Precipitation on the other hand determines the availability of reproduction sites (Piperaki, 2016). The development from a larvae into adult mosquitos all require aquatic breeding sites, which is only possible through rainfall (Agusto, 2015). Highlighting this difference is important in understanding the effects of climatic variables on the distribution of malaria. This could potentially explain why some warm regions with low precipitation, for example North Africa, have few mosquito reproduction sites. While mosquitos could survive in regions where temperatures are not extreme, the need for reproduction sites is essential in malaria prevalence. Gao et al., (2012) tried to understand the re-emergence of malaria in the Anhui Province, China. They found that monthly incidences between 1990–2009 were significantly associated with temperature, rainfall, relative humidity, and El Niño patterns. According to Lingala et al., (2020) rainfall is considered one of the major determinants for malaria outbreaks and found significant associations between malaria outbreaks and rainfall in India. Guarda et al., (1999) also found positive correlations between malaria transmission periods and the Amazon River level and rainfall in the Peruvian Amazon region. The importance of rainfall in determining the prevalence and understanding the distribution of malaria concurs with the findings of this systematic literature review.

The implications of precipitation on the prevalence of malaria is, similar to temperature, multifaceted. In addition, similar to temperature there are lagged effects present (Adeola, 2019). This means that the onset of an event, such as an increase in precipitation, does not immediately translate to higher malaria incidences. Given that precipitation and temperature are both such significant climatic variables in determining the distribution and prevalence of malaria, it is imperative to underestimate the potential synergy between temperature and precipitation. It should be noted that precipitation predictions, compared to temperature predictions, are generally more difficult to produce (Yamana, 2013). Furthermore, both temperature and precipitation need to be in certain ranges in order for mosquitos to thrive (Abrha, 2018). Too extreme temperatures or little to no precipitation cause a negative effect on mosquito population growth rates. It is evident that mosquitos depend on temperature and precipitation for survival. Given that malaria incidence rates depend on mosquito populations, it is apparent that these climatic variables are strong predictors in determining the geographical prevalence of malaria. There are, however, still two variables left to discuss, namely large-scale climate phenomena and geographical features.

4.3 Geographical features

Up until now, the main focus has been set on temperature and precipitation. While these are one of the most discussed climatic variables in explaining the distribution of malaria in the African continent, there are other variables affecting malaria prevalence, providing valuable information on the distribution of malaria. Here we will focus on the geographical features of a region, these could exhibit certain characteristics limiting or enabling mosquito development and malaria prevalence. For instance, precipitation affects the general wetness and vegetation of an area, leading to potentially suitable habitats for mosquitos (Amadi, 2018). An example of this would be that the predicted suitability of the Anopheles arabiensis increases with the wet season vegetation index in East Africa (Kulkarni, 2016). Wet season vegetation indices also correlate with altitudes, declining at lower altitudes and increasing in higher altitudes (Kulkarni, 2016). Additionally, geographic features can influence climatic variables like precipitation and temperature. Adeola et al., (2019) argue that to explain the spatial variability of rainfall, it is important to analyse the topography of a region. In the Soutpansberg Mountain, which is located in South Africa and peaks at 1747 meters above sea level, the orographic effect is known to be causing an increase in rainfall in the eastern region, influencing malaria transmission. In addition, many studies in this systematic literature review noted the importance of elevation and altitude. It seems that mosquitos are now more prevalent in highland areas, compared to lowland areas (Ermert, 2012; Kulkarni, 2016).

Land cover changes and land use affect temperatures and the relative humidity of certain areas, providing higher survival rates for mosquitos, and, consequently leading to higher malaria incidence rates (Kweka, 2016). For instance, Deforestation affects the temperature and relative humidity of a region and creates sustainable habitats for the Anopheles mosquitos, and, consequently the development of malaria (Kulkarni, 2016). Additionally, different land cover types have different soil water input capacities, leading to varying mosquito abundance and malaria transmission rates.

Irrigation activities, croplands, and wetlands, for example, exhibit high Anopheles abundance, leading to year-round mosquito habitats in the lowlands (De Souza et al., 2010; Amadi, 2018).

A significant alteration of a certain type of land cover may enable an area, previously unsustainable, to be suitable for certain types of mosquitos. For instance, Cameroon, central Africa, saw the introduction of Anopheles gambiae into a habitat that used to be dominated by Anopheles moucheti due to deforestation (Davies, 2016). Ricotta et al., (2014) noted that a high probability of malaria distribution is associated with high ground cover, comprising of moist, riparian vegetation. Another foci for year-round malaria transmission are complex and large river networks. The Nile in particular has historically been regarded as a suitable mosquito breeding habitat, leading to many malaria outbreaks. The Niger and Senegal rivers in Mali and Senegal, and Webi Juba and Webi Shabeelie rivers in Somalia are similarly predicted as climatically suitable breeding habitats (Smith, 2020).

It is evident that malaria probability exhibits variability depending on the geographical features of a region. This could mean that environmental and climatic variability may explain the variation in malaria incidence rates across different regions (Adeola, 2019). Stefani et al., (2013) conducted a systematic literature review and identified seventeen studies characterizing land cover or land use features, and relating them to malaria in the Amazon subregion. They found that water and wetlands were a predominant risk factor for malaria transmission. They noted that water bodies that were not stagnant, were not suitable as breeding sites. Instead breeding sites were located at the banks only. This is in line with our findings. However, Stefani et al., (2013) also argued that agriculture areas showed contradicting results, whereas our findings suggest that agricultural areas are generally characterized by high malaria presence due to irrigation activities. Furthermore, they noted high malaria presence in deforested areas. In addition, aquatic habitats in deforested areas can, in some cases, exhibit mean water temperatures that are higher than forested areas (Amadi, 2018). This leads to increases in larval-to-adult survivorship, the shortening of the larval development rate, increases population size, shortening the parasitic development time and shortening the mosquitoes' gonotrophic cycle (Kweka, 2013; Amadi, 2018). The positive impact of deforestation on mosquito populations was also seen in Southeast Asia and Brazil (Zhong, 2016; Olson, 2010).

Our systematic literature review found that precipitation affected the general wetness and vegetation of an area. However, it is important to note that this relationship is not unidirectional, but rather bidirectional. For instance, changes in land-surface characteristics, according to Pielke et al., (2001), affect heat and moisture fluxes within the lowest part of our atmosphere. In addition, tropical deforestation also causes a reduction in evapotranspiration, leading to increased surface temperatures (Spracklen, 2018). This underscores the interplay between the different climatic variables. It is evident that land cover affects the prevalence of malaria significantly. Additionally, The spatial limitations of malaria due to geographical features may help in determining the effects of climate change on the distribution of malaria. The geographical features of a region could influence malaria in significant ways, contributing in explaining the distribution of malaria in the African continent.

4.4 Large-scale climate phenomena

Variations in malaria incidence rates are associated with large-scale climate phenomena, such as the El Niño Southern Oscillation, La Niña, Indian Ocean (subtropical) Dipole, tropical cyclones from the Mozambique Channel and sea surface temperature variabilities (Agusto, 2015; Kulkarni, 2016; Ikeda, 2017; Malahlela, 2018).

Large-scale climate phenomena impact global climates, leading to storms and droughts depending on the region. Generally, El Niño years are signified by below average malaria incidences in South Africa, contrary to the above average malaria incidences during the La Niña years (Malahlela, 2018). Agusto et al., (2015) concur and find that rainfall above normal and high malaria cases seem to be associated with positive sea surface temperature anomalies, La Niña conditions in the Pacific Ocean as well as tropical cyclones from the Mozambique Channel. Moreover, the results of Ikeda et al., (2017) agree with Malahlela et al., (2018) and Agusto et al., (2015) and provides evidence supporting a positive association between malaria incidence and large-scale climate phenomena, such as La Niña and positive Indian Ocean Subtropical Dipole patterns.

Ikeda et al., (2017) analyzed the Seasonally lagged effects of climatic factors on malaria incidence in South Africa for the period 1998-2014 and argues that wetter conditions in September at a two-months lag in Southeastern Mozambique are caused by La Niña patterns. Since mosquitos need sufficient support during their early aquatic life stages, the increase in rainfall leads to an increase in malaria cases. Furthermore, Ikeda et al., (2017) highlight that there are seasonal lagged effects of climatic factors from local regions and neighboring countries, that affect the timing and severity of malaria outbreaks in Limpopo (Ikeda, 2017). This could mean that an increase in malaria transmission rates due to Large-scale climate phenomena in one country could enhance malaria transmissions in a neighboring country.

It is possible that malaria incidences rise only after two to three months after a significant rainfall, caused by Large-scale climate phenomena (Agusto, 2015). The two-month lagged effect coincides with the malaria cycle, which consists of three components. The first being the growth of the Anopheles female mosquito. Followed by the development of the Plasmodium parasites and lastly, the incubation period in the human host. The implications of large-scale climate phenomena are not limited to a few months but could affect malaria transmissions in the following year. Additionally, periods of high rainfall due to La Niña, combined with adequate temperatures and relative humidity levels, could benefit saturated soil moisture content and cause water bodies to persist longer (Agusto, 2015). In the eastern side of the African continent the Indian Ocean Dipole significantly influences regional rainfall patterns and malaria incidence rates, being particularly prevalent in Kenya (Malahlela, 2018). Since mosquitos thrive in the wet and humid climate conditions, an above normal increase in rainfall could lead to an increase in population growth, leading to higher malaria transmissions (Malahlela, 2018). This highlights the significance of large-scale climate phenomena due to their impact on precipitation. However, large-scale climate phenomena are not limited to precipitation and can also influence humidity and moisture levels (Malahlela, 2018).

The importance of large-scale climate phenomena in the prevalence of malaria is not limited to Africa. The results of Hurtado et al., (2018) show that some malaria outbreaks in Guna Yala, northeast Panama, are associated with the El Niño–Southern Oscillation climate pattern (ENSO). In addition, Gagnon et al., (2002) found a statistically significant relationship between El Niño and malaria epidemics in Colombia, Guyana, Peru, and Venezuela. Kovats et al., (2003) also notes an association between El Niño and malaria in coastal regions of Venezuela and Colombia. The results Hashizume et al., (2012) argue that climatic anomalies other than the El Niño are associated with malaria outbreaks in the highlands in East Africa. Moreover, Hashizume et al., (2012) consider the Indian Ocean Dipole as a driving force in the resurgence of malaria in the East African highlands. Large-scale climate phenomena influence various climatic variables, such as temperature, precipitation, humidity, moisture and indirectly the vegetation. This underlines the importance of large-scale climate phenomena in explaining the distribution and prevalence of malaria.

4.5 The distribution of malaria

To answer our research question, it was imperative to discuss the effects of temperature, precipitation, geographical features, and large-scale climate phenomena on the prevalence of mosquito and larval development, and consequently on malaria incidence rate. However, to fully construct an answer to our research question, we need to discuss the distribution of malaria.

The overwhelming majority of malaria burden is currently concentrated in Sub-Saharan Africa, where temperatures are expected to increase greater than the global average (Agusto, 2015). When looked at the precipitation data for all African countries over the period of 1901-1995, it indicates a nonuniform distribution in precipitation levels, where precipitation seems to be increasing in East Africa and decreasing in North and West Africa (Kakmeni, 2018). Additionally, the dry conditions in the horn of Africa also restrict malaria transmission (Ermert, 2012). This suggest the importance of climatic variables in restricting malaria transmission in certain areas. However, climate could also render previously unsuitable regions into sustainable habitats for mosquito populations.

Amadi et al., (2018) analyzed the relationship between climatic and environmental conditions and mosquito abundance, and focused on modelling the Anopheles gambiae distribution in Baringo County, in Kenya, East Africa. While the center part of Baringo Country high precipitation and high topographic wetness, the temperatures are low. This could mean that in order for mosquitos populations to grow, all climatic variables need to be within certain ranges. This also implies that one variable alone is not optimal in predicting the distribution of mosquitos in a certain area due to mosquitos being dependent on a variety of variables. The distribution of mosquitos also shows variability when different altitudes are taken into consideration. For instance, Kulkarni et al., (2016) noted that the Lowland areas in Tanzania experienced a decline in mosquito density, while highland areas experienced an increase in mosquito density. In the case of Baringo Country, the lowland and riverine zones had highest Anopheles species density. Additionally, high altitude areas used to show low presence of Anopheles arabiensis, however, the central Kenyan highlands, in the range of 1720-1921 meters above sea level, now show presence of the Anopheles arabiensis. It should be noted that not all highlands are associated with increases in mosquito populations. The central highlands in Madagascar, similar to the highlands in eastern Africa, are characterized by very low malaria transmissions (Kakmeni, 2018). Deforestation also enables certain areas in East Africa to provide suitable habitats for mosquitos, due to elevated humidity rates, ambient temperatures, water temperatures and rainfall values (Parham, 2010). Additionally, deforestation can increase larval productivity, accelerate larval development time, and increase larval pupation rate as well as adult emergence rate (Kweka, 2016). Furthermore, the distribution of mosquitos and malaria is also affected by the availability of water bodies. For instance, the Webi Juba and Webi Shabeelie rivers in Somalia are observed foci of malaria transmission.

In the endemic region of West Africa, malaria is not uniformly distributed (Kakmeni, 2018). The northern part of West Africa has lower malaria incidence rates due to low mean annual precipitation values and high temperatures (Yamana, 2013; Diouf, 2020). However, southern Mali and Burkina Faso do exhibit high malaria incidences (Yamana, 2013). In addition, the Niger and Senegal rivers in Mali and Senegal are also foci for malaria transmission. The southern part of West Africa consists of wetter parts and higher precipitation and exhibits high malaria prevalence due to temperature and precipitation enabling mosquito development (Yamana, 2013; Diouf, 2020). It is evident that there are heterogeneities in the spatial variability of malaria prevalence, this means that not all regions experience malaria in the same way.

South Africa, similarly to central Angola (neighboring country), exhibits low malaria incidence rates, however, northeastern provinces of South Africa and Maputo, capital of Mozambique, still experience seasonal outbreaks. Malaria in South Africa is majorly endemic in three provinces, namely Limpopo, Mpumalanga, and KwaZulu-Natal. The highest malaria cases in Limpopo are concentrated in the Mopani and Vhembe districts. These districts also receive the highest amount of rainfall, compared to the other districts in Limpopo. The other three districts, namely Waterberg, Capricorn, and Sekhukhune, have very low malaria cases. The distribution of malaria in Maputo, Mozambique, is similar to Limpopo, not uniformly distributed. The high malaria risk districts in 2001 were Moamba and Magude, compared to the low malaria risk zones Marracuene, Matutuine and Namaacha. Boane and Manhiça were categorized as medium risk zones.

Similar to West Africa, Central Africa can be seen as malaria endemic (Ermert, 2012; Kakmeni, 2018).

The Democratic Republic of the Congo, Republic of the Congo, Central African Republic, northern parts of Angola and Gabon exhibits high risk of malaria (Ermert, 2012; Kakmeni, 2018). In addition, the Congo Basin in the Democratic Republic of the Congo has year-round malaria transmission. Furthermore, southwest of Cameroon is characterized by a high rate at which people are bitten by mosquitos and a strong year-to-year variability (Ermert, 2012). However, Western Cameroon, similar to Central Angola, is characterized by very low malaria transmissions (Kakmeni, 2018). Mountainous areas also influence malaria distribution. The Adamawa Plateau leads to lower transmission, shorter and delayed malaria seasons, and diminished infection rates (Ermert, 2012).

According to Sinka et al., (2012), the three primary Anopheline vectors in the African continent are the Anopheles gambiae, Anopheles funestus and the Anopheles arabiensis, which confirms the findings in our systematic literature review. After performing a systematic literature review, it is now clear that malaria is not uniformly distributed across all African countries. North and South Africa experience the least amount of malaria incidence rates, while East, West and Central Africa experience the most amount of malaria incidence rates. In the beginning of this systematic literature review it was said that the burden of malaria is disproportionately located in the African continent.

According to Na-Bangchang et al., (2007), the highest malaria burden is located in Sub-Saharan Africa, however, Southeast Asia, the Pacific Islands, India and Central and South America also share, to a lesser extent, the disease burden.

According to Manguin et al., (2008) the Anopheles minimus, which is considered one of the main malaria vectors in hilly regions in the Oriental Region, is present in northern India, Myanmar, Thailand, Laos, Cambodia, Vietnam, southern China, and Taiwan. Ren et al., (2016) concur with the presence of malaria in the aforementioned regions. In Laos the seasonal malaria peak coincides with the rainy season, indicating the importance of precipitation in the presence of malaria (Pholsena, 1992). It should be noted that Thailand is mostly malaria free, the border region shared with Myanmar, however, is an endemic area (Parker, 2015). The landscape of the border region consists of watersheds, river basins and valleys. In addition, agricultural fields and plantations are also present (Parker, 2015). In addition, temperatures in Myanmar are positively influenced by large-scale climate phenomena, such as the positive phase of the Indian Ocean Dipole and ENSO (Mie Sein, 2021). In our systematic literature review we discussed the importance of water presence and adequate temperatures in the development of mosquitos and the impact of large-scale climate phenomena on local climates, which seems to remain valid in other parts of the world.

The distribution of malaria incidence in India, according to Kumar et al., (2007), is not uniformly distributed. Most of the malaria incidences occur in the northern parts of India, and to a lesser extend in the western part of India. Bhattacharya et al., (2006) tried to establish the conditions conductive to malaria transmission and found that average relative humidity range (55 to 80 per cent) coincided with maximum number of malaria cases occurring between May to October. Additionally, the average temperature remains between the range of 15 to 30°C throughout the year, which enables malaria transmissions. However, Bhattacharya et al., (2006) did not find a correlation between rainfall and malaria cases. They argue that when rainfall values drop significantly, malaria still persist. In our systematic literature review, it was argued that the effects of precipitation and temperature are in some cases not immediate. This means that lagged effects could impact the prevalence of malaria. In China the distribution of malaria is limited to the southeastern provinces (Ren, 2016). The prevalence of malaria is, similar to our systematic literature review, correlated with precipitation, humidity and temperature values (Bi, 2003).

In Central America malaria is prevalent in Guatamala, Panama and Honduras, with limited presence in Mexico (Arevalo-Herrera, 2012). When looked at the current distribution of malaria in Latin America, the overwhelming majority of malaria cases occur in Brazil. The remaining malaria cases occur in Colombia, Peru, Venezuala, Bolivia and Ecuador (Arevalo-Herrera, 2012). While spatial distribution of the different mosquito types varied, malaria was associated with higher temperatures across South America. Moreover, the presence of water and wetlands were a predominant risk factor for malaria transmission (Stefani, 2013).

While the burden of malaria is most notable in the African continent, it is not limited to Africa. Malaria poses a significant risk on numerous countries all around the globe.

Before analysing the effects of climate change on the distribution of malaria, we started this systematic literature review by breaking climate change down into four major parts, namely temperature, precipitation, geographical features, and large-scale climate phenomena. We analyzed the effects of these variables on the prevalence of malaria to understand what drives mosquito population growth and malaria incidence rate. We found that these variables had a significant effect on mosquito population dynamics and the prevalence of malaria.

Temperature regulates malaria transmission due to it directly affecting the survival rate and development of the mosquito. Extreme temperatures can hinder development, in contrast to moderate temperatures enabling or enhancing development, shortening the larval development period, benefiting the digestive system of mosquitos allowing for faster digestion and shortening juvenile incubation, increasing biting rates, accelerating vector life cycles, decreasing the incubation period of the parasite, affecting transmission intensity, adult mortality rate, eggs laid per adult female per day, and egg-to-adult survival probability (Parham, 2010; Paaijmans, 2010; Komen, 2015; Agusto, 2015; Piperaki, 2016; Abiodun, 2017; Ikeda, 2017; Kakmeni, 2018; Diouf, 2020)

The effects of temperature are multifaceted, however, temperature alone may not be enough in determining malaria prevalence. Precipitation is, similar to temperature, essential but focusses more on enabling the availability of reproduction sites (Piperaki, 2016). For instance, the development from a larvae into adult mosquitos requires aquatic breeding sites, which is only possible through rainfall (Agusto, 2015). Moreover, precipitation influences the laying of mosquito eggs, the size of the parasite's reservoir, development to larvae, general wetness and vegetation of an area, puddle size, amount of available water bodies, and relative humidity. This could explain the low presence of malaria in warm regions with low precipitation values, for example north Africa (Zacarias, 2010; Piperaki, 2016; Abiodun, 2017; Agusto, 2015; Amadi, 2018). The effects of precipitation and temperature are generally not immediately visible due to lagged effects. Some time, usually more than one month, needs to pass before malaria can manifest in a region. The lag time is a timeframe where the vector-parasite-host cycle can be developed and completed (Komen, 2015; Ikeda, 2017; Adeola, 2017).

In addition to temperature and precipitation, the geographical features of a region also influence malaria prevalence. The topography of a region, the presence of rivers, the orographic effect, elevation and altitude, the wetness of vegetation, and Land cover and land use changes, all impact (indirectly) the prevalence of malaria (Pielke Sr, 2001; Komen, 2015; Kulkarni, 2016; Adeola, 2019). While we discussed the importance of precipitation and temperature, it is important to note the interdependency between the aforementioned two climatic variables and geographic features. For instance, Land cover changes could influence temperatures, heat fluxes and moisture fluxes in the lowest part of the atmosphere, the relative humidity, evapotranspiration, and mean water temperatures (Pielke Sr, 2001; Davies, 2016; Kulkarni, 2016; Amadi, 2018; Spracklen, 2018):

The last part consists of large-scale climate phenomena, such as the El Niño Southern Oscillation, La Niña, Indian Ocean (subtropical) Dipole, tropical cyclones from the Mozambique Channel and sea surface temperature variabilities (Agusto, 2015; Kulkarni, 2016; Ikeda, 2017; Malahlela, 2018). They exert influence over global climates, leading to storms, droughts, rainfall anomalies, changes in humidity and moisture levels, temperatures, and persistence and the quantity of water bodies

(Agusto, 2015; (Ikeda, 2017; Malahlela, 2018). It is clear that large-scale climate phenomena indirectly impact malaria distribution and prevalence.

After the variables were explored in depth, the distribution of malaria was discussed to provide a clear picture of the current distribution of malaria in the African continent. The overwhelming majority of malaria burden is currently concentrated in Sub-Saharan Africa (Thomson, 2005). North and South Africa presented the lowest number of malaria cases, in contrast to East, West and Central Africa, where malaria has a strong impact and presence. We found that malaria endemic areas provided suitable climatic environments for mosquito and malaria development.

Our systematic literature review highlights the importance of climate change in the distribution of malaria. Our results were in line with related research, giving us confident in our conclusion.

5 Conclusions

Our systematic literature review provided the necessary insight in the current body of literature regarding the effects of climate change on the distribution of malaria. Each variables was extensively analysed. Our systematic literature review showed the importance of Temperature on the survivability of mosquitos and malaria. Precipitation, however, was needed in the aquatic stages of the development. This means that temperature and precipitation are both essential in the survival of mosquitos and the prevalence of malaria. In Addition, the effects of the geographical features and large-scale climatic phenomena on temperature and precipitation was also analysed. Furthermore, we showed the interplay between these variables. This underlines the complex mechanisms of the effects of climatic variables. In conclusion, climate plays an essential and direct role in the distribution of malaria. Policy makers should use this systematic literature review to understand that the distribution of malaria dependent on climate change, however, it should be noted that the implications of climate change are multifaceted, making this no easy task. Additionally, this systematic literature review provides insights in the current distribution of malaria in the African continent. This means that policy makers could use this to find the endemic areas and the causes.

There were, however, some limitations. When we analysed the effects of climate on the distribution of malaria, we did not take mosquito control measure into consideration. Some of these control measures are pesticides, indoor residual spraying, and insecticidal nets. The importance of these control measures should not be forgotten as they can influence the prevalence of malaria significantly. Other factors include economic and social factors such as population movement, housing conditions, drug and insecticide resistance and sanitation condition. These factors could alter the distribution of malaria in Africa significantly.

6 References

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7 Appendix

Table 7 All excluded articles

Articles not included after screening title and abstract screening
A comparative molecular survey of malaria prevalence among Eastern chimpanzee populations in Issa Valley (Tanzania) and Kalinzu (Uganda)
A Major Role for the Plasmodium falciparum ApiAP2 Protein PfSIP2 in Chromosome End Biology
A Research Agenda for Microclimate Ecology in Human-Modified Tropical Forests
Altitude, temperature, and malaria vectors in Nainital and Udham Singh Nagar districts of Uttarakhand, India: An evidence-based study
Altitudinal variation in haemosporidian parasite distribution in great tit populations
Analysis of the El Nino/La Nina-Southern Oscillation variability and malaria in the Estado Sucre, Venezuela
Anopheline mosquitoes in District Ramgarh (Jharkhand), India
Assessing socioeconomic vulnerability to dengue fever in Cali, Colombia: statistical vs expert-based modeling
Avian Haemosporidian Diversity on Sardinia: A First General Assessment for the Insular Mediterranean
Avian haemosporidians in the cattle egret (Bubulcus ibis) from central-western and southern Africa: High diversity and prevalence
Avian malaria in Hawaiian forest birds: infection and population impacts across species and elevations
BRAZILIAN MOSQUITO (DIPTERA: CULICIDAE) FAUNA. I. Anopheles SPECIES FROM PORTO VELHO, RONDONIA STATE, WESTERN AMAZON, BRAZIL
Changes in malaria burden and transmission in sentinel sites after the roll-out of long-lasting insecticidal nets in Papua New Guinea
Changing Patterns of Malaria in Grande Comore after a Drastic Decline: Importance of Fine-Scale Spatial Analysis to Inform Future Control Actions
CHARACTERIZATION OF THE LARVAL BREEDING SITES OF ANOPHELES BALABACENSIS (BAISAS), IN KUDAT, SABAH, MALAYSIA
Climate change increases the risk of malaria in birds
Climate Change Influences Potential Distribution of Infected Aedes aegypti Co-Occurrence with Dengue Epidemics Risk Areas in Tanzania
Climate-based seasonality model of temperate malaria based on the epidemiological data of 1927-1934, Hungary
Comparative physiological plasticity to desiccation in distinct populations of the malarial mosquito Anopheles coluzzii
Comparison of climatic factors on mosquito abundance at US Army Garrison Humphreys, Republic of Korea
Comparison of malaria incidence rates and socioeconomic-environmental factors between the states of Acre and Rondonia: a spatio-temporal modelling study
Composition of Anopheline (Diptera: Culicidae) Community and Its Seasonal Variation in Three Environments of the City of Puerto Iguazu, Misiones, Argentina
Detecting transmission areas of malaria parasites in a migratory bird species
Determinants of avian malaria prevalence in mountainous Transcaucasia
Distribution of mosquito larvae in various breeding sites in National Zoo Malaysia
Distribution, diversity and drivers of blood-borne parasite co-infections in Alaskan bird populations
Diversity of anopheline mosquitoes (Diptera: Culicidae) and classification based on the characteristics of the habitats where they were collected in Puerto Iguazú, Misiones, Argentina
Do blood parasites infect Magellanic penguins (Spheniscus magellanicus) in the wild? Prospective investigation and climatogeographic considerations

Drivers of community turnover differ between avian hemoparasite genera along a North American latitudinal gradient
Ecological characterization and molecular differentiation of Culex pipiens complex taxa and Culex torrentium in eastern Austria
Ecological Drivers of Mansonella perstans Infection in Uganda and Patterns of Co-endemicity with Lymphatic Filariasis and Malaria
Ecological Niche Modeling and Land Cover Risk Areas for Rift Valley Fever Vector, Culex tritaeniorhynchus Giles in Jazan, Saudi Arabia
Effect of land use and land cover modification on distribution of anopheline larval habitats in Meghalaya, India
Effects of habitat suitability for vectors, environmental factors and host characteristics on the spatial distribution of the diversity and prevalence of haemosporidians in waterbirds from three Brazilian wetlands
El Ni(n)over-tildeo Southern Oscillation as an early warning tool for malaria outbreaks in India
Emerging vector-borne zoonoses: eco-epidemiology and public health implications in India
Environmental modelling for health
Environmental risk factors and hotspot analysis of dengue distribution in Pakistan
Environmental Temperature Affects Prevalence of Blood Parasites of Birds on an Elevation Gradient: Implications for Disease in a Warming Climate
Field evaluation of synthetic lure (3-methyl-1-butanol) when compared to non odor-baited control in capturing Anopheles mosquitoes in varying land-use sites in Madagascar
Fine-scale distribution modeling of avian malaria vectors in north-central Kansas
Gene silencing through RNAi and antisense Vivo-Morpholino increases the efficacy of pyrethroids on larvae of Anopheles stephensi
Genetic characterization of Plasmodium falciparum allelic variants infecting mothers at delivery and their children during their first plasmodial infections
Geographical information system (GIS) modeling territory receptivity to strengthen entomological surveillance: Anopheles (Nyssorhynchus) case study in Rio de Janeiro State, Brazil
Geographical variation of haemosporidian parasites in Turkish populations of Kruper's Nuthatch Sitta krueperi
Geospatial tools for the identification of a malaria corridor in Estado Sucre, a Venezuelan north-eastern state
High-accuracy detection of malaria vector larval habitats using drone-based multispectral imagery
Histone 4 lysine 8 acetylation regulates proliferation and host-pathogen interaction in Plasmodium falciparum
HLA-G expression during hookworm infection in pregnant women
Host species, and not environment, predicts variation in blood parasite prevalence, distribution, and diversity along a humidity gradient in northern South America
Housing type and risk of malaria among under-five children in Nigeria: evidence from the malaria indicator survey
Human exposure to zoonotic malaria vectors in village, farm and forest habitats in Sabah, Malaysian Borneo
Human-Induced Expanded Distribution of Anopheles plumbeus, Experimental Vector of West Nile Virus and a Potential Vector of Human Malaria in Belgium
Identification of Environmental Covariates of West Nile Virus Vector Mosquito Population Abundance
Impact of climate variability on Plasmodium vivax and Plasmodium falciparum malaria in Yunnan Province, China
Implications for changes in Anopheles darlingi biting behaviour in three communities in the peri-Iquitos region of Amazonian Peru
Infectious Diseases and Climate Vulnerability in Morocco: Governance and Adaptation Options
Insecticide resistance status of Aedes aegypti and Aedes albopictus mosquitoes in Papua New Guinea

Intensive trapping of blood-fed Anopheles darlingi in Amazonian Peru reveals unexpectedly high proportions of avian blood-meals
Investigation of Ctenocephalides felis on domestic dogs and Rickettsia felis infection in the Democratic Republic of Sao Tome and Principe
Kerteszia cruzii and extra-Amazonian malaria in Brazil: Challenges due to climate change in the Atlantic Forest
Landscape ecology and epidemiology of malaria associated with rubber plantations in Thailand: integrated approaches to malaria ecotoping
Larval habitat characterization of Anopheles darlingi from its northernmost geographical distribution in Chiapas, Mexico
Larval habitats of Anopheles species in a rural settlement on the malaria frontier of southwest Amazon, Brazil
Larvicidal Activities of 2-Aryl-2,3-Dihydroquinazolin-4-ones against Malaria Vector Anopheles arabiensis, In Silico ADMET Prediction and Molecular Target Investigation
Latitudinal gradients of haemosporidian parasites: Prevalence, diversity and drivers of infection in the Thorn-tailed Rayadito (Aphrastura spinicauda)
Little pigeons can carry great messages: potential distribution and ecology of Uranotaenia (Pseudoficalbia) unguiculata Edwards, 1913 (Diptera: Culicidae), a lesser-known mosquito species from the Western Palaearctic
Malaria in India: The Center for the Study of Complex Malaria in India
Malaria Prevalence, Risk Factors and Spatial Distribution in a Hilly Forest Area of Bangladesh
Malaria risk assessment and mapping using satellite imagery and boosted regression trees in the Peruvian Amazon
Malaria surveillance-response strategies in different transmission zones of the People's Republic of China: preparing for climate change
Malaria vector research and control in Haiti: a systematic review
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The dominant Anopheles vectors of human malaria in Africa, Europe and the Middle East: occurrence data, distribution maps and bionomic précis
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