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Climate change and the resurgence of malaria in the East African highlands

Simon I. Hay[*,†], **Jonathan Cox**[‡], **David J. Rogers**[*], **Sarah E. Randolph**[§], **David I. Stern**[||], **G. Dennis Shanks**[¶], **Monica F. Myers**[#], and **Robert W. Snow**[†,*]

[*]TALA Research Group, Department of Zoology, University of Oxford, South Parks Road, Oxford OX1 3PS, UK

[†]Kenya Medical Research Institute/Wellcome Trust Collaborative Programme, PO Box 43640, Nairobi, Kenya

[‡]Department of Infectious and Tropical Diseases, London School of Hygiene and Tropical Medicine, Keppel Street, London, WC1E 7HT, UK

[§]Oxford Tick Research Group, Department of Zoology, University of Oxford, South Parks Road, Oxford OX1 3PS, UK

[||]Centre for Resource and Environmental Studies, The Australian National University, Canberra ACT 0200, Australia

[¶]US Army Medical Research Unit – Kenya, Box 30137, Nairobi, Kenya

[#]Decision Systems Technologies, Inc. (DSTI), 1700 Research Boulevard, Suite 200, Rockville, Maryland 200850, USA

[*]Centre for Tropical Medicine, University of Oxford, John Radcliffe Hospital, Oxford OX3 9DU, UK

Abstract

The public health and economic consequences of *Plasmodium falciparum* malaria are once again regarded as priorities for global development. There has been much speculation on whether anthropogenic climate change is exacerbating the malaria problem, especially in areas of high altitude where *P. falciparum* transmission is limited by low temperature[1-4]. The International Panel on Climate Change has concluded that there is likely to be a net extension in the distribution of malaria and an increase in incidence within this range[5]. We investigated long-term meteorological trends in four high-altitude sites in East Africa, where increases in malaria have been reported in the past two decades. Here we show that temperature, rainfall, vapour pressure and the number of months suitable for *P. falciparum* transmission have not changed significantly during the past century or during the period of reported malaria resurgence. A high degree of temporal and spatial variation in the climate of East Africa suggests further that claimed associations between local malaria resurgences and regional changes in climate are overly simplistic.

The resurgence of malaria caused by *P. falciparum* in the East African highlands has been reported widely (see Supplementary Information). From 1986 to 1998, the tea estates of

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Correspondence and requests for materials should be addressed to S.I.H. (simon.hay@zoo.ox.ac.uk)..

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Competing interests statement
The authors declare that they have no competing financial interests.

Kericho in western Kenya saw a rise in severe malaria cases from 16 to 120 per 1,000 per year[6]. In Kabale, southwestern Uganda, the average monthly incidence has increased from about 17 cases per 1,000 (1992–96 average) to 24 cases per 1,000 (1997–98 average)[7,8]. Gikonko in southern Rwanda has seen annual incidence rise from 160 to 260 cases per 1,000 from 1976 to 1990 (ref. 1). Muhanga in northern Burundi had an average of 18 malaria deaths per 1,000 during the 1980s, which rose to between 25 and 35 deaths per 1,000 in 1991 (ref. 9). These increases, considered alongside evidence of a global increase in the average surface temperature of 0.6 °C this century[10], have fuelled speculation that temperature-related increases in transmission of *P. falciparum* are already manifest[1-4]. Although these claims have met with robust counter argument[11,12], there has been no critical examination of climate change at these sites.

We have investigated long-term trends in meteorological data at these four highland sites using a 95-year data set of global terrestrial climate[13,14] (see Supplementary Information). Reliable data were available for monthly mean temperature, vapour pressure and rainfall from January 1911 to December 1995. Reliable data for diurnal temperature range (DTR) spanned the 1950–95 period. We excluded observations from periods when the distribution of meteorological stations was too sparse for reliable interpolation[14]. The remaining data were divided into two sample periods before being examined for trends using augmented Dickey–Fuller (ADF) test procedures[15,16].

To make use of the longest series possible from the primary meteorological variables (Methods), but exclude the anomalous pre-1911 data, we tested monthly mean temperature, rainfall and vapour pressure from January 1911 to December 1995 (Table 1). To check that a low signal-to-noise ratio in the monthly data was not causing false rejection of the null hypothesis of a stochastic trend, the analyses were repeated on average annual data for the same period (Table 2). The suitability of each month for *P. falciparum* malaria transmission depends on a combination of temperature and rainfall conditions[10]; the annual numbers of such months were tested for trends from 1901 to 1995 (Table 2, Fig. 1). In addition, ADF tests for the period January 1970 to December 1995 were examined for trends in the monthly data during the period coincident with the reported resurgences in malaria (Table 3, Fig. 2). These tests also included the additional secondary variables (Methods) of monthly minimum and maximum temperature (Table 3) to check for trends in temperature range that might have been masked by analyses of monthly mean data.

The ADF tests indicated that all of the monthly meteorological time series during the two time periods examined were stationary around a linear time trend (that is, contained no stochastic trends); therefore, standard statistical distributions could be applied and used to infer whether time trends were present. If all the time series actually contain random walks, then we would find no trends, because the t-statistics associated with α are not significant. We adjusted adequately for serial autocorrelation in all tests (Q statistic not significant).

The analyses showed that there were no significant changes in temperature or vapour pressure at any of the four locations during the 1911–95 period. Rainfall increased only at Muhanga, and the months suitable for *P. falciparum* transmission increased only at Kabale. The average number of months suitable for transmission was consistently low, which validated the choice of highland locations as areas that are sensitive to climate-mediated increases in malaria transmission. There were also no changes in any of the meteorological variables during the period after 1970. Several of the ADF tests repeated with the annual data indicated the presence of stochastic trends. Because malaria transmission responds to climate, the presence of a random walk in the climate data could induce a random walk (but without a significant drift) in the malaria data. But in these cases the t-statistic for α is not significant, and thus there is no systematic drift in the series. At Muhanga, the annual data, similar to the monthly data, show a significant increase in rainfall. The absence of long- and short-term change in the climate variables and the duration of *P. falciparum* malaria transmission suitability at these highland sites are not consistent with the simplistic notion that recent malaria resurgences in these areas are caused by rising temperatures.

Further analysis showed significant spatial and temporal variation in the differences between mean decadal temperature and rainfall (Fig. 3) and their respective 1901–95 averages. Positive and negative deviations in a decade can be greater than any of the long-term differences shown in Table 1; cooling and wetting in the 1960s are particularly evident. Marked independent and variable changes in meteorological conditions have also been found in recent analyses of minimum and maximum temperature trends in the East African subregion, using daily records from 71 meteorological stations between 1939 and 1992 (ref. 17). These complexities warn against attributing local changes in malaria transmission simply to a regional warming of the East African highlands. For example, the decadal means from 1971 to 1995 show a general warming and wetting coincident with the resurgence of malaria in the past two decades, but historical data from Kericho[18] show a series of very severe malaria epidemics in the 1940s—a decade that was substantially cooler and drier than average. Similar inconsistencies in attributing recent epidemiological changes to climate have been identified for the highlands of Uganda, Tanzania and Madagascar[12].

If climate has not changed at the four study sites, other changes must have been responsible for the observed increases in malaria. At Kericho, the evidence suggests that the control of malaria implemented since the large epidemics of the 1940s (ref. 18) has failed recently because of a rise in antimalarial drug resistance[6,19]. Like wise, the resurgence of malaria in the Usambara mountains of Tanzania has been linked to a rise in drug resistance[20], casting doubt on the previous interpretation of local changes in climate caused by deforestation[21]. In southern Uganda, epidemiological changes have been attributed to the shorter-term climate phenomenon of El Niño[7], which is suggested to cause changes in vector abundance[8]. At Muhanga, both land use changes and elevated temperatures have been proposed to have caused the malaria increases[9]. In other highland locations in Africa, increases in malaria have been attributed to population migration and the breakdown in both health service provision and vector control operations[22]. Economic, social and political factors can therefore explain recent resurgences in malaria and other mosquito-borne diseases[12] with no need to invoke climate change.

Global climate change continues to generate considerable political, public and academic interest and controversy, reflected in conflicting statements from international bodies on climate change and its implications for human health[5,23] (see Supplementary Information). We have shown that at four sites in the highlands of East Africa there has been very little change in any meteorological variables during the past century or during the period of reported malaria resurgences. In addition, the spatio-temporal variability of the climate in the region suggests that any links between malaria increases and climate change can only be examined using data coincident in space and time. The most parsimonious explanation for recent changes in malaria epidemiology involves factors other than climate change. The more certain climatologists become that humans are affecting global climates, the more critical epidemiologists should be of the evidence indicating that these changes affect malaria.

Methods

Data

Meteorological data were obtained from a global 0.5 × 0.5° gridded data set of monthly terrestrial surface climate for the 1901–95 period[13,14]. Primary variables of precipitation (hereafter rainfall), mean temperature and DTR were interpolated from extensive meteorological station records using angular distance weighted averaging of anomaly fields to produce spatially contiguous climate surfaces[13,14]. The secondary variable of vapour pressure was interpolated where available, and calculated from primary variables where the coverage of meteorological stations was insufficient. Minimum and maximum monthly temperature estimates were created from the original climate surfaces by subtracting or adding, respectively, half the DTR from mean monthly temperature. Time series were derived for each of the highland study sites using an extraction routine developed in ENVI (Research Systems) and georeferencing information obtained from Encarta (Microsoft). We selected subsets of the full climatic data series for trend analysis as described in the main text.

To investigate whether a combination of meteorological conditions, or the occurrence of extreme meteorological events, was changing to facilitate transmission, we categorized months as suitable for malaria transmission using threshold figures defined for the highland regions of Kenya[24]: that is, mean monthly temperature above 15 °C and total monthly rainfall exceeding 152 mm. Two consecutive months of such conditions are required to develop a population of infective mosquitoes. The numbers of suitable months for transmission were summed for each year and tested from 1901 to 1995.

Statistical theory

If a time series can be characterized as the sum of a stationary stochastic process and a linear time trend, then the appropriate test for a trend is to regress the series on a linear trend and carry out a t-test on the slope. If the series is a random walk, or a more complex stochastically trending process, the critical levels for the distribution of the t-score in this regression are much greater than usual[25] and alternative tests should be used. Because many climate time series contain a stochastically trending component[26], the nature of the series must be explored before testing for climate change.

In the first-order autoregressive model:

$$yt=\alpha+\rho y_{t-1}+\beta t+\epsilon_t \qquad (1)$$

where α, β and ρ are regression parameters, ε_t is normally distributed with mean zero, and t is a deterministic time trend. If the autoregressive parameter, ρ, is <1, the effects of the shocks introduced by the error term ε_t fade over time. In addition, if β is zero the variable y has a constant mean and is stationary. If β is not zero, then y is non-stationary, but subtraction of βt from both sides of equation (1) would yield a stationary process with β distributed normally; in this case y is called a trend-stationary variable.

If $\rho = 1$ (a unit root in the autoregressive process) and $\beta = 0$, then y is a random walk. The random walk may also have a deterministic drift term ($\alpha \neq 0$). In either case, however, the series is non-stationary and classical regression inference does not apply. The non-standard distributions of α, β and ρ have been tabulated[15,16].

Statistical methods

We estimate the following generalization of equation (1):

$$\Delta y_t=\alpha+\beta_t+\gamma y_{t-1}+\sum_{i=1}^{p}\delta_i\Delta y_{t-1}+\sum_{j=1}^{12}\mu_j d_j+\epsilon_t \qquad (2)$$

which allows for higher order autoregressive terms through the lagged dependent variables and for seasonal effects by way of the centred dummy variables, d_j, that model monthly variations in climate for the monthly meteorological series. The coefficients μ_j sum to zero. We chose the number of lags, p, using the adjusted R^2 statistic. The maximal number of lags, p, considered was 12 for the monthly and 4 for the annual series. y_{t-1} has been subtracted from both sides of equation (2) and therefore $\gamma = (\rho - 1)$. The null hypothesis is that $\gamma = 0$, which implies that y is a random walk with drift α; the alternative hypothesis is that y is a trend-stationary variable with slope β. The critical value for the ADF t-statistic associated with γ at the 5% level is −3.45. Values of the t-statistic for a more negative value of γ than this critical value indicate that the series is not a random walk and vice versa. If the null hypothesis is rejected, then the t-statistics associated with α and β are normally distributed. If the unit root hypothesis is accepted, then these statistics also have non-standard distributions. The correct test for a trend is, then, the t-test on a in α version of equation (2) that omits the linear trend. Its critical value at the 5% significance level is 2.54. Because meteorological time series may be noisy and result in the ADF test incorrectly rejecting the null hypothesis that $\gamma = 0$ (ref. 27), we present the t-statistic for a, even when the stochastic trend hypothesis is formally rejected. The tests were also repeated on annual data for the full time period to check whether the reduction in noise caused by annual averaging affected the results.

Supplementary Material

Refer to Web version on PubMed Central for supplementary material.

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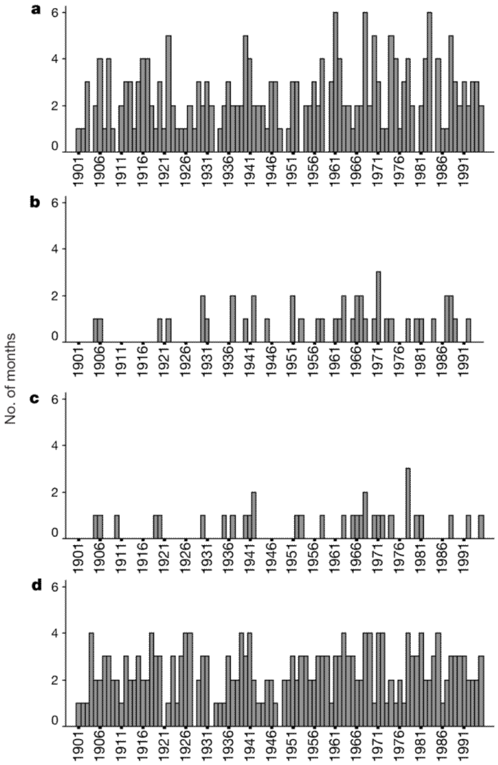

Figure 1.

Number of months suitable for *P. falciparum* malaria transmission defined by the Garnham criteria (temperature > 15 °C and rainfall > 152 mm in two consecutive months)[24]. Shown are annual observations from 1901 to 1995 for Kericho (**a**), Kabale (**b**), Gikonko (**c**) and Muhanga (**d**).

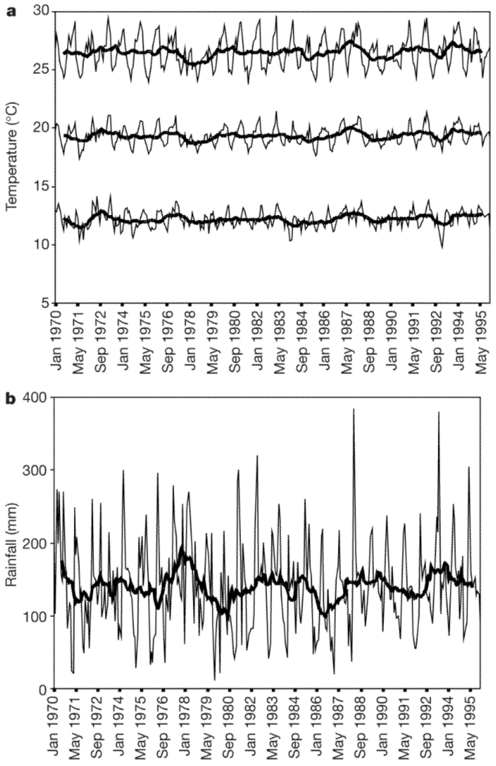

Figure 2.

Meteorological time series from Kericho. **a**, Minimum (bottom), mean (middle) and maximum (top) monthly temperatures, plotted with a 13-point moving average (thick line) to show the long-term movement in these data. **b**, Total monthly rainfall, plotted with a 13-point moving average (thick line). For a comprehensive version with time series for all four highland sites, see Supplementary Information.

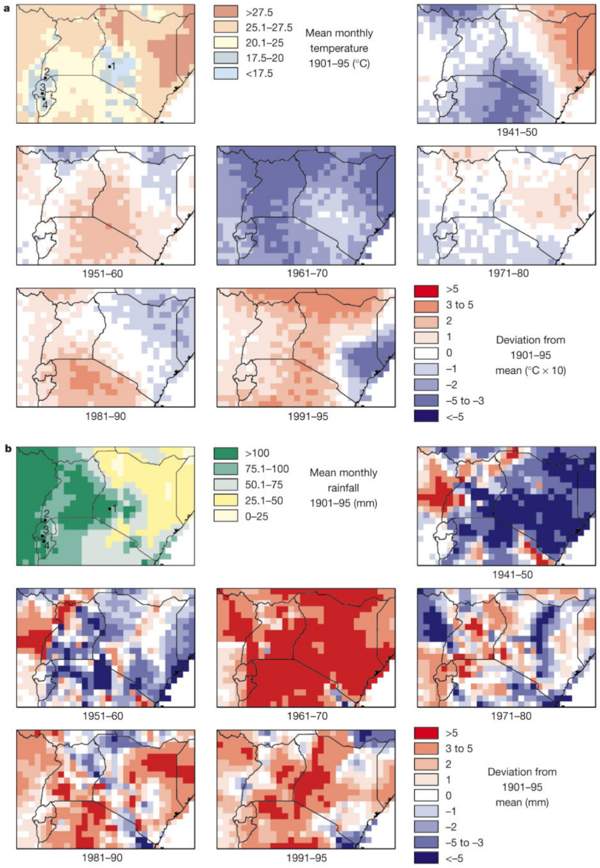

Figure 3.

Spatio-temporal variation in temperature and rainfall in East Africa. **a**, Mean monthly temperature for the 1901–95 period, and deviations from this long-term average by decade (1940–95). The four sites are indicated: 1, Kericho; 2, Kabale; 3, Gikonko; 4, Muhanga. b, Mean monthly rainfall for the 1901–95 period, and deviations from this long-term average by decade (1940–95).

Table 1

Trend of monthly meteorological variables in four sites in the highlands of East Africa (1911-95)

	ρ	ADF	β	t	*P* value	τα	Q	Sig. of *Q*
Kericho, western Kenya (0.33°S, 35.37°E; 1,700–2,200 m)								
Temp. mean (°C)	7	−6.50*	0.0004	0.65	0.5482	−0.0372	49.2885	0.0690
Rainfall (mm)	4	−12.03*	0.0396	0.69	0.5149	0.0432	23.1425	0.9520
Vapour pressure (hPa)	10	−5.47*	0.0034	0.65	0.5827	−0.0594	23.7975	0.9408
Kabale, southwestern Uganda (1.25°S, 29.98°E, 1,500–2,400 m)								
Temp. mean (°C)	10	−5.99*	-4.17×10^{-5}	0.00	0.9421	−0.0806	28.3227	0.8155
Rainfall (mm)	10	−7.96*	0.0679	1.37	0.1803	0.1030	26.7531	0.8686
Vapour pressure (hPa)	11	−5.45*	−0.0032	−0.40	0.5851	−0.0456	23.3893	0.9480
Gikonko, southern Rwanda (2.48°S, 29.85°E, 1,485–1,596 m)								
Temp. mean (°C)	10	−5.76*	1.18×10^{-5}	0.11	0.9833	−0.0634	30.3167	0.7353
Rainfall (mm)	10	−8.09*	0.0686	2.01	0.0508	0.0742	20.1771	0.9846
Vapour pressure (hPa)	11	−5.15*	−0.0025	−0.23	0.6993	−0.0261	30.2362	0.7388
Muhanga, northern Burundi (3.02°S, 29.83°E, 1,420–1,450 m)								
Temp. mean (°C)	11	−5.40*	2.19×10^{-5}	0.15	0.9698	−0.0175	35.1080	0.5108
Rainfall (mm)	6	−11.80*	0.0767	2.39*	0.0203	0.0034	23.7328	0.9420
Vapour pressure (hPa)	11	−5.12*	−0.0022	−0.16	0.7274	0.0024	39.3357	0.3229

[*] Significance at the 5% level. ρ is the number of lagged differenced dependent variables (equation 2) selected. ADF is the augmented Dickey–Fuller *t*-test for $\gamma = 0$ in equation (2). The 5% critical value is −3.45. Exact *P* values are not available for the ADF and τα statistics. The distribution of the *t*-statistic for the slope parameter β has the standard *t* distribution under the assumption that $\gamma < 0$. τα is the *t*-statistic for the intercept term in the autoregression without a linear time trend. This is the appropriate test for a trend if $\gamma = 0$. Its 5% critical value is 2.54. The *Q* statistic is a portmanteau test for general serial correlation and is distributed as χ^2 (ref. 27).

Table 2

Trend of annual meteorological variables in four sites in the highlands of East Africa (1911–95)

	ρ	ADF	β	t	P	τ α	Q	Sig. of *Q*
Kericho, western Kenya (0.33°S, 35.37°E; 1,700–2,200 m)								
Temp. mean (°C)	3	−2.79	0.0010	0.66	0.5096	0.0031	16.0974	0.7106
Rainfall (mm)	2	−5.96[*]	0.8246	0.83	0.4082	−0.0153	17.4068	0.6264
Vapour pressure (hPa)	2	−3.03	0.0125	0.75	0.4556	−0.0332	12.8234	0.8848
Malaria (months)[†]	1	−8.34[*]	0.0106	1.85	0.0665	0.1881	16.4162	0.8369
Kabale, southwestern Uganda (1.25°S, 29.98°E, 1,500–2,400 m)								
Temp. mean (°C)	0	−5.42[*]	−0.0002	−0.13	0.8950	0.0096	18.0473	0.6460
Rainfall (mm)	4	−2.95	0.5861	0.82	0.4123	0.2656	8.9009	0.9840
Vapour pressure (hPa)	4	−4.25[*]	−0.0071	−0.51	0.6086	−0.0716	11.3198	0.9375
Malaria (months)[†]	0	−9.03[*]	0.0062	2.26[*]	0.0265	0.0594	23.7327	0.4187
Gikonko, southern Rwanda (2.48° S, 29.85° E, 1,485–1,596 m)								
Temp. mean (°C)	2	−3.32	0.0005	0.38	0.7044	−0.1591	19.5274	0.4878
Rainfall (mm)	4	−3.13	0.8200	1.69	0.0943	0.1957	15.6722	0.7367
Vapour pressure (hPa)	4	−3.94[*]	−0.0042	−0.27	0.7868	−0.0808	13.0386	0.8757
Malaria (months)[†]	0	−9.21[*]	0.0034	1.53	0.1291	0.0680	23.7327	0.4187
Muhanga, northern Burundi (3.02° S, 29.83° E, 1,420–1,450 m)								
Temp. mean (°C)	2	−3.22	0.0005	0.42	0.6734	−0.1263	17.6252	0.6121
Rainfall (mm)	1	−8.63[*]	1.1091	3.05[*]	0.0031	−0.0159	19.2302	0.5704
Vapour pressure (hPa)	3	−3.57[*]	−0.0005	−0.03	0.9740	−0.0986	15.2409	0.7625
Malaria (months)[†]	1	−7.25[*]	0.0057	1.35	0.1794	0.2470	13.0610	0.9507

[*] Significance at the 5% level. For definitions of the statistical terms and validity of the tests see Table 1.

[†] Indicates the number of months suitable for *P. falciparum malaria* transmission defined by the Garnham criteria[24] and includes annual observations from 1901 to 1995.

Table 3

Trend of monthly meteorological variables in four sites in the highlands of East Africa (1970–95)

	ρ	ADF	β	t	P	τ α	Q	Sig. of *Q*
Kericho, western Kenya (0.33° S, 35.37° E; 1,700–2,200 m)								
Temp. min (°C)	0	−9.30*	0.0038	1.07	0.2844	−0.0306	33.1183	0.6064
Temp. mean (°C)	4	−6.11*	0.0031	1.01	0.3140	0.0052	31.0197	0.7042
Temp. max (°C)	4	−6.46*	0.0031	0.62	0.5387	0.1469	41.2922	0.2504
Rainfall (mm)	0	−15.11*	−0.0586	−0.16	0.8702	0.0121	40.4090	0.2817
Vapour pressure (hPa)	0	−9.42*	0.0383	1.18	0.2400	−0.0289	34.5958	0.5354
Kabale, southwestern Uganda (1.25° S, 29.98° E, 1,500–2,400 m)								
Temp. min (°C)	2	−5.28*	0.0009	0.28	0.7810	−0.0765	36.9004	0.4271
Temp. mean (°C)	2	−4.98*	0.0040	1.32	0.1886	−0.0358	40.9733	0.2614
Temp. max (°C)	3	−6.96*	0.0082	1.86	0.0636	0.0450	38.9686	0.3377
Rainfall (mm)	0	−17.94*	−0.2388	−0.90	0.3690	0.0006	39.3606	0.3219
Vapour pressure (hPa)	2	−5.23*	0.0084	0.28	0.7804	−0.0713	37.7502	0.3892
Gikonko, southern Rwanda (2.48° S, 29.85° E, 1,485–1,596 m)								
Temp. min (°C)	6	−3.64*	0.0008	0.26	0.7931	0.025	30.1194	0.7438
Temp. mean (°C)	1	−6.59*	0.0041	1.38	0.1671	0.0433	45.1175	0.1418
Temp. max (°C)	3	−5.55*	0.0087	1.95	0.0517	0.0623	35.3523	0.4992
Rainfall (mm)	0	−18.52*	−0.2029	−1.20	0.2305	0.0003	45.1086	0.1420
Vapour pressure (hPa)	6	−3.69*	0.0100	0.29	0.7735	0.0198	31.2663	0.6932
Muhunga, northern Burundi (3.02° S, 29.83° E, 1,420–1,450 m)								
Temp. min (°C)	6	−3.93*	0.0007	0.22	0.8246	−0.0045	32.7525	0.6238
Temp. mean (°C)	1	−6.95*	0.0042	1.41	0.1595	0.0616	42.9407	0.1982
Temp. max (°C)	3	−5.54*	0.0089	1.95	0.0517	0.0884	32.9237	0.6157
Rainfall (mm)	0	−18.71*	−0.1238	−0.80	0.4271	−0.0007	41.2654	0.2513
Vapour pressure (hPa)	6	−3.95*	0.0094	0.27	0.7850	−0.0142	35.5576	0.4895

[*] Significance at the 5% level. For definitions of the statistical terms and validity of the tests see Table 1.