

5. Relevant temperatures in mosquito and malaria biology

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Abstract

Most biological process-based models that approximate malaria risk use mean (usually monthly) outdoor air temperature to estimate the various mosquito and parasite life history variables that influence disease transmission intensity. However, mosquitoes, and parasites within them, do not experience 'average temperatures', but are exposed to temperatures that can fluctuate considerably throughout the day. In addition, endophilic mosquitoes will be exposed to indoor temperatures and not directly to outdoor air temperature. Further, mosquito larvae live in aquatic habitats and so again, are not exposed directly to outdoor air temperatures. In this chapter we highlight how these different temperatures can all change malaria risk predictions. To understand malaria dynamics, inform operational control objectives and predict consequences of climate change, we need a better mechanistic understanding of vector-parasite interactions, with improved integration of the biological and environmental parameters at a scale relevant to conditions actually experienced by both mosquitoes and malaria parasites.

Keywords: *Anopheles* vectors, *Plasmodium* malaria, aquatic habitats, daily temperature variability, ectotherms, climate change

Introduction

A proper understanding of the basic biology and ecology of both mosquito vectors and malaria parasites is a prerequisite for development of effective and sustainable malaria control (e.g. Chaves and Koenraadt 2010, Ferguson *et al.* 2010, Marsh 2010). Given the global impact of malaria, it is rather surprising that after more than 100 years of malaria research the mechanistic link between environmental variables, such as temperature, and the risk of malaria remains poorly defined (Lafferty 2009, Paaijmans *et al.* 2009b, 2010b, Pascual *et al.* 2009).

The influence of temperature on malaria can be explored by the basic reproductive number (R_0), which defines the number of cases of a disease that arise from one case of the disease introduced into a population of susceptible hosts. R_0 is commonly described by the formula (Rogers and Randolph 2006):

$$R_0 = \frac{1}{r} \left[\frac{ma^2bc p^{EIP}}{-\ln p} \right] \quad (1)$$

where m is the vector:human ratio, a vector biting frequency, bc transmission coefficients defining vector competence, p daily vector survival rate, EIP the extrinsic incubation or development period of the parasite within the vector, and r the recovery rate of the vertebrate hosts from infection.

Given that 6 out of 7 of these parameters relate in some way to mosquito abundance, ecology or physiology and that mosquitoes are small ectotherm insects, it is clear that the transmission intensity of malaria will be strongly influenced by environmental temperature (see e.g. Craig *et al.* 1999, Guerra *et al.* 2008, Harvell *et al.* 2002, Parham and Michael 2010, Patz and Olson 2006, Rogers and Randolph 2006).

In general, ectothermic performance across temperature is traditionally summarized as a nonlinear asymmetric curve (Brière *et al.* 1999, Lactin *et al.* 1995, Logan *et al.* 1976). This nonlinear relationship has been described for various malaria mosquito and parasite life-history characteristics, such as immature mosquito development (Bayoh and Lindsay 2003), length of the gonotrophic cycle (Lardeux *et al.* 2008) and parasite development time (Ikemoto 2008, Paaijmans *et al.* 2009b) (Figure 1).

Most biological process-based models that approximate malaria risk use mean (usually monthly) outdoor air temperature to estimate various variables that influence disease transmission intensity (Craig *et al.* 1999, Guerra *et al.* 2008, Guerra *et al.* 2010, Killeen *et al.* 2000, Martens *et al.* 1999, Rogers and Randolph 2000). The aim of this chapter is to critically revisit this approach by exploring whether outdoor mean air temperature is the appropriate environmental driver for understanding different aspects of mosquito and parasite biology. Specifically, for traits relating to the adult mosquitoes we consider the influence of mean vs. variable temperatures and outdoor vs. indoor temperatures. Additionally, for the juvenile mosquitoes we consider the influence of air vs. water temperatures.

Overview of methods

Temperature-dependent physiological models

We use two types of temperature-dependent models (i.e. the widely-applied linear rate models and nonlinear asymmetric thermodynamic models (Figure 1)) to compare the effects of these different environmental metrics on various mosquito/malaria life history traits that influence malaria transmission, considering both current and future climate scenarios (note we consider climatic change to include changes in local conditions due to factors such as deforestation (Afrane *et al.* 2008, Lindblade *et al.* 2000) or changes in building structure (Atieli *et al.* 2009, Okech *et al.* 2004a,b)).

To examine the effects of temperature on mosquito/parasite life history traits we used a range of published thermal performance curves (Figure 1). For malaria parasite development we compared

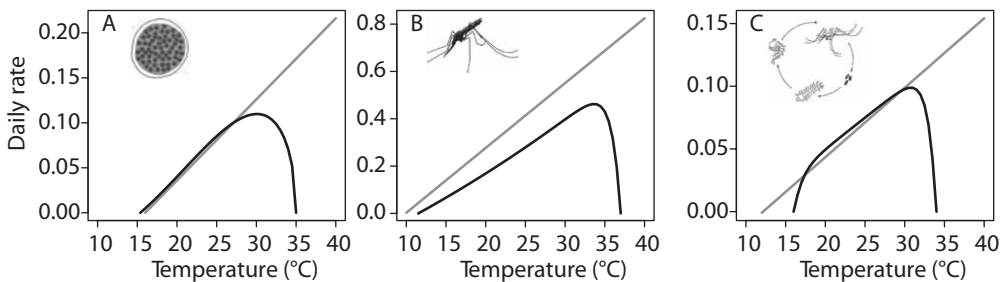


Figure 1. Published thermal performance curves showing the relationship between temperature (in °C) and (A) parasite development rate, (B) the inverse of the gonotrophic cycle length, (C) larval development rate. Grey lines show linear thermal performance curves presented by (A, B) Detinova (1962) and (C) Craig *et al.* (1999). Black lines represent the non-linear thermal performance curves presented by (A) Paaijmans *et al.* (2009b), (B) Lardeux *et al.* (2008) and (C) Bayoh and Lindsay (2003).

the linear rate model of Detinova (1962) with the equivalent non-linear thermodynamic model of Paaijmans *et al.* (2009b). For the gonotrophic cycle (or feeding frequency) we used the linear rate model of Detinova (1962) and the non-linear thermodynamic model of Lardeux *et al.* (2008). Finally, for larval development we compared the linear rate model of Craig *et al.* (1999) with the non-linear thermodynamic model of Bayoh and Lindsay (2003).

Rates were calculated at 30 min intervals using either the mean temperature, or the actual temperature at that given time-point (see below). Growth rates were accumulated until they reached a value of 1, which defines the completion of the rate process (see Paaijmans *et al.* 2009b).

Environmental temperature data

The minimum and maximum air temperature data used in the Section 'Mean vs. variable temperature' were obtained from the National Climatic Data Center (<http://www.ncdc.noaa.gov/oa/mpp/freedata.html>). Mean monthly air temperature and mean monthly daily temperature range (DTR) were calculated at five met-stations (Kericho, Nakuru, Kisumu, Voi and Khartoum) in East Africa for March 2001. The indoor and outdoor minimum and maximum temperature data that are used in the Section 'Outdoor vs. indoor temperature' were recorded in Tanzania by Bødker *et al.* (2003). Air temperatures and water temperatures reported in the Section 'Water vs. air temperature' were derived from the studies of Paaijmans *et al.* (2008, 2010a).

Modeling daily temperature variation between minimum and maximum temperatures

The phase and form of the diurnal rhythm of the air temperature (T) is given by a sinusoidal progression during daytime (Equation 2) and a decreasing exponential curve during the night (Equation 3) (Parton and Logan 1981):

$$T = T_{min} + (T_{max} - T_{min}) \sin \left[\pi \frac{t - 12 + D/2}{D + 2p} \right] \quad (2)$$

for $t_{rise} \leq t < t_{set}$

$$T = \frac{T_{min} - T_{set} \exp(-N/\tau) + (T_{set} - T_{min}) \exp(-(t - t_{set})/\tau)}{1 - \exp(-N/\tau)} \quad (3)$$

for $t_{set} \leq t < t_{rise}$

where T_{min} and T_{max} (°C) are the minimum and maximum daily air temperature, respectively, t (hours) the time, D (12 hours) the daylength, p (hours) the time duration between solar noon and maximum air temperature, t_{rise} (hours) the time of sunrise, t_{set} (hours) the time of sunset, T_{set} (°C) the temperature at sunset, N (hours) the duration of the night and τ the nocturnal time constant.

Using the reported minimum and maximum temperatures in the Sections 'Mean vs. variable' and 'outdoor vs. indoor' temperature, we modeled the air temperature at 30 min intervals. Mean temperatures are calculated with these 30 min interval data, and not by taking the mean of the minimum and maximum temperature.

Effects of temperature on transmission intensity (basic reproduction rate) of malaria

Temperature affects multiple parameters that comprise R_0 . However, for simplicity, in the following sections we consider changes in single parameters only. In Sections 'Mean vs. variable' and 'outdoor vs. indoor' temperature we consider the extrinsic incubation period and feeding frequency (the latter is given by the inverse of the gonotrophic cycle length). Unless stated, we follow others and assume a median daily mosquito survivorship of 0.860 (Kiszewski *et al.* 2004) and a maximum mosquito lifespan of 31 days (Guerra *et al.* 2008).

In the Section 'Water vs. air temperature' we consider changes in larval development period and its effect on population growth rate (which will affect the vector:host ratio). For this we calculate the intrinsic rate of increase, r , using the analytical approximation:

$$r = \ln R_n / G \quad (4)$$

where R_n the net reproductive rate and G is mean length of a generation (Gotelli 2001). Parameter estimates for G and R_n were derived from the study of Afrane *et al.* (2006) who measured adult longevity and daily reproductive fitness for *Anopheles gambiae* Giles at a lowland and highland site in Western Kenya during the rainy season when mean air temperatures were almost identical to those of the current study. Net reproductive rate (R_n) was estimated directly by Afrane *et al.* (2006) with values of $R_n=346.0$ and $R_n=434.8$ for the lowland and highland sites, respectively. Mean length of a generation was calculated as the median time for adult reproduction (24.7 and 20.7 days for the lowland and highland sites, respectively, data derived from Afrane *et al.* (2006)) plus the relevant duration of larval development from this study to obtain the mean length of a complete generation (i.e. including all immature stages).

The reported changes in R_0 or r might be conservative if other mosquito and parasite life-history traits scale similarly with temperature. However, there is a possibility that there are trade-offs between traits, whereby a gain in one trait could be offset by losses in another. For example, in many biological systems, faster development at higher temperatures is costly and can trade-off with survival. For several parasite species it has been shown that development rates interact with survival (e.g. Kutz *et al.* 2009, Studer *et al.* 2010), and for *An. gambiae*, faster immature development at warmer temperatures is offset by fewer numbers surviving (Bayoh and Lindsay 2003). However, potential trade-offs between traits remain largely unexplored for malaria so they are not further considered here. Nonetheless, understanding the potentially complex effects of temperature across multiple interacting traits is an important area for further research.

Mean vs. variable temperature

Mosquitoes and parasites are poikilothermic, and therefore their temperature will track that of their direct surrounding environment. The daily temperature range (DTR; the difference between the daily minimum and maximum temperature) can easily be larger than 10 °C in Africa (Geerts 2003, Paaijmans *et al.* 2010b) (Table 1). Thus, mosquitoes, and parasites within them, do not experience 'average temperatures', but are exposed to temperatures that can fluctuate considerably throughout the day.

In an earlier theoretical study we assessed the potential effects of temperature fluctuation on development of the malaria parasites within the mosquito and revealed that parasite development is expected to be faster under fluctuating low temperatures, and slower under fluctuating high

Table 1. Mean monthly air temperature and mean monthly daily temperature range (DTR) as recorded in March 2001 at five meteorological stations in East Africa. Data obtained from the National Climatic Data Center.

	Kericho	Nakuru	Kisumu	Voi	Khartoum
altitude	1,976 m	1,901 m	1,146 m	579 m	380 m
N ¹	23 days	30 days	31 days	28 days	29 days
Mean T _a	16.7 °C	19.9 °C	23.9 °C	27.7 °C	29.5 °C
DTR	11.6 °C	14.9 °C	13.0 °C	13.3 °C	15.9 °C

¹ Number of days with available temperature (minimum and maximum) data in March 2001.

temperatures, compared with the respective baseline mean temperatures (Paaajmans *et al.* 2009b). In follow-up experimental studies we showed that this theory is robust, and extends to various aspects of life-history of the mosquito (Paaajmans *et al.* 2010b).

The observed non-linear rate summation effect is characterized as the Kaufmann effect (Kaufmann 1932) or Jensen's inequality (see e.g. Ruel and Ayres 1999) and has long been recognized in a range of host-pathogen/parasite systems (see e.g. Arthurs *et al.* 2003, Giannakou *et al.* 1999, Ruissen *et al.* 1993, Scherm and Van Bruggen 1994, Xu 1996) and for many insect-related rate processes in general (Worner 1992), but until recently has not been considered with respect to mosquitoes and pathogens.

To show the potential effects of daily temperature variability on parasite development and feeding frequency, we selected temperature data sets from five locations in East Africa (Table 1, Figure 2A) The extent of malaria transmission in these areas is not uniquely determined by temperature but we select them here to illustrate differential effects of temperature across diverse environments.

Extrinsic incubation period

As indicated previously, daily temperature fluctuation around cool temperatures acts to speed up parasite development relative to the baseline mean temperatures. This can be seen in the cooler areas of Kericho and Nakuru, with effects getting more pronounced as temperatures decline (nonlinear model; Figure 2B).

In Nakuru, parasites are predicted to fully develop in 26.6 days (i.e. within the maximum mosquito lifespan) when temperature fluctuates, but to take 32.5 days (i.e. beyond the maximum mosquito lifespan) at the baseline mean temperature (Figure 2B).

If we relax the mosquito lifespan threshold, and apply a maximum mosquito lifespan of 56 days as used by Craig *et al.* (1999), parasite development will be completed within mosquito lifespan in Kericho under variable temperature conditions (51.9 days), but not at the baseline mean temperature (189.2 days). This means that at the fringes of malaria transmission, fluctuation makes transmission possible at lower mean temperature.

Fluctuation around warmer temperatures has the reverse effect, slowing down growth rate relative to the equivalent constant mean temperatures. This effect is more pronounced as mean

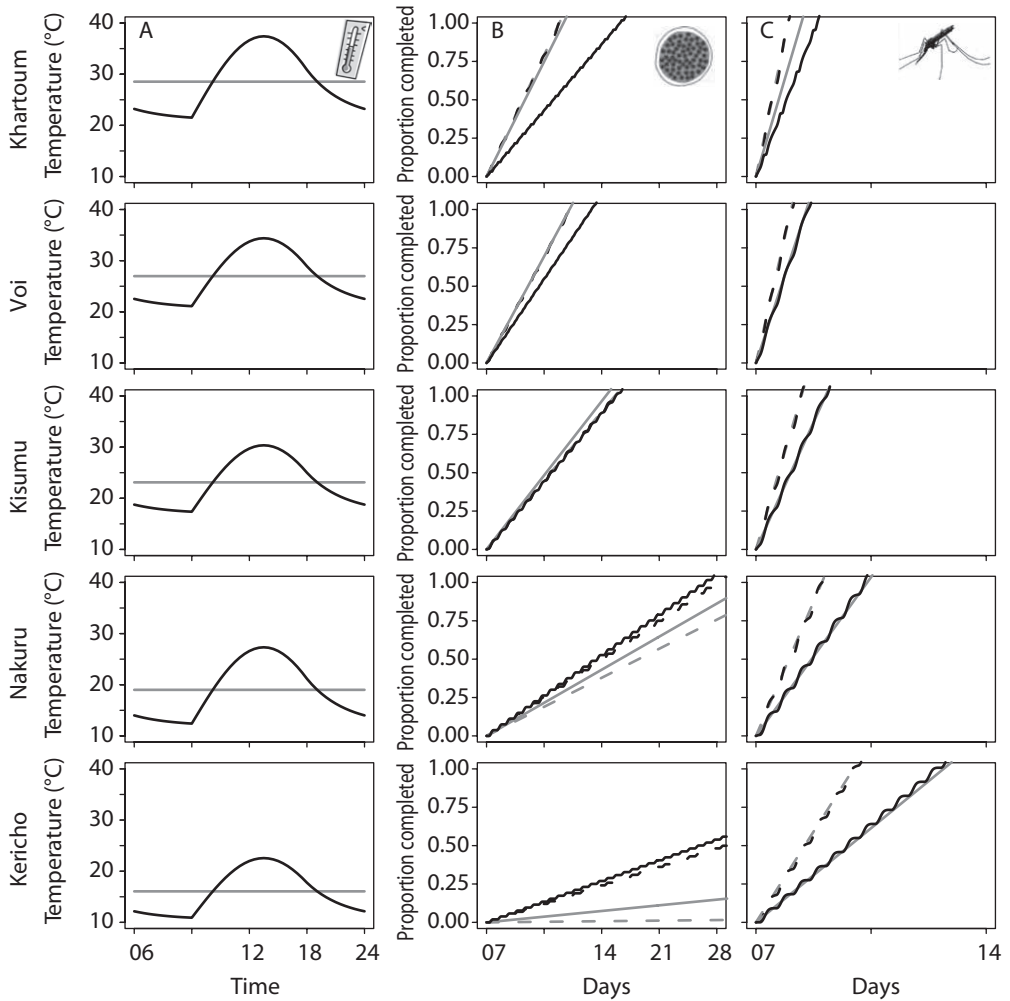


Figure 2. (A) Mean monthly temperatures (°C; grey lines) and modeled mean monthly daily temperature fluctuations (°C; black lines) at five different met-stations in East-Africa (March 2001). (B) Parasite development times, and (C) gonotrophic cycle lengths, at these locations, as estimated by the mean temperature (grey lines) or by taking daily temperature fluctuation into account (black lines). Dashed lines show development as predicted with the linear models, solid lines as predicted with the non-linear models. Development/cycle is completed when the proportion equals 1. Drawings of oocysts were generated by the US Centers for Disease Control and Prevention (<http://www.dpd.cdc.gov/dpdx/HTML/Malaria.htm>).

temperatures increase (Figure 2B, Kisumu: lengthened by 1.2 days, Voi by 2.7 days, and Khartoum by 6.9 days).

Qualitatively similar results are observed with the linear rate development model of Detinova (Figure 2B) when temperature fluctuates around lower mean temperatures (for Kericho and Nakuru). However, there is no difference in EIP estimates when applying the mean temperature or daily temperature variability in the warmer areas. This is due to the fact that temperature fluctuates over the linear part of the growth curve, so gains during daytime are offset by losses during nighttime. Furthermore, there is no upper temperature threshold in this type of model, so growth rate continues to increase with temperature.

Gonotrophic cycle length

The effect of daily temperature variation on the length of the gonotrophic cycle is much less pronounced than its effects on *EIP*. In Kericho fluctuation reduces the gonotrophic cycle by 0.5 days, whereas in Khartoum fluctuation creates a delay of 0.9 days, compared with the baseline mean temperatures (nonlinear model; Figure 2C).

These smaller effects are caused by the shape of the temperature-dependent model, which spans a wider temperature range than that of the *EIP* (Figure 1A,B). So in most of the selected areas, temperature will fluctuate over the linear part of the thermal performance curve.

Detinova's equation predicts no difference in gonotrophic cycle length when temperature variability is considered, due to a combination of a low minimum threshold temperature (9.9 °C) and temperatures fluctuating along the linear part of the growth curve (Figure 2C). However, the accuracy of the Detinova model is questionable since it predicts very short gonotrophic cycles even at cooler temperatures (e.g. 6 and 4 days in Kericho and Nakuru, respectively), which is at odds with empirical data (Afrane *et al.* 2005, Lardeux *et al.* 2008).

Changing climate

The relative effects of increases in mean temperature are likely to be less than expected when daily temperature fluctuation is taken into account (see Paaijmans *et al.* 2009b). We have illustrated this further in Figure 3, where we consider influence of temperature variation on a generic non-linear thermal performance curve (Figure 3A) (this curve is not specific for any particular life history trait but is used for illustration).

When we consider a longer-term prospective scenario with increases in mean monthly temperature of 3.2 °C, corresponding to the median increase in terrestrial temperature predicted by the IPCC for the months March-May in East-Africa by 2100 (Christensen *et al.* 2007), we see that at cooler temperatures the relative change in rate is much less at larger DTRs compared to the change in rate at the baseline constant temperature (black arrows in Figure 3B). However, it is important to note that the rate itself is already higher.

At higher temperatures, it is not necessarily the case that climate warming will only result in higher rates: no effect of further warming could be observed at certain DTRs (e.g. upper grey arrow in Figure 3B), and at some mean temperature-DTR combinations a decrease in rate could be observed under climate warming.

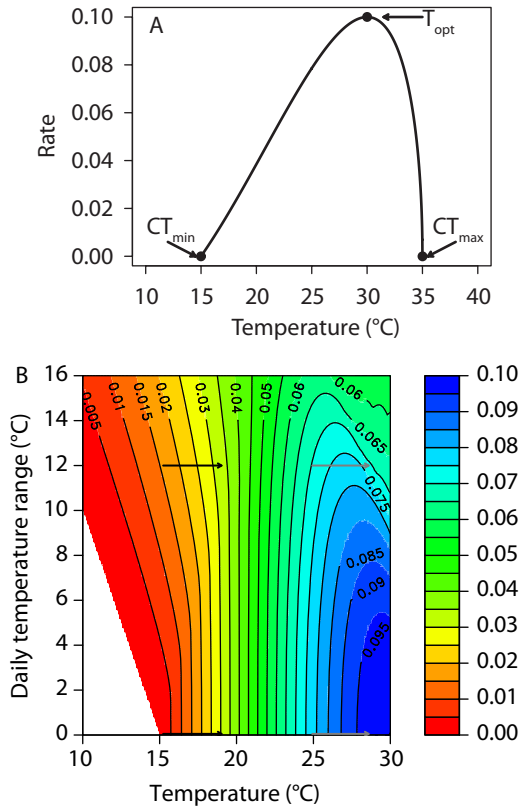


Figure 3. (A) Typical asymmetrical thermal ectotherm performance curve, indicating lower (CT_{min}) and upper (CT_{max}) critical temperatures for a given rate process and the temperature at which performance is maximum (T_{opt}). For illustration purposes we have selected a window of operation of 20 °C, which is typical for many insect species (Dixon *et al.* 2009), and a rate process that completes in 10 days at T_{opt} . (B) The rate of the same exemplary life-history trait across a range of mean temperatures (10–30 °C) and a wide range of daily temperature ranges (0–16 °C). Arrows indicate a shift in the mean temperature of approx. 3.2 °C due to global warming (see text).

An additional complication is that global warming is unlikely to result in a symmetrical shift in minimum and maximum temperatures. Several studies predict proportionately greater increases in daily minima than in daily maxima, resulting in decreases in DTR (Easterling *et al.* 1997, King'uyu *et al.* 2000, Lobell *et al.* 2007), although the reverse is possible at local scales (Hulme *et al.* 2001, King'uyu *et al.* 2000). Defining the nature of these changes at particular sites will be important for predicting local changes in disease burdens because changes in DTR can exacerbate or mitigate the influence of increases in mean temperatures, depending on initial starting conditions (Paaijmans *et al.* 2009b).

Short-term changes in climate, due to e.g. land-use changes, could also result in an asymmetrical shift of the daily minimum and maximum temperature. Work by Afrane *et al.* (2005) showed that both the mean and maximum temperatures increased substantially following deforestation in a

highland area in western Kenya. Again, diurnal temperature fluctuation could reduce the relative impact of such changes in mean temperature on life-history characteristics, although the nonlinearities, together with changes in DTR, make patterns complex.

In summary, neither the essential transmission parameters nor the upper or lower temperature thresholds for transmission can be estimated with the mean temperature alone. Models that ignore diurnal variation overestimate malaria risk in warmer environments and underestimate risk in cooler environments, and will tend to exaggerate the impact of climate change.

Outdoor vs. indoor temperature

The gonotrophic cycle of an anopheline mosquito can be as short as two days, but could take over a week, depending on temperature (Afrane *et al.* 2005, Lardeux *et al.* 2008, Rúa *et al.* 2005). As oviposition, host-seeking and blood-meal uptake are likely to happen in a single night, mosquitoes can spend a considerable part of the gonotrophic cycle (and hence their adult life) resting, during which the blood meal is digested and eggs develop.

An. gambiae s.s., arguably the most important malaria vector in sub-Saharan Africa, will spend a considerable time indoors, as it typically rests indoors (endophily) (Githeko *et al.* 1996b, Faye *et al.* 1997, Highton *et al.* 1979, Mnzava *et al.* 1995, Service 1970), although the reverse (exophily) has been reported (Bockarie *et al.* 1994; Mahande *et al.* 2007).

Unfortunately, there are only a few studies that actually measure the mean indoor and outdoor temperature simultaneously, and even fewer studies that keep track of the actual daily temperature variability in both environments. A generality in those studies is that the mean indoor temperature in traditional houses tends to be a few degrees Celsius higher than the outdoor temperature (Afrane *et al.* 2005, 2006, 2007, 2008, Alonso *et al.* 2011, Bødker *et al.* 2003, Garnham 1945, 1948, Minakawa *et al.* 2006), and this observation is qualitatively robust to changes in altitude. Thus, endophilic mosquitoes, and parasites within them, will be exposed to warmer temperatures than the outdoor air temperature.

Using indoor and outdoor temperature data from a study carried out in Tanzania (Bødker *et al.* 2003) (Figure 4A), we assessed the effects of these different microclimate datasets on the extrinsic incubation period of the parasite and gonotrophic cycle length of the mosquito.

Extrinsic incubation period

When we compare mean outdoor with mean indoor temperatures, applying a nonlinear model, we see that warmer indoor temperatures result in faster parasite development, with the difference getting larger with altitude (3.6 and 12.2 days faster at 640 and 1,040 m, respectively). At 1,686 m *EIP* is successfully completed indoors (30.1 days), whereas outdoor temperatures are too low for successful development (Figure 4B).

Comparing estimates based on the outdoor and indoor actual temperature fluctuations yields qualitatively similar results (Figure 4B). Also, incorporating DTR into the model has no real effect on *EIP* when compared to the baseline mean temperatures, but the reasons for the outdoor and indoor environment are different. Outdoor temperatures fluctuate along the linear part of the growth model. Indoors the DTRs are simply too small to have any impact.

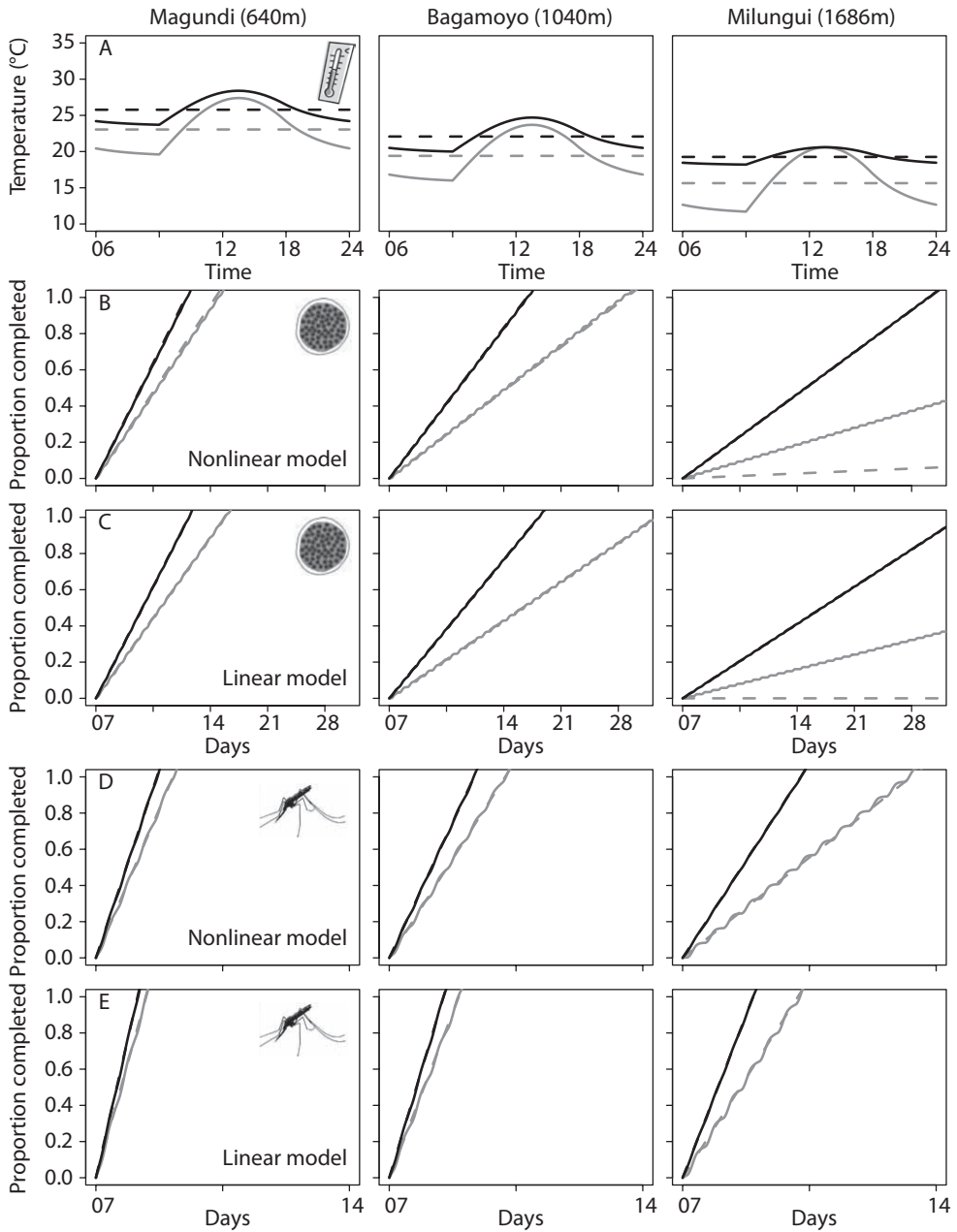


Figure 4. (A) Mean temperatures (°C; dashed lines) and modeled daily temperature dynamics (°C; solid lines) outside (°C; grey lines) and inside (°C; black lines) human dwellings, as recorded by Bødker et al. (2003). (B, C) Parasite development times, and (D, E) gontrophic cycle length, are modeled using the mean outdoor temperature (dashed grey lines), mean indoor temperature (dotted black lines) or the daily temperature fluctuation recorded outdoors (solid grey lines) or indoors (solid black lines). (B, D) Estimates with the non-linear models, (C, E) Estimates with the linear models. Development/cycle is completed when the proportion equals 1. Drawings of oocysts are generated by the US Centers for Disease Control and Prevention (<http://www.cdc.gov/dpdx/HTML/Malaria.htm>).

Having said that, large DTRs of 10-15 °C are observed indoors, including in highland environments (Okech *et al.* 2004a; Okech *et al.* 2004b; Afrane *et al.* 2006; Afrane *et al.* 2008). In the study by Bødker *et al.* (2003) that we used as an example here, temperature data are averaged over a period of several months, masking any larger day-to-day variations in DTR.

The linear Detinova model predicts that parasites will not develop successfully at 1,686 m (for neither indoor nor outdoor temperature data) (Figure 4C). At 1,040 m parasites will similarly not be able to complete development in exophilic mosquitoes, whereas the non-linear model predicts that malaria will fully develop in exo- and endophilic mosquitoes and in endophilic mosquitoes at 1,040 and 1,686 m, respectively. The difference between the two models is due to a small difference in the lower minimum threshold temperature for parasite development (Figure 1A).

Gonotrophic cycle length

Again, as seen in the Section 'Mean vs. variable temperature', a qualitatively similar outcome is observed for the gonotrophic cycle length. Compared to indoor conditions, and applying a nonlinear model, outdoor temperatures lengthen the gonotrophic cycle by 0.9 and 1.7 days at 640, 1,040 m altitude, respectively, and predictions based on the mean temperature are similar to those based on the daily temperature variability (Figure 4D). At 1,686 m, the gonotrophic cycle takes 6.1 (mean) or 5.9 days (DTR) longer to complete, compared to the indoor temperature. The reasons for the small differences in the length of the gonotrophic cycle between mean vs. fluctuating temperature are similar to those discussed in the previous Section 'Mean vs. variable temperature'. The Detinova curve again predicts much shorter gonotrophic cycles (see Section 'Mean vs. variable temperature', Figure 4E).

Changing climate

The potential effects of a changing climate on the outdoor air temperature, and hence on mosquito and parasite life-history characteristics, is described in the previous section. How indoor microclimate will be affected by longer-term climate change is hard to predict. There are multiple factors that will ultimately play a role. Humans can manipulate their direct thermal environment by changing the nature of the building structure (Atieli *et al.* 2009, Okech *et al.* 2004a,b), or its surroundings (Afrane *et al.* 2005, 2006, 2007, 2008). Mosquitoes might also react to unfavourable indoor conditions; in a study exploring the effects of steadily increasing temperature on behaviour (Kirby and Lindsay 2004), *An. gambiae* and *An. arabiensis* Patton exhibited escape responses at 33 °C and 35.7 °C, respectively.

Moreover, the use of insecticides on bednets (ITNs) (Lindsay *et al.* 1991, Lines *et al.* 1987, Mbogo *et al.* 1996, Miller *et al.* 1991), on eaves curtains (Githeko *et al.* 1996a) or by spraying insecticides indoors (IRS) (Service *et al.* 1978), all have the potential to keep/drive malaria vectors outdoors. This change in behaviour means that vectors will immediately be exposed to different microclimatic conditions.

The well-documented consequences of deforestation on climate provide us with an insight of climate warming on a very short temporal scale. Deforestation in cooler highland areas in western Kenya result in warmer mean and maximum indoor temperatures, increasing the indoor DTR (Afrane *et al.* 2005, 2006). Increases in the minimum temperature have also been observed after deforestation (Afrane *et al.* 2008). Such changes in temperature could result in increased parasite development rates and shorter gonotrophic cycles. Both have been observed empirically: for *EIP*, see Afrane *et al.* (2008) and for gonotrophic cycle length, see Afrane *et al.* (2005).

In summary, existing models that use outdoor air temperatures will tend to underestimate the speed of rate processes such as parasite development, blood meal digestion and egg-production of indoor resting mosquito populations, with differences being larger in cooler environments. The impact of climate warming is hard to assess due to many uncertainties. Clearly we need a better understanding of mosquito whereabouts and the associated microclimate.

Water vs. air temperature

The relationship between immature mosquito biology and temperature is central to numerous studies exploring the temporal and/or spatial patterns of malaria risk (Bayoh and Lindsay 2003, Craig *et al.* 1999, Ebi *et al.* 2005, Hoshen and Morse 2004, Ikemoto 2008, Pascual *et al.* 2006). A feature of nearly all such studies is the use of mean ambient air temperature to drive the relevant growth processes. While this might be appropriate for processes relating to transmission by the adult mosquito (but see Sections 'Mean vs. variable' and 'outdoor vs. indoor' temperature), the immature stages of malaria mosquitoes, such as *An. gambiae*, inhabit aquatic environments such as small, transient, sunlit pools (e.g. Gimnig *et al.* 2001, Mutuku *et al.* 2006).

Water temperatures are generally higher than corresponding air temperatures throughout most of the day, with mean water temperature exceeding mean air temperature by a few degrees Celsius, in both lowland and highland areas (Table 2, Figure 5A, Minakawa *et al.* 2006, Munga *et al.* 2005, Munga *et al.* 2006, Paaijmans *et al.* 2008, 2010a). Given the fundamental fact that mosquito larvae live in aquatic and not terrestrial habitats, immature mosquitoes do not experience air temperatures, but are exposed to warmer water temperatures.

To illustrate the difference in impact of water vs. air temperature on mosquito biology, we estimated immature development using both linear and non-linear development models (Figure 1C), driven by temperatures recorded in a lowland (Kisian) and highland area (Fort Ternan) in western Kenya. A day with predominant clear sky was selected. Mean air and water temperature, as well as daily temperature ranges are given in Table 2 and Figure 5A.

Table 2. Mean air and water temperatures, and their daily temperature ranges, as recorded on a day with no overcast in a lowland and a highland site in western Kenya.

Kisian (1,126 m)	29 March 2005
Total incoming short wave radiation	26.8 MJ/m ²
Mean air temperature	23.8 °C
DTRair	13.3 °C
Mean water temperature	28.4 °C
DTRwater	11.9 °C
Fort Ternan (1,552 m)	22 May 2006
Total incoming short wave radiation	26.7 MJ/m ²
Mean temperature	19.5 °C
DTR	12.7 °C
Mean water temperature	25.1 °C
DTRwater	12.1 °C

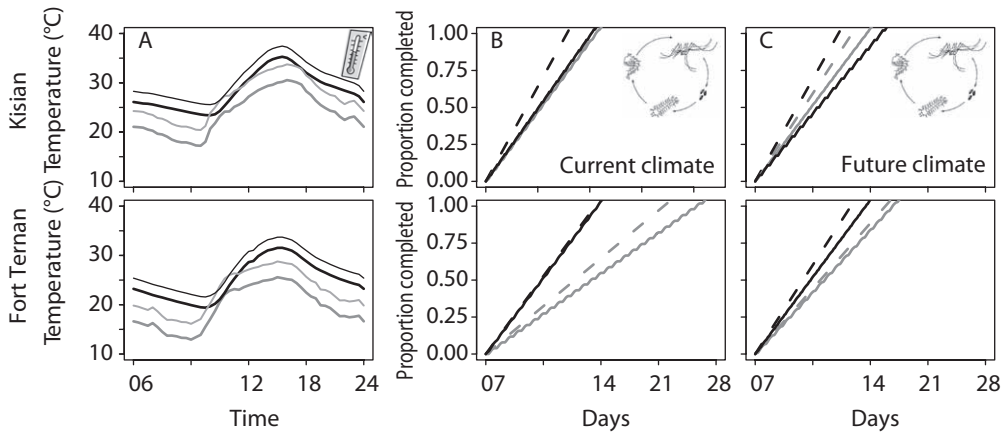


Figure 5. (A) Air temperature (grey lines) and water temperature dynamics (black lines) in a typical mosquito breeding puddle as recorded in Kisian and Fort Ternan, a lowland and a highland site, respectively, in western Kenya. Thick lines are actual measured temperatures, thin lines the forecasted temperatures (see text). (B, C) Immature development times predicted with the non-linear model using the mean temperature (dashed lines) or the daily temperature variation (solid lines) of the air (grey lines) or water temperatures (black lines). (C) Similar to B, but now showing the effects of climate warming on larval development times. Development is completed when the proportion equals 1.

Water temperatures in Kisian and Fort Ternan were higher than corresponding air temperatures throughout the day, with mean water temperature exceeding mean air temperature by 4.6 and 5.6 °C, respectively.

Larval development times

Larval development rates as estimated with mean water temperatures are much higher than estimates that are based on mean air temperatures. Higher mean water temperatures shorten larval development times by 3.6 days in the lowland and 8.3 days in the highland area (nonlinear model; Figure 5B).

When daily water temperature variability is included in the model, we get qualitatively similar results: larval duration is shortened by 0.6 days in Kisian compared to fluctuating air temperatures. The fact that immature mosquito develop slower under variable conditions, compared to constant conditions, is caused by a period of high water temperatures during daytime, which slow down and even inhibit development for a short period during the day (Figure 5B). In the highland area larval duration is shortened by 12 days, compared with estimates based on the variable air temperature (Figure 5B). This is not only the result of the air temperature being lower than the water temperature, and hence predicting lower development rates; another factor is that air temperatures drop below the minimum critical temperature for larval development (CT_{min}) during night-time, resulting in a shorter period of growth compared to estimates that are based on fluctuating water temperatures.

The immature development times that are derived using aquatic temperatures in the current study are consistent with the observed larval development times in several field studies in western Kenya (Gimnig *et al.* 2002, Minakawa *et al.* 2006, Munga *et al.* 2006, Paaijmans *et al.* 2009a).

The linear model provides a qualitatively similar outcome to the nonlinear model described above (4.4 days reduction in development time in the lowlands, and 10.8 days in the highlands, under both mean and variable conditions; data not shown), as the models overlap over a large part of the operable temperature range. The linear model does, however, not capture the slower development (as described above) at the lower temperature end due to differences in model-shape at cooler temperatures (Figure 1C). Due to a combination of (1) there being no upper temperature threshold in the linear model, and (2) the fact that temperatures observed in our field sites fluctuate over the linear part of the growth curve, the linear model predicts similar development rates in both constant and variable environments.

Changing climate

The relative impact of temperature warming is likely to be less when the relevant water temperatures are taken into account. This is because (1) water temperature of typical malaria mosquito breeding sites is higher than the surrounding air temperature, and therefore the baseline larval development and population growth rates themselves are much higher, and will therefore see a smaller increase compared to estimates that are based on the air temperature (Paaijmans *et al.* 2010a) and (2) the actual increase in water temperature is expected to be less than the actual increase in air temperature since the slopes of the regression lines describing the relationship between water and air temperature are <1 (Paaijmans *et al.* 2010a).

To illustrate this we consider a longer-term prospective scenario with increases in mean monthly air temperature of 3.2 °C (see Section 'Mean vs. variable temperature'). The actual increase in water temperature is expected to be to be 3.2×0.677 (slope) = 2.2 °C. For simplicity we assumed no changes in the diurnal ranges of air and water temperatures (Figure 5A).

Adding the projected increase of 3.2 °C in temperature to current mean air temperatures dramatically shortens larval development times (Figure 5C) and increase population growth rates. Again, however, the magnitude of these effects is greatly reduced when the relationship between air and water temperature is taken into account; instead of decreases in larval development times of 2.7 days in the lowland and 5.8 days in the highland area, development times are predicted to shorten by only 0.8 days and 1.7 days, respectively.

As a consequence, the increases in population growth rates compared to present day are predicted to be in the order of 2.3% in the lowland area and 5.1% in the highland area rather than 7.4% and 15.9%, respectively, as predicted with the mean air temperature.

When temperature variability is taken into account similar patterns emerge; instead of decreases in larval development times of 1.3 days in the lowland and 8.9 days in the highland area, development times are predicted to lengthen by 1.1 days and shorten by 0.1 days, respectively. The longer larval development time in the lowlands is caused by the fact that larvae are exposed even longer to unfavourable temperatures during daytime, which inhibit development. This results in a decrease in population growth rate of 2.8% compared to present day, rather than an increase of 3.3% in the lowland area. In the highland area there is an increase in the intrinsic rate of increase of only 0.4% rather than the 23.7% that is predicted with the variable air temperature.

Essentially, although warming is expected to increase growth rate via effects on larval development, the relative change is expected to be much less, and could even be reversed, when the relevant water temperatures are considered.

Unfortunately, we have a poor understanding of how climate warming will eventually change the daily temperature dynamics of mosquito breeding habitats. On shorter time scales, changes in microclimate due to deforestation (or swamp reclamation) have been observed to increase mean temperatures in larval habitats (increase of 4.8 °C in the lowland and 4.7 °C in the highland area), with larger increases in the daily maximum water temperature than in the daily minimum water temperature. In these warmer pools, larval development times are shortened by several days in the lowlands, and by a week or more in a cooler highland area (Minakawa *et al.* 2006).

In summary, air temperature alone does not provide an appropriate variable for estimating immature mosquito development or for setting threshold temperatures. Existing models will tend to underestimate mosquito population growth under current conditions. On the other hand, the relative increases in larval development rates predicted due to climate change are substantially less. Again, existing models may overestimate relative increases in population growth under future climate change.

Concluding remarks

This book chapter highlights how the standard use of the mean outdoor air temperature in malaria risk models fails to capture important features of the actual microclimate experienced by mosquitoes. Immature and adult mosquitoes, as well as the parasites within the adults, are likely to be exposed to considerable different temperatures than currently taken into account. In addition, daily temperature variations (in outdoor and indoor air temperature, as well as in water temperature) and the type of model (linear vs. non-linear) that is used clearly affect malaria risk predictions as well.

Given the need to understand malaria dynamics for setting operational control objectives and for predicting consequences of climate change, this chapter highlights an urgent need to develop a better mechanistic understanding of vector-parasite interactions, with improved integration of the biological and environmental parameters at a scale relevant to conditions actually experienced by both mosquitoes and malaria parasites.

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