Supporting Information for

Detecting the impact of temperature on transmission of Zika, dengue and chikungunya using mechanistic models

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Supplementary Results

Sensitivity analyses

We explored several methods of sensitivity analyses to examine how model predictions change with different thermal response assumptions. Because no temperature-sensitive vector competence or extrinsic incubation period (EIP) data were available for CHIKV or ZIKV, we were particularly interested in the R_0 model sensitivity to the thermal responses for these traits. We explored the impact of changes in *b, c,* and *PDR* by calculating R_0 for all posterior parameter samples with those focal traits shifted in the following ways: entire curves shifted ±3°C and ±5°C for all three traits, entire curves shifted ±3°C and ±5°C for each trait individually, and curves made 3°C wider or narrower without changing the mean for all three traits. We examined the impact of each modification on the thermal minimum, maximum, and optimum (T_0, T_m, and T_{pk}) for R_0. For *Ae. albopictus*, all shifts in trait thermal responses shifted T_{pk} by < 1°C, T_0 by approximately the amount of the trait shift (e.g., +3°C for the models with the traits shifted by +3°C), and had little effect on T_m (Fig. S9). Similarly, for *Ae. aegypti* all models shifted T_{pk} by < 2°C, T_0 by less than or equal to the amount of the trait shift, and had little effect on T_m, with the exception of the -5°C trait shift, which reduced T_m by 5°C (Fig. S10). These analyses indicate that the optimal and maximum temperatures for transmission are robust to error in the vector competence and EIP thermal responses. By contrast, the minimum and maximum temperature for transmission may be sensitive to these trait thermal responses, so it is important to experimentally measure vector competence and EIP, particularly at low temperatures, for each mosquito and pathogen species pair of interest.

We also used sensitivity analyses to characterize the degree to which the temperature response of each individual trait drives the overall temperature response of R_0 (i.e., $(1/R_0)(dR_0/dX)$ for each parameter X). For both the *Ae. aegypti* and the *Ae. albopictus* models, we found that the *PDR* thermal response dramatically increased the response of R_0 to temperature (Figs. S11-S12). The *Ae. albopictus* model was additionally sensitive to the thermal response of adult mosquito lifespan, which had a negative effect on the sensitivity of R_0 to temperature (Fig. S11).

We were interested in which trait's thermal response was driving the difference in optimal temperature for *Ae. aegypti* versus *Ae. albopictus* transmission. To investigate this, we sequentially swapped thermal responses from one model to the other (e.g., calculated R_0 with all *Ae. albopictus* trait thermal responses except one from *Ae. aegypti* and vice versa). Mosquito lifespan was the key driver in the difference between the two R_0-versus-temperature models. Although the optimal temperatures for mosquito lifespan were similar, the thermal breadth was much narrower for *Ae. albopictus* than for *Ae. aegypti*. R_0 is strongly limited by short mosquito lifespans at high temperatures, where viral extrinsic incubation is very rapid, so expanding the thermal breadth for this trait has a large effect on the optimum.

Uncertainty analyses

We estimated how uncertainty in the trait thermal responses contributed to uncertainty in R_0 versus temperature. First, we calculated the width of the 95% credible interval for R_0 with all parameters sampled from their posterior distributions across temperatures. Then, we calculated the width of the 95% credible interval for R_0 when each trait was sampled from its posterior distribution individually, while the remaining parameters were fixed at their posterior mean. We compared the width of the intervals when just one parameter was sampled from its posterior

distribution to the width when all parameters were sampled to calculate the relative contribution of each parameter to uncertainty at each temperature. For *Ae. albopictus*, mosquito lifespan (*lf*) contributed most to uncertainty from 24-35°C and transmission probability (*b*), followed by infection probability (*c*), contributed most to uncertainty from 16-24°C (Fig. S13). For *Ae. aegypti*, biting rate (*a*) contributed most to uncertainty from 29-35°C, transmission probability (*b*) contributed most to uncertainty from 13-28°C, and mosquito lifespan (*lf*), fecundity (*EFD*), and infection probability (*c*) all contributed substantially to uncertainty from 13-35°C (Fig. S14).

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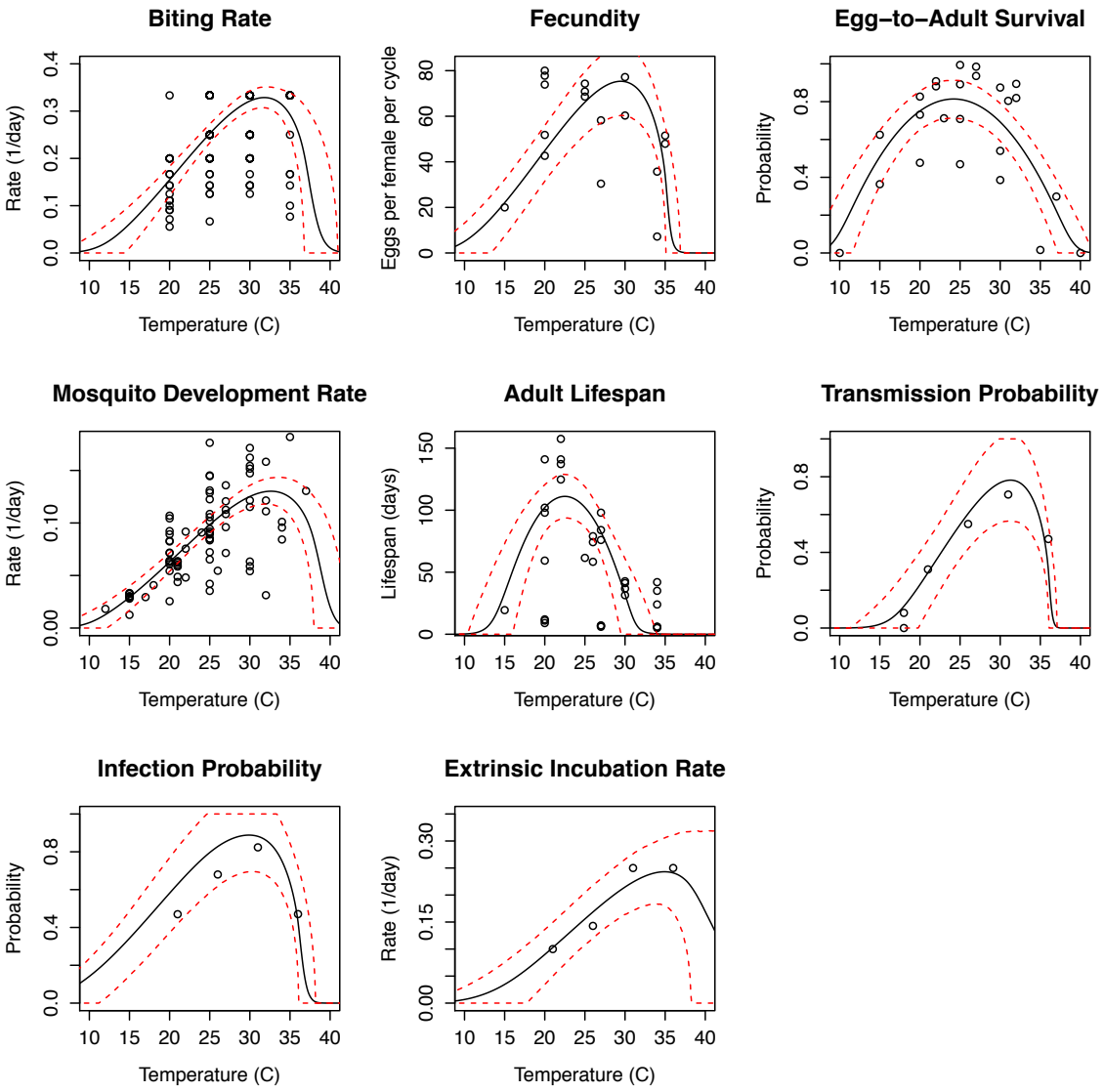

Fig. S1

Thermal responses of *Ae. albopictus* and DENV traits that drive transmission (parameter names and data sources listed in Table S1). Informative priors based on data from additional *Aedes* spp. and flavivirus studies helped to constrain uncertainty in the model fits (see Materials and Methods; Table S3). Points are the data. Black solid lines are the mean model fits; red dashed lines are the 95% credible intervals.

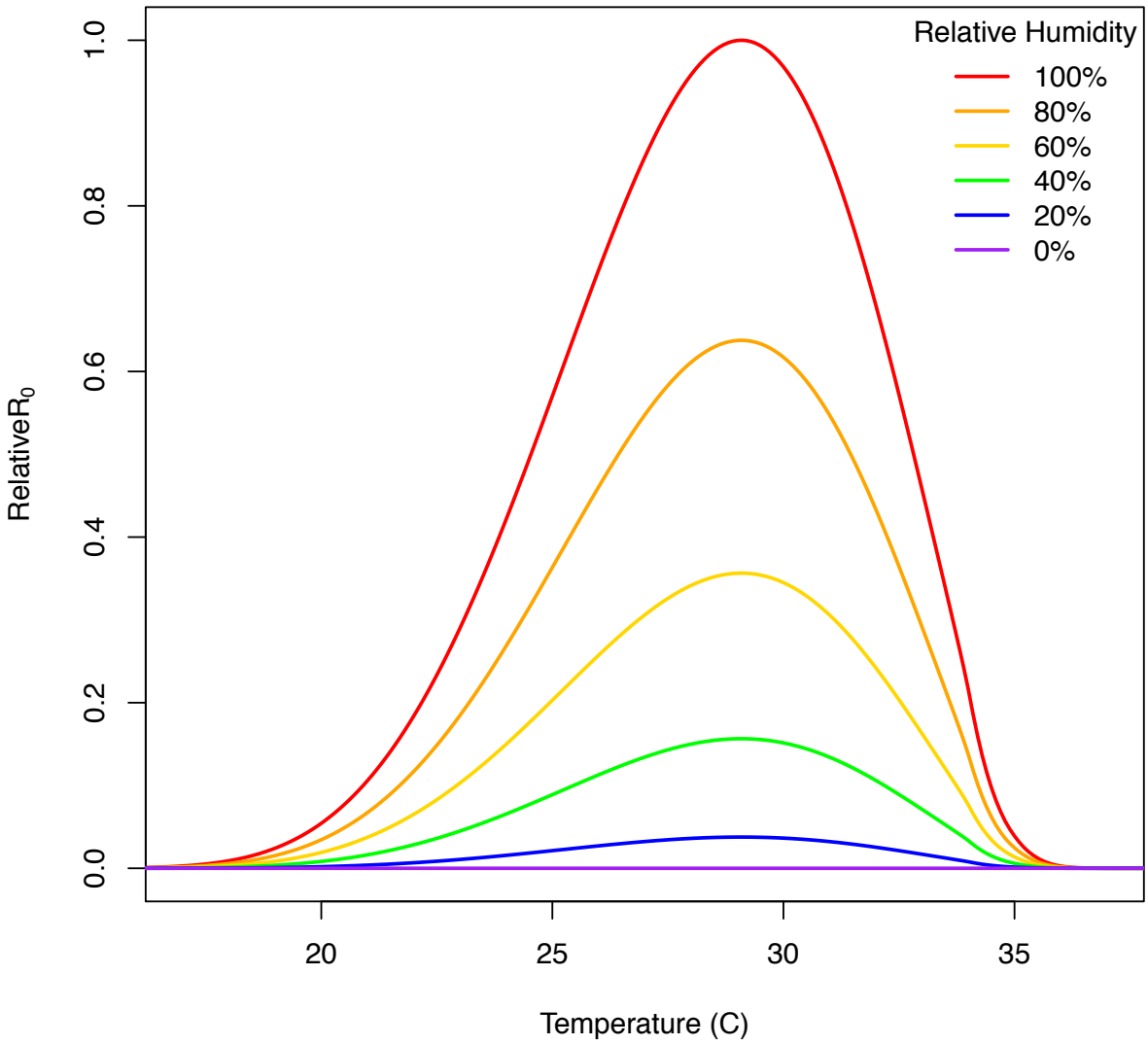

Fig. S2

Effects of relative humidity on relative R_0 versus temperature for *Ae. aegypti*, assuming constant temperatures. Humidity increases R_0 exponentially but does not affect the shape of the thermal response of R_0 (i.e., minimum, maximum, or peak temperature).

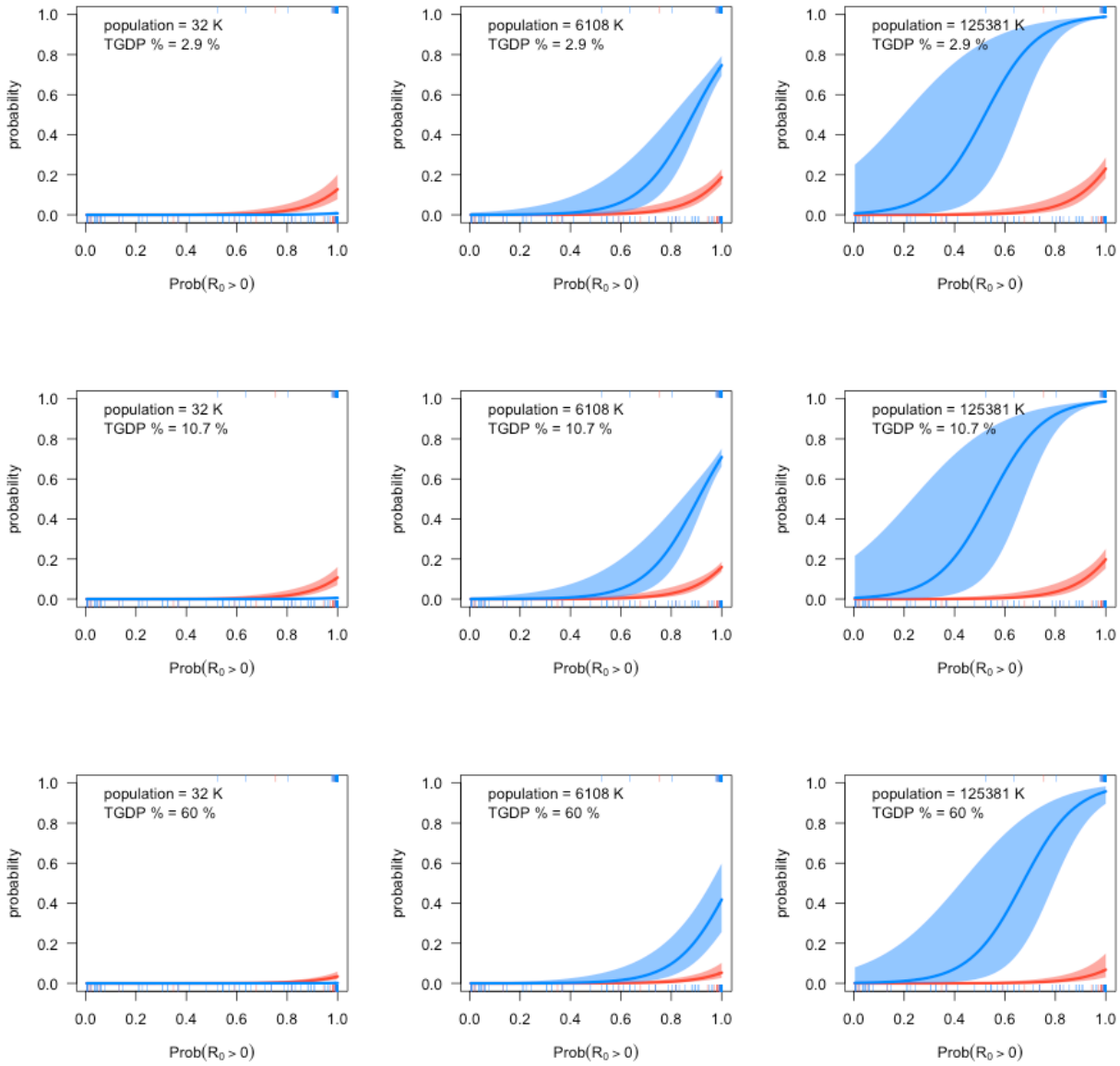

Fig. S3

Plots of the probability that $R_0 > 0$ (GR_0) versus the probability of transmission predicted from presence/absence model PA5, for different levels of percent tourism in GDP (TGDP) across different rows and population size (population) across different columns, at the median value of GDP (per capita GDP = $7274). Red lines: CHIKV and ZIKV. Blue lines: DENV. Lines are the mean model fits and shaded areas are the standard errors. Tick marks show the data.

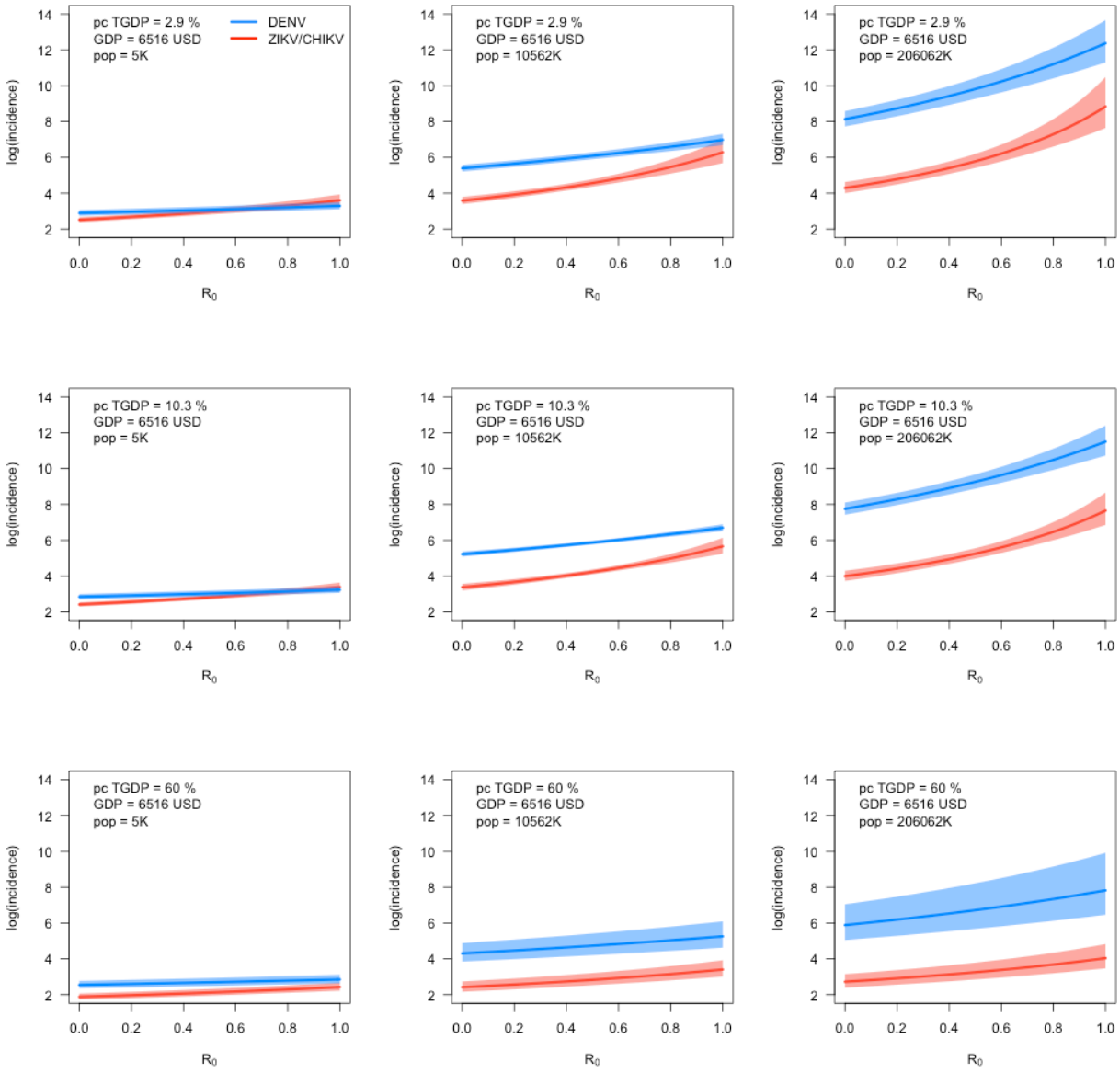

Fig. S4

Plots of R_0 versus the log of incidence predicted from incidence model IM5, for different levels of percent tourism in GDP (pc TGDP) across different rows and of population size (pop) across different columns, at the median value of GDP (per capita GDP = $6516). Red lines: CHIKV and ZIKV. Blue lines: DENV. Lines are the mean model fits and shaded areas are the standard errors.

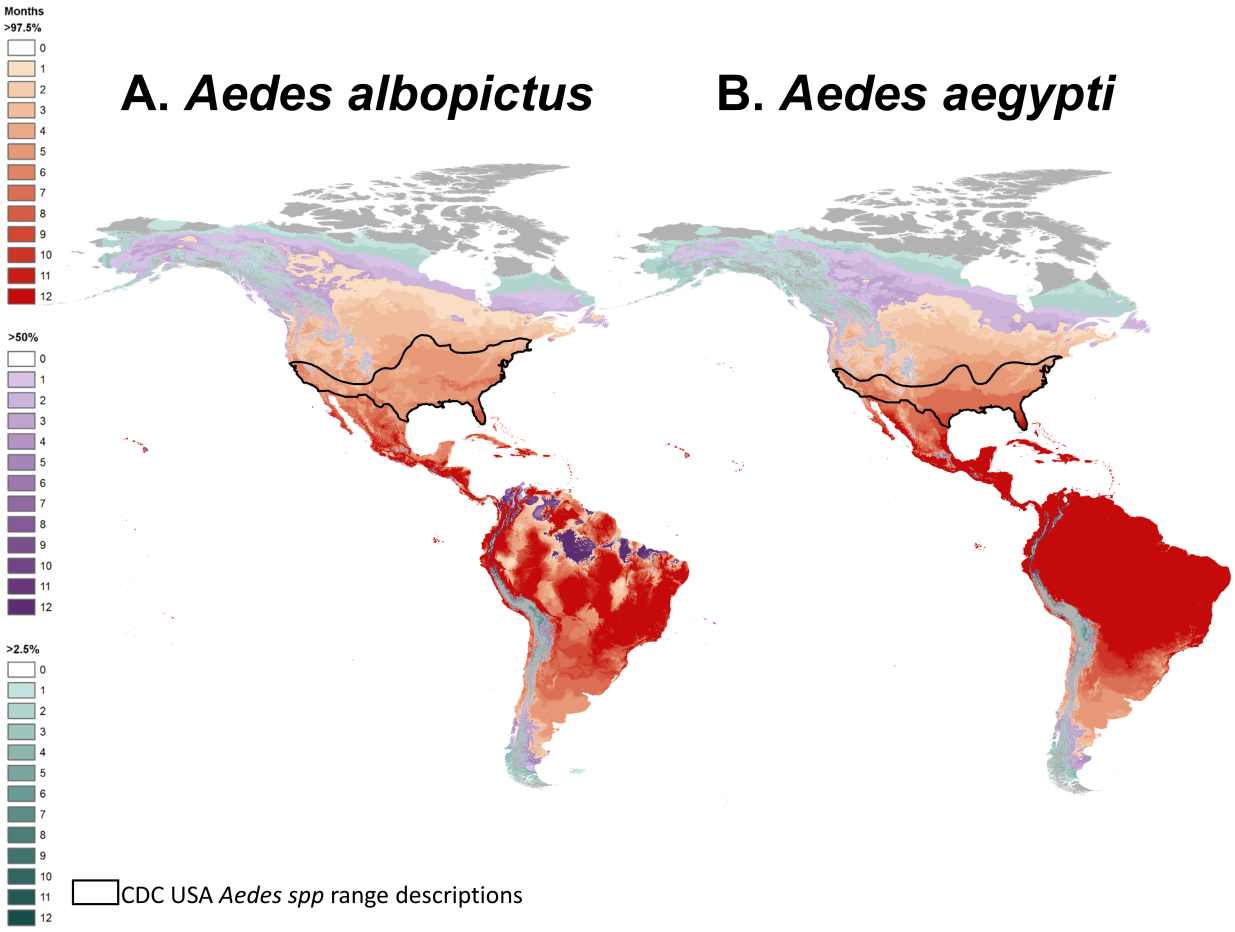

Fig. S5

Map of predicted temperature suitability for virus transmission by *Ae. albopictus* (A) and *Ae. aegypti* (B). Color indicates the consecutive months in which temperature is permissive for transmission (predicted $R_0 > 0$) for *Aedes* spp. transmission. Red, minimum likely range (> 97.5% probability that $R_0 > 0$), purple, median likely range (> 50% probability that $R_0 > 0$), teal, maximum likely range (> 2.5% probability that $R_0 > 0$). Black line indicates the CDC *Aedes* spp. range estimates in the United States. Model suitability predictions combine temperature mean and 8°C daily variation and are informed by laboratory data (Figs. 1, S1) and validated against field data (Fig. 3).

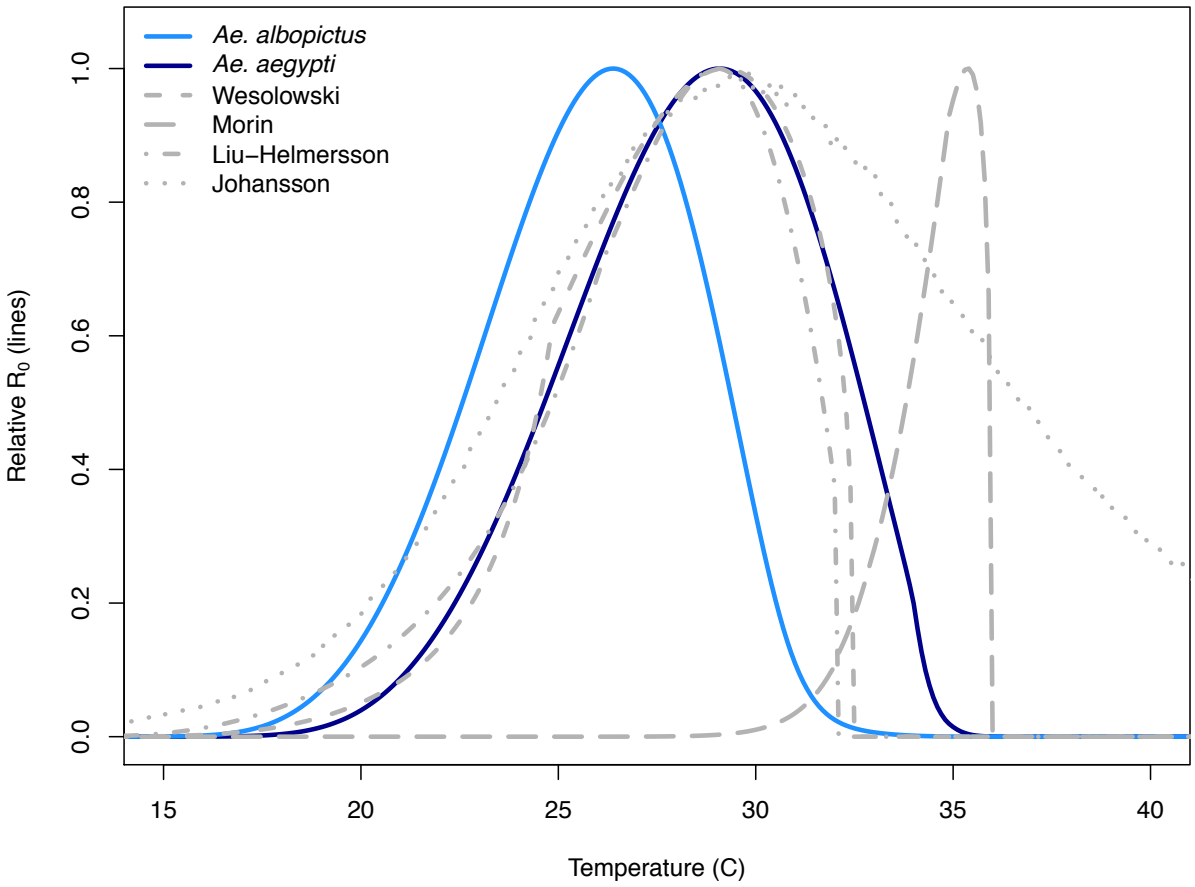

Fig. S6

R_0 versus temperature models for *Ae. aegypti* (dark blue line) and *Ae. albopictus* (light blue line) and models of DENV transmission by *Ae. aegypti* based on the thermal responses listed in three previous studies: Wesolowski et al. (1) (dashed gray line), Morin et al. (2) (wide dashed gray line), Liu-Helmersson et al. (3) (dash-dotted gray line), and Johansson et al. (4) (dotted gray line).

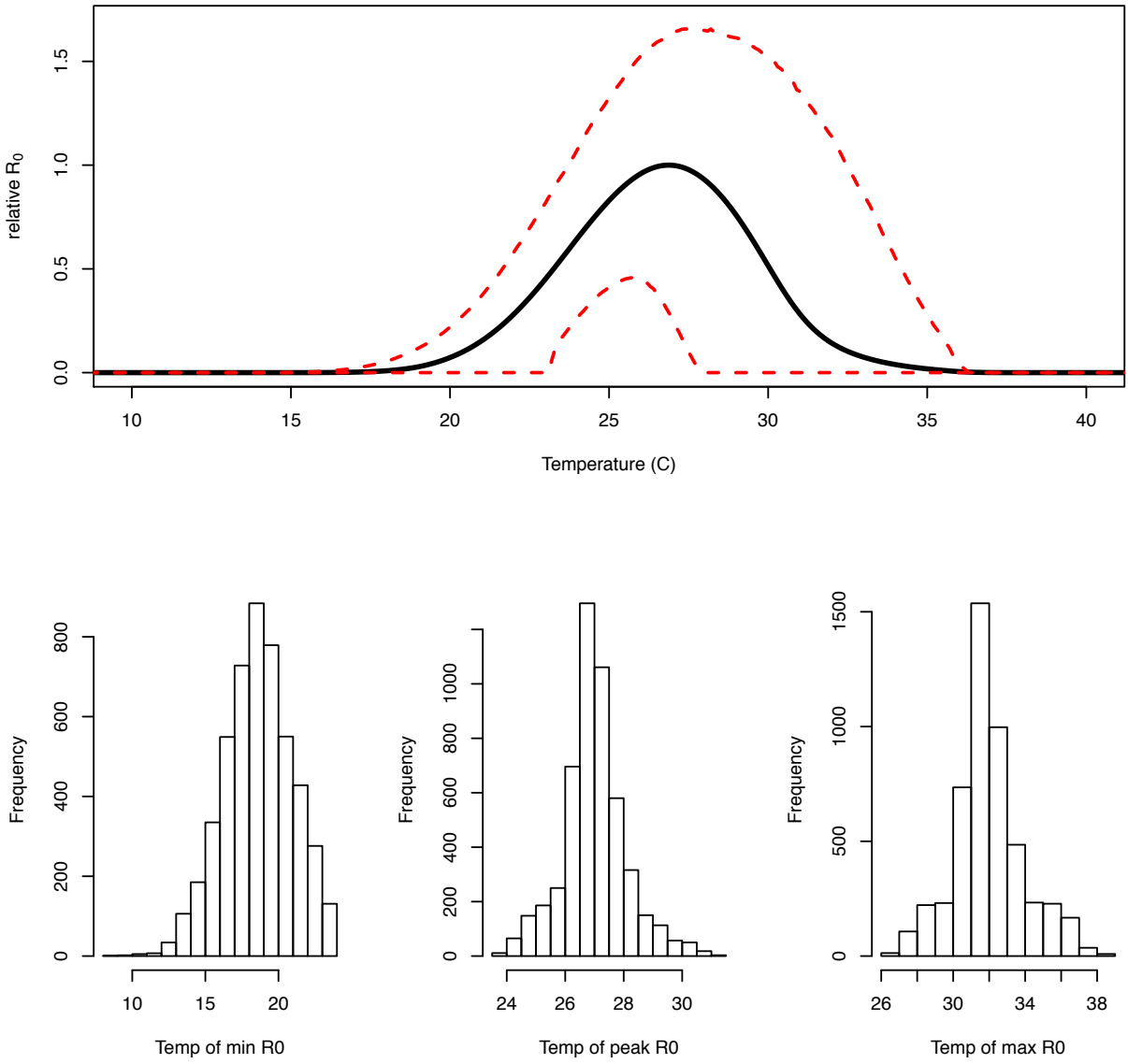

Fig. S7
Top, uninformative prior model of *Ae. albopictus* R_0 versus temperature model mean (black line) and 95% highest posterior density intervals (red dashed lines), for constant temperatures. Bottom, histograms of the minimum, maximum, and optimum temperatures for transmission.

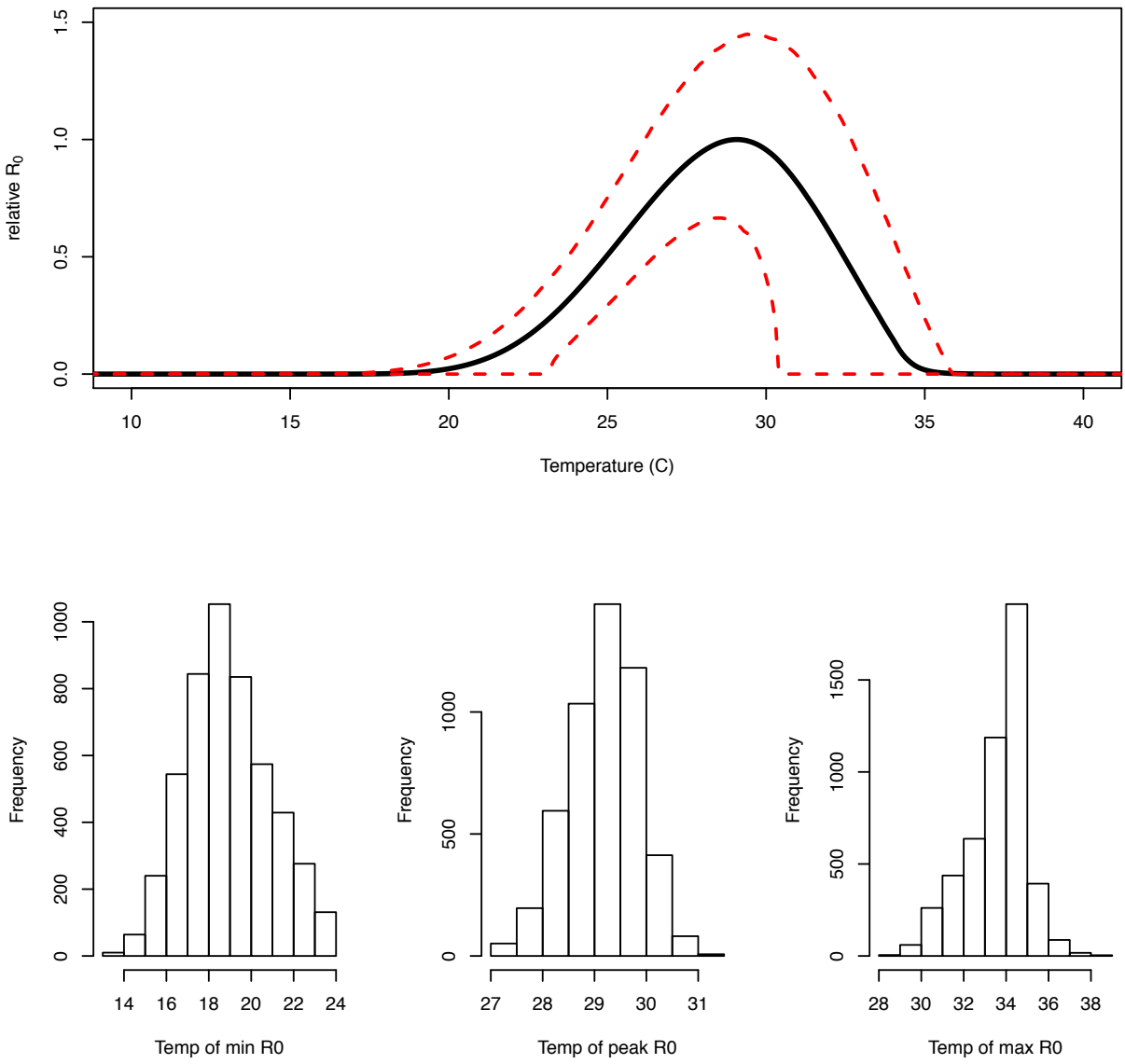

Fig. S8

Top, uninformative prior model of *Ae. aegypti* R_0 versus temperature model mean (black line) and 95% highest posterior density intervals (red dashed lines), for constant temperatures. Bottom, histograms of the minimum, maximum, and optimum temperatures for transmission.

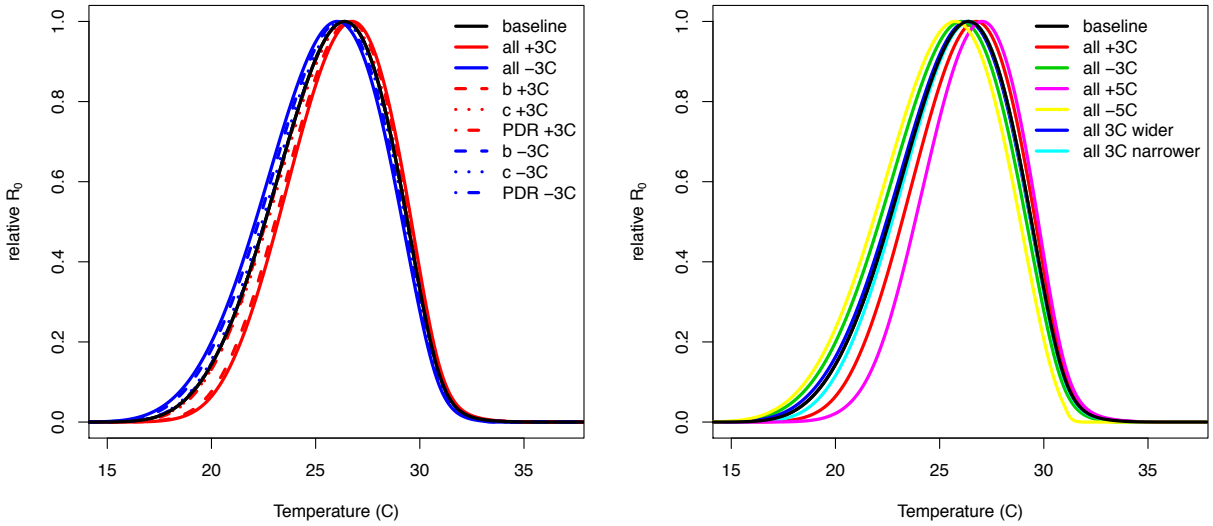

Fig. S9

Sensitivity analysis on the *Ae. albopictus* R_0 model at constant temperatures for vector competence (*b* and *c*) and parasite development rate (*PDR* = 1/extrinsic incubation period), in which these traits are shifted individually and together +/-3°C (left panel), or all three are shifted +/-3°C, +/-5°C, or the curves are made 3°C narrower or wider with the same optimum (right panel).

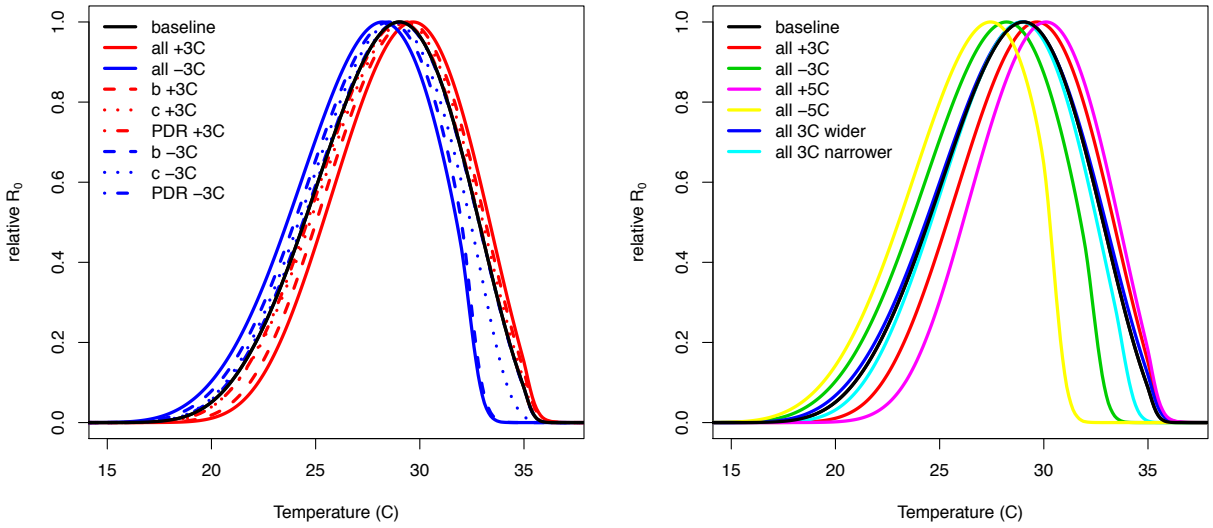

Fig. S10

Sensitivity analysis on the *Ae. aegypti* R_0 model at constant temperatures for vector competence (*b* and *c*) and parasite development rate (*PDR* = 1/extrinsic incubation period), in which these traits are shifted individually and together +/-3°C (left panel), or all three are shifted +/-3°C, +/-5°C, or the curves are made 3°C narrower or wider with the same optimum (right panel).

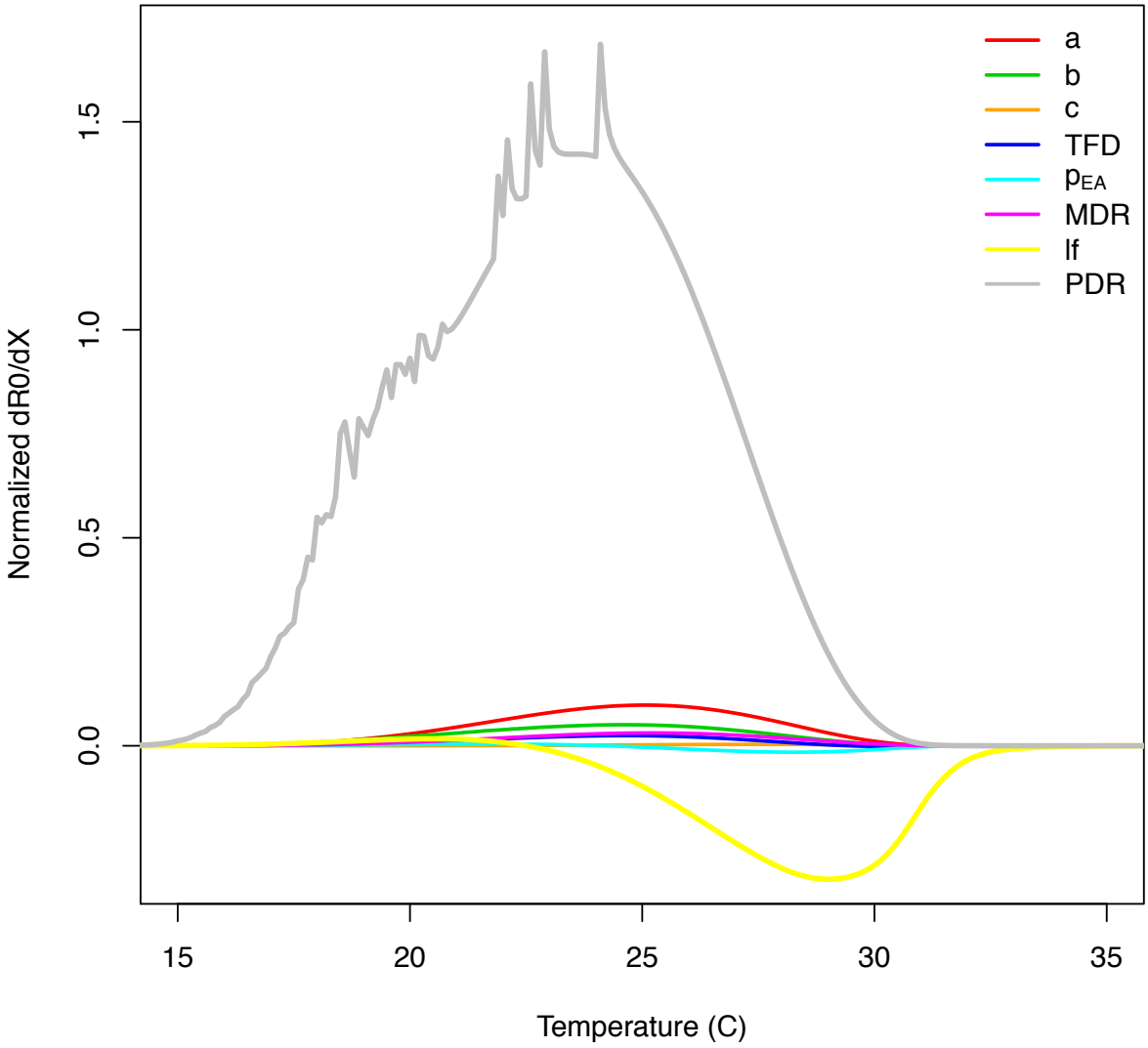

Fig. S11

Sensitivity analysis on the *Ae. albopictus* R_0 model, showing the derivative of R_0 with respect to each parameter, divided by R_0, at each temperature. Parasite development rate (PDR) has the largest effect on R_0 for most of the temperature range, while mosquito lifespan (lf) has a strong negative effect at warm temperatures. Parameter names are listed in Table S1.

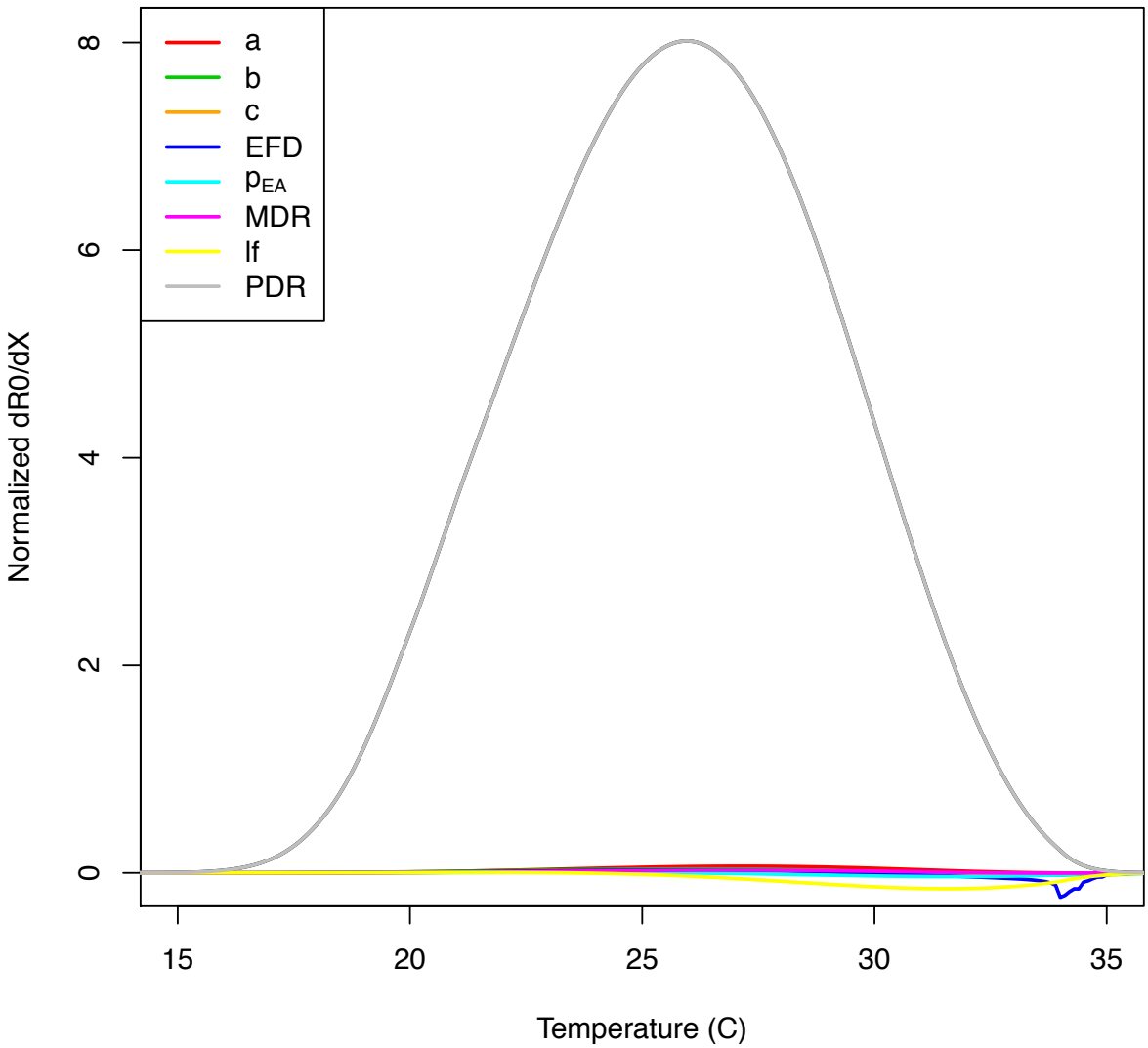

Fig. S12

Sensitivity analysis on the *Ae. aegypti* R_0 model, showing the derivative of R_0 with respect to each parameter, divided by R_0, at each temperature. Parasite development rate (PDR) has the largest effect on R_0 for most of the temperature range. Parameter names are listed in Table S1.

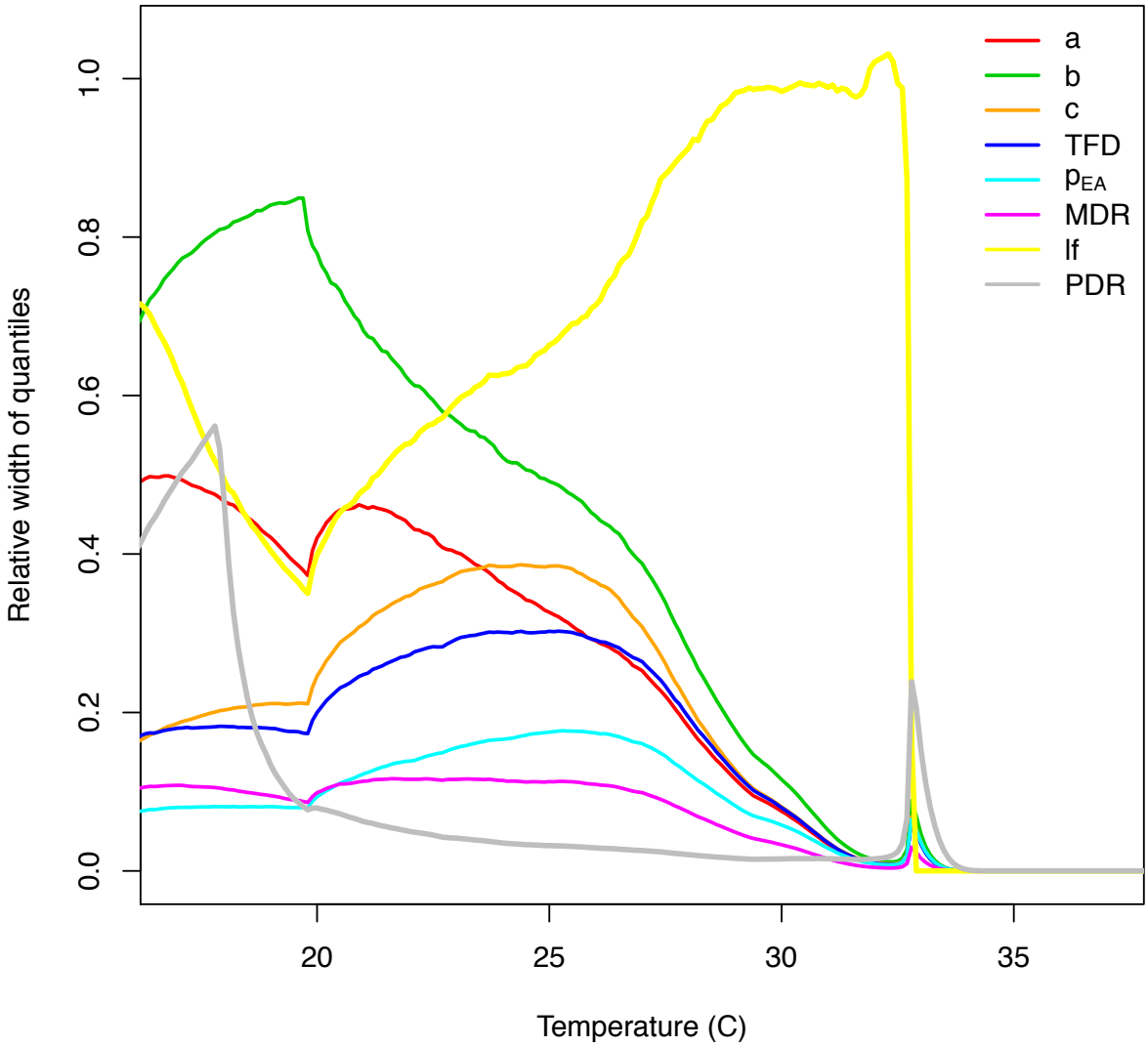

Fig. S13

Uncertainty analysis for *Ae. albopictus* R_0 model, showing the relative width of the 95% HPD intervals on R_0 that is due to each parameter, compared to the overall uncertainty. Each line shows the width of the 95% HPD interval on R_0 when calculated using draws from the posterior distribution of the focal parameter and the posterior means of the other parameters, divided by the width of the 95% HPD interval on R_0 when all parameters are drawn from their posterior distribution. This illustrates the degree to which uncertainty in R_0 arises from uncertainty in the component parameters at each temperature value. Mosquito infection probability (b) and lifespan (LF) dominate model uncertainty. Parameters are defined in Table S1.

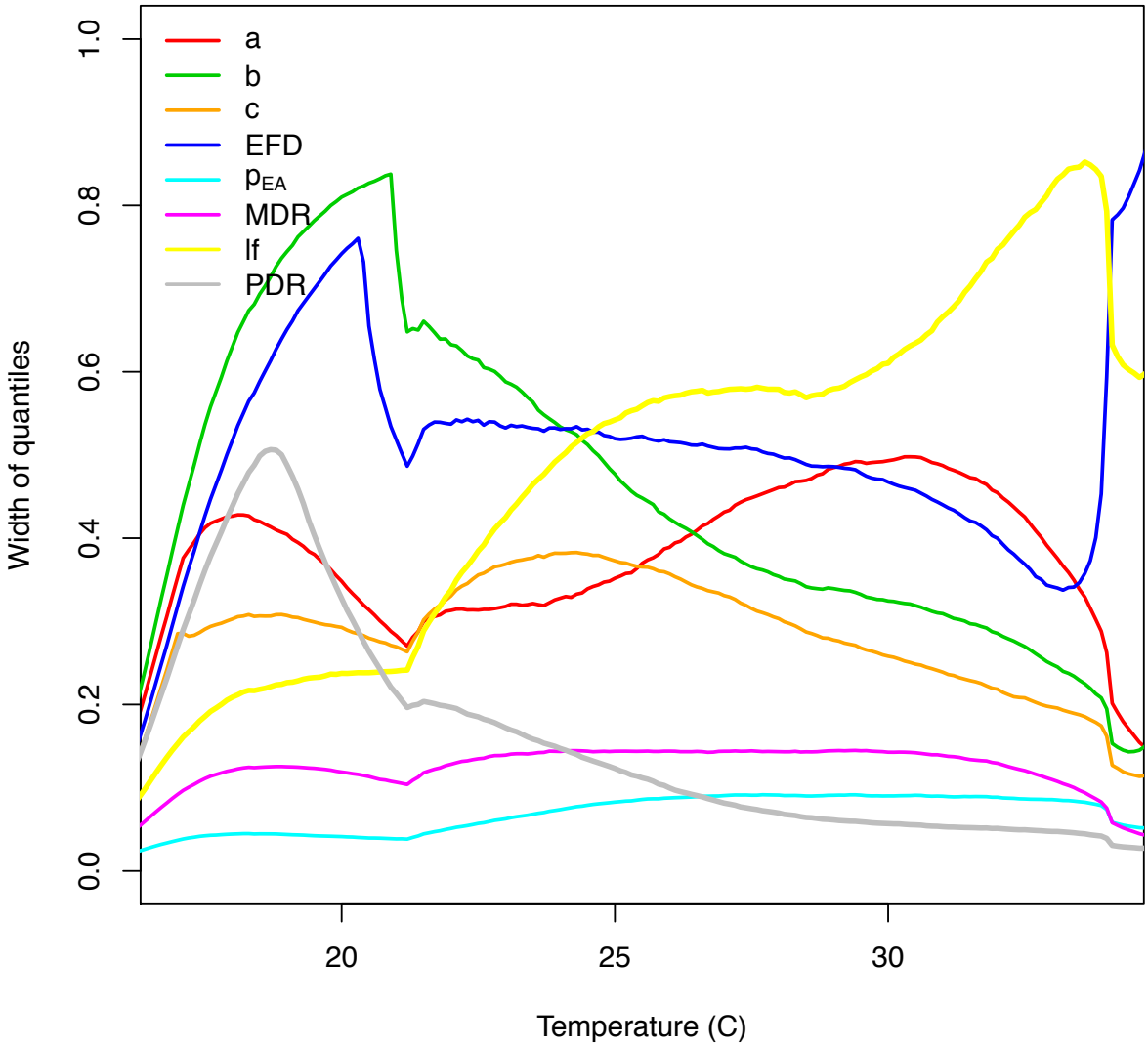

Fig. S14

Uncertainty analysis for *Ae. aegypti* R_0 model, as described in the caption for Fig. S13. Parameters are defined in Table S2.

Table S1. Data used in the *Ae. albopictus* R_0 model. Each trait parameter symbol, definition, data sources, and thermal response function (Quad = quadratic) are shown on the left. Mean and 95% credible interval (95% HPD interval) for the critical thermal minimum (T_0), maximum, (T_m), and a rate constant (c) are given for each trait in the three right sections. * indicates unpublished data provided by Francis Ezeakacha.

Trait	Definition	Refs	Function	T_0			T_m			c		
				Mean	95% CI		Mean	95% CI		Mean	95% CI	
a	biting rate, calculated as reciprocal of oviposition cycle length (1/days)	(5)	Brière	10.25	5.84	14.82	38.32	36.60	40.51	1.93E-04	1.27E-04	2.61E-04
TFD	eggs laid per female per gonotrophic cycle (number/female)	(5,6)	Brière	8.02	3.18	13.08	35.65	35.00	36.51	4.88E-02	3.21E-02	6.72E-02
pEA	mosquito egg-to-adult survival probability	(5,7–10)	Quad	9.04	6.37	11.67	39.33	37.17	41.62	-3.61E-03	-4.74E-03	-2.59E-03
MDR	mosquito egg-to-adult development rate (1/days)	(5–8,10–14)*	Brière	8.60	4.43	12.29	39.66	37.78	41.70	6.38E-05	4.67E-05	8.23E-05
lf	mosquito adult lifespan (days)	(6,11,15)	Quad	13.41	10.53	16.11	31.51	29.14	33.57	-1.43E+00	-2.16E+00	-6.89E-01
b	probability that a mosquito infected with DENV becomes infectious (has virus in the salivary glands)	(16)	Brière	15.84	11.42	19.87	36.40	36.00	36.93	7.35E-04	4.36E-04	1.04E-03
c	probability that a mosquito fed on DENV-infected blood becomes infected	(16)	Brière	3.62	0.00	9.90	36.82	36.00	37.88	4.39E-04	3.29E-04	5.66E-04
PDR	DENV extrinsic incubation rate (reciprocal of the extrinsic incubation period: the time required for an exposed mosquito to become infectious; 1/days)	(16)	Brière	10.39	2.82	17.60	43.05	37.54	49.56	1.09E-04	5.45E-05	1.76E-04

Table S2.

Data used in the *Ae. aegypti* R_0 model. Each trait parameter symbol, definition, data sources, and thermal response function (Quad = quadratic) are shown on the left. Mean and 95% credible interval (95% HPD interval) for the critical thermal minimum (T_0), maximum, (T_m), and a rate constant (c) are given for each trait in the three right sections.

Trait	Definition	Refs	Function	T_0			T_m			c		
				Mean	95% CI		Mean	95% CI		Mean	95% CI	
a	biting rate, calculated as reciprocal of oviposition cycle length (1/days)	(2,17)	Brière	13.35	8.27	17.41	40.08	40.00	40.28	2.02E-04	1.20E-04	2.80E-04
EFD	eggs laid per female per day (number/female/day)	(18, 19)	Brière	14.58	8.08	20.60	34.61	34.00	35.77	8.56E-03	3.78E-03	1.41E-02
pEA	mosquito egg-to-adult survival probability	(7,20–23)	Quad	13.56	12.56	14.51	38.29	37.54	39.02	-5.99E-03	-6.82E-03	-5.13E-03
MDR	mosquito egg-to-adult development rate (1/days)	(7,20–24)	Brière	11.36	7.19	15.03	39.17	39.00	39.54	7.86E-05	5.75E-05	9.93E-05
lf	mosquito adult lifespan (days)	(18, 19)	Quad	9.16	6.69	12.33	37.73	35.68	39.89	-1.48E-01	-2.06E-01	-9.77E-02
b	probability that a mosquito infected with DENV becomes infectious (has virus in the salivary glands)	(25–27)	Brière	17.05	12.56	21.26	35.83	35.06	36.69	8.49E-04	5.07E-04	1.20E-03
c	probability that a mosquito fed on DENV-infected blood becomes infected	(25, 27)	Brière	12.22	5.61	17.76	37.46	35.70	39.29	4.91E-04	3.33E-04	6.41E-04
PDR	DENV extrinsic incubation rate (reciprocal of the extrinsic incubation period: the time required for an exposed mosquito to become infectious; 1/days)	(25, 27–31)	Brière	10.68	3.86	18.33	45.90	39.73	52.92	6.65E-05	3.60E-05	1.09E-04

Table S3.

Aedes spp. trait thermal response data used to generate informative priors for the main *Ae. albopictus* and *Ae. aegypti* R_0 models. Mean and 95% credible interval (95% HPD interval) for the critical thermal minimum (T_0), maximum, (T_m), and a rate constant (c) are given for each trait in the three right sections.

Trait	Definition	Refs	Function	T_0			T_m			c		
				Mean	95% CI		Mean	95% CI		Mean	95% CI	
a	biting rate, calculated as reciprocal of oviposition cycle length (1/days)	(15)	Brière	14.67	10.67	18.34	41.00	37.56	44.99	2.71E-04	1.59E-04	4.09E-04
EFD	eggs laid per female per day (number/female/day)	(32)	Brière	14.06	11.32	16.60	32.03	30.95	33.35	2.08E-02	1.36E-02	2.89E-02
pEA	mosquito egg-to-adult survival probability	(33)	Quad	7.68	6.48	8.90	38.31	36.99	39.57	-3.36E-03	-4.02E-03	-2.72E-03
MDR	mosquito egg-to-adult development rate (1/days)	(32, 33)	Brière	15.12	9.56	19.93	37.67	36.54	38.45	1.49E-04	8.59E-05	2.17E-04
lf	mosquito adult lifespan (days)	(32)	Quad	16.63	15.93	17.25	31.85	31.16	32.64	-1.24E+00	-1.50E+00	-9.76E-01
b	probability that a mosquito infected with flavivirus becomes infectious (has virus in the salivary glands)	(34)	Brière	12.05	8.18	15.09	32.79	32.02	34.32	9.86E-04	5.97E-04	1.34E-03
c	probability that a mosquito fed on flavivirus-infected blood becomes infected	(34)	Brière	1.51	0.00	4.11	34.74	32.87	37.18	5.23E-04	4.10E-04	6.32E-04
PDR	WNV, SLEV, WEEV extrinsic incubation rate (reciprocal of the extrinsic incubation period: the time required for an exposed mosquito to become infectious; 1/days)	(35)	Brière	11.50	3.43	18.55	38.97	33.08	45.00	1.04E-04	3.79E-05	1.93E-04