BILINGUAL PUBLISHING GROUP

Journal of Atmospheric Science Research
https://journals.bilpubgroup.com/index.php/jasr/index

ARTICLE

Analysis of Extreme Temperature Variability in Rwanda

Protais Seshaba[1], ***Edouard Singirankabo***[2*], ***Donat Nsabimana***[3]

[1] *Department of Science and Humanities, Protestant Institute of Arts and Social Sciences, P O Box 619, Huye, Rwanda*
[2] *Department of Mathematics, Science and Physical Education, University of Rwanda, College of Education, P O Box 55, Rukara, Rwanda*
[3] *Department of Forestry, University of Rwanda, College of Science and Technology, P O Box 55, Huye, Rwanda*

ABSTRACT

The temperature is one of the most important factors in weather and climate forecasting. Studying its behaviour is crucial to understanding climate variability, which could vary spatially and temporally at local, regional, and global scales. Several recent studies on air temperature findings show that the Earth's near surface air temperature increased between 0.6 °C and 0.8 °C throughout the twentieth century. Using temperature records from ten meteorological stations, this study examined climate variability in Rwanda from the 1930s to 2014. The air temperature data were collected from Meteo Rwanda. Before making the analysis, the authors used software, such as Excel 2007 and INSTAT to control the quality of the raw data. The analysis of maxima and minima indicated that the trends of maximum air temperature were positive and significant at height meteorological stations, whereas the trends for minimum air temperature were found to be at 10 meteorological stations. For all parameters analysed, Kigali Airport meteorological station indicated the higher significance of the trends. The majority of meteorological stations showed an increase in both hot days and nights, confirming Rwanda's warming over time. The analysis of average seasonal air temperature showed almost similar trends even though not all were significant. This similarity in trends could be attributed to the fact that Rwanda's short and long dry seasons coincide with rainy seasons.

Keywords: Climate variability; Air temperature; Solar radiation; Meteorological station

*CORRESPONDING AUTHOR:
Portain Seshaba, Department of Science and Humanities, Protestant Institute of Arts and Social Sciences, P O Box 619, Huye, Rwanda;
Email: nkabo12edus@gmail.com

ARTICLE INFO
Received: 27 November 2023 | Revised: 15 January 2024 | Accepted: 22 January 2024 | Published Online: 26 January 2024
DOI: https://doi.org/10.30564/jasr.v7i1.6107

CITATION
Seshaba, P., Singirankabo, E., Nsabimana, D., 2024. Analysis of Extreme Temperature Variability in Rwanda. Journal of Atmospheric Science Research. 7(1): 74–89. DOI: https://doi.org/10.30564/jasr.v7i1.6107

1. Introduction

One of the elements in weather control is temperature, which is measured for a variety of purposes. Apart from the temperature variation such as ground, soil, and sea water temperature, air temperature is the most common variable measured at various heights. WMO defined air temperature as "*the temperature indicated by a thermometer exposed to the air in a place sheltered from direct solar radiation*" [1]. Thermometers that indicate the prevailing temperature are often known as ordinary thermometers, while those that indicate extreme temperatures over a period of time are called maximum or minimum thermometers. Enz et al. [2] indicated that the measured air temperature around the Earth's surface originates from the sun and emits its radiation of high temperature (5,727 °C or 10,341 °F) which consists of very short wavelengths that carry large amounts of energy. The Earth, after being heated by the sun radiation, becomes a radiating body and it radiates energy to the atmosphere in long waveforms that carry only small amounts of energy, compared with that carried by solar radiation.

Normally, land accumulates the temperature during the daytime and as the sun sets the temperature falls rapidly and continues to fall until it reaches its minimum as the Earth's surface keeps emitting the energy received in the daytime than it receives [2,3]. The WMO [1] showed that air temperature distribution varies at any place due to factors like the latitude of the place, the longitude of the place, the air mass circulation, the presence of warm and cold ocean currents and local aspects.

IPCC [4] reported that the signs of warming of the climate system are clear and prevailing, as it is now evident from observations of increases in global average air and ocean temperatures, widespread melting of snow and ice and rising global average sea level. The average global surface air temperature has warmed 0.8 °C in the past century and 0.6 °C in the past three decades [5], due to different human activities [6]. However, Katz and Brown [7] argued that this warming was not spatially or temporally uniform. The IPCC [8] has projected that greenhouse gas emissions lead to the cause of climate change and contribute to the tremendous rise of temperature, which influences global warming hence the world temperature should increase by 1.4–5.8 °C by the end of the 21st century.

Observational records show that during the 20th century, the continent of Africa has been warming at a rate of about 0.05 °C per decade, with slightly larger warming in the June–November seasons than in December–May [9]. By 2000, the five warmest years in Africa had all occurred since 1988, where the years 1988 and 1995 are the two warmest years [10]. Warming projections under medium scenarios indicate that extensive areas of Africa exceeded 2 °C during the last 2 decades of this century relative to the late 20th century means annual temperature and all of Africa under high emission scenarios [11].

DFID [12] indicated that countries of Eastern Africa are exposed to extreme climatic events such as droughts. For instance, during the 1970s and 1980s, droughts caused widespread famine and economic hardships in many countries of the sub-Saharan region, which is in agreement with the study of Nash and Ngabitsinze [13].

Numerous studies on long-term climate fluctuations in various parts of the world show that it is likely that the effects of climate change will challenge and even reverse the advancements made in many African countries' socio-economic well-being [14]. It was indeed shown that Rwanda has experienced temperature increases higher than the global average (1.4 °C since 1970), accompanied by air temperature extremes that generated negative impacts throughout the country [15]. Hence, the current study aimed at the analysis of patterns of climate variability in Rwanda as indicated by air temperature records (maximum and minimum) and determined related impacts on the socio-economic sector.

In Rwanda, different research on climate variability has been conducted, but they mainly referred to Kigali meteorological station [16]. However, this represents a lack of information from all representative climatic zones in Rwanda. For example, Safari [17] analysed the mean annual temperatures during the last 52 years in Rwanda using only five meteorological stations, such as Kigali, Gitarama, Rubona, Kibuye and Gisenyi. Additionally, Habiyaremye [18] has also studied precipitation, temperature, and humidity variability in Rwanda for 30 years using only data from Kigali Aero meteorological station. The study of (Edouard Singirankabo E. I., 2023) [19] looked at the modelling of maximum extreme temperature in Rwanda using extreme value analysis. They argued that the temperature in Rwanda will continue to rise in the future.

It is observed that these studies did not cover the whole climatic zones of Rwanda which would contribute to showing the real image of climate variability of the country. In addition, the mean annual temperature variability studied by Safari (2012) [17] does not reflect the impact that could be caused by temperatures below or above fixed thresholds on biodiversity such as high drought that could cause plants to dry, low temperatures that could cause crop injury through the hail process and impacts on human health especially high temperatures that could cause death to people and animals. The main objective of the current study is to evaluate and analyse climatic variability in terms of temperature records over the past 83 years. We analyse the trends of minimum and maximum air temperature and discuss the impacts of climate variability in Rwanda. The rest of this paper is organized as follows: Section 2 represents materials and methods; Section 3 describes numerical results and discussion; Section 4 shows conclusions and recommendations.

2. Materials and methods

2.1 Description of the study area

Rwanda is a small, landlocked country in equatorial East Africa covering 26,338 km^2, located at 02°00 Latitude South and 30°00 Longitude East. As indicated on the below political map of Rwanda (**Figure 1**), the country is bordered by the Democratic Republic of Congo (DRC), Burundi, Uganda and Tanzania respectively Western, Southern, Northern and Eastern parts. Rwanda is known as the "*land of a thousand hills*" as its topography is characterized by steep slopes and green hills, upon which its predominantly rural population survives on subsistence agriculture [16]. The average temperature of Rwanda is around 20 °C and varies topographically (**Figure 2**), with a short dry season happening in January–February and a long dry season occurring in June–August [17].

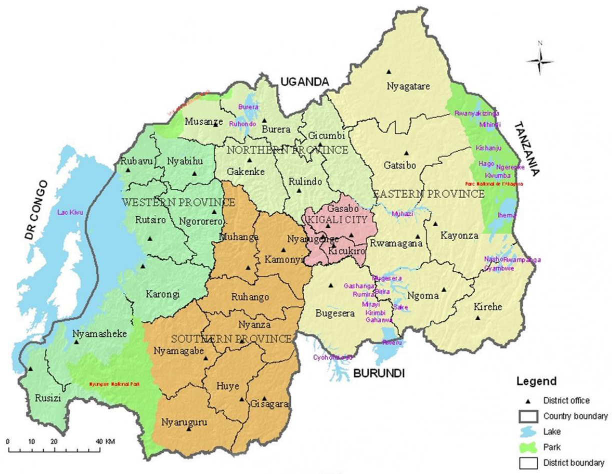


Figure 1. Political map of Rwanda.

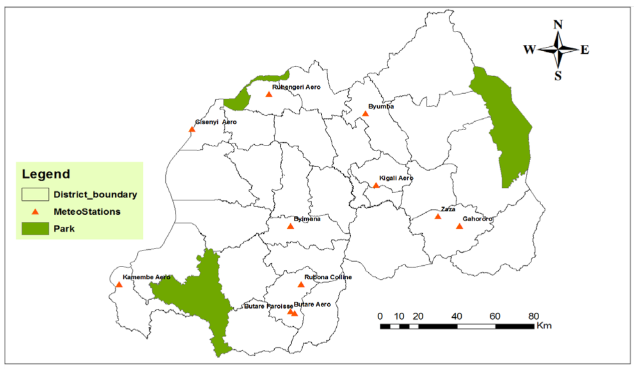


Figure 2. Geographical location of meteorological stations.

Table 1 below lists the meteorological stations whose temperature records were considered in this study.

2.2 Research design

Data source and data collection techniques

This research is both qualitative and quantitative. The data used in this study are collected from the National Meteorological Service, and the time-series of temperature records were collected from Meteo Rwanda based in Kigali. Quality control was performed on raw data before analysis in Excel 2007 and INSTAT Software. The analysis was based on daily minimum and maximum temperature data series.

Sampling techniques

Until today, the total number of meteorological stations that existed plus those still functioning in Rwanda is about 183. The 1990–1994 Tutsi genocide and the war in Rwanda destroyed more than 80% of meteorological infrastructure and a few of them reopened afterwards [20]. During the sampling process, meteorological stations for the current study were purposively selected, based on the availability of daily minimum and maximum temperature data, period of record and fair distribution of the stations across Rwanda [21,22]. The most important criterion in consideration was to select the meteorological station that presents at least 20 years of observation period.

The data of Butare Paroisse and Butare Aero meteorological stations were combined not only because they are located at the same elevation (1760 m, ASL), but also because Butare Paroisse meteorological station stopped working in 1967 and was shifted to Butare Aerodrome in 1971, and the distance between the two locations is less than 1 km. The meteorological stations in Rwanda were not established in the same period and not all are still functioning. Hence, a sub-period-based analysis of air temperature consists of selecting meteorological stations that present the complete temperature datasets at the same subperiod in order to make a realistic comparison of air temperature trends.

2.3 Extreme temperature and thresholds

Changes in annual frequencies of the amount of days and nights with maximum and minimum temperatures in defined categories have been investigated based on some of the indices developed by Collins [23] (see **Table 2**), but also it is important to keep in mind that climate seems to be complex; i.e., temperature can vary differently throughout different places depending on various factors. However, for our study, it was important to consider the temperature categories employed by the forecasting section of Meteo Rwanda, for which temperature thresholds are defined for forecasting purposes (**Table 3**), e.g., when a day or night is defined as hot or cold.

Table 1. List of meteorological stations used in this study.

Meteo-Station	Longitude	Latitude	Elevation (m)	District	Province	Period
Butare Paroisse	29.73	–2.61	1760	Huye	South	1935–1967
Butare Aerodrome	29.71	–2.6	1760	Huye	South	1971–1993
Rubona Colline	29.76	–2.46	1706	Huye	South	1958–2012
Byimana	29.71	–2.16	1750	Ruhango	South	1960–2014
Kamembe Aerodrome	28.91	–2.46	1591	Rusizi	West	1957–2014
Gisenyi Aerodrome	29.25	–1.66	1554	Rubavu	West	1975–2014
Ruhengeri Aerodrome	29.61	–1.48	1878	Musanze	North	1977–2014
Byumba Pref	30.06	–1.58	2235	Gicumbi	North	1945–2011
Kigali Aero	30.11	–1.95	1490	Gasabo	Kigali City	1971–2014
Zaza	30.4	–2.11	1515	Ngoma	East	1945–1994
Gahororo	30.5	–2.16	1607	Ngoma	East	1960–1993

Table 2. Temperature indices used in the analysis of extreme temperatures developed by Collins et al., 2000.

Maximum Temperature Extreme Indices	Minimum Temperature Extreme Indices
Very hot days: $T_x \geq 35$ °C	Hot nights: $T_n \geq 20$ °C
Hot days: 30 °C $\leq T_x <$ 35 °C	Warm nights: 15 °C $\leq T_n <$ 20 °C
Cold days: $T_x \leq 15$ °C	Very cold nights: $T_n \leq 0$ °C
Cool days: 15 °C $< T_x \leq$ 19 °C	Cold nights: 0 °C $< T_n \leq$ 5 °C

Note: T_x: maximum temperature; T_n: minimum temperature.

Table 3. Temperature indices used in the analysis of extreme temperatures developed by Meteo Rwanda.

Maximum Temperature Extreme Indices	Minimum Temperature Extreme Indices
Hot days: Tx ≥ 28 °C	Hot nights: Tn ≥ 18 °C
Cold days: Tx ≤ 25 °C	Cold nights: 0 ºC < Tn ≤ 16 °C

Note: T_x: maximum temperature; T_n: minimum temperature.

3. Numerical results and interpretations

3.1 Monthly maxima and minima in air temperature

Figure 3 indicates trends of monthly maxima and minima air temperatures measured at the 10 meteorological stations in Rwanda. Major stations indicate that minimum temperatures rapidly occurred compared to maximum temperatures as indicated by the regression coefficients. The analysis of 10 meteorological stations (**Figure 3**) showed that 8 of the 10 stations indicated positive trends for the maximum of maximum air temperature, whereas all 10 meteorological stations showed positive trends for the minimum of minimum air temperature.

The results showed the trends of maximum air temperature. Seven out of the ten weather stations showed noteworthy upward trends which is significant. Butare, Gahororo, and Ruhengeri Aero are the three remaining meteo-stations that displayed negative trends and insignificant. Kigali meteorological station presented a greater increase in temperature ($R^2 = 0.2013, p = 0.000$). All 10 meteorological stations showed positive and significant trends for the minimum and minimum air temperature, with Kigali presenting again a higher value of R-squared and a highly significant trend ($R^2 = 0.3702$, p = 0.000) as indicated in **Table 4**.

It was reported by various authors that the minimum air temperature increased faster than the maximum air temperature because of different factors. Folland [24] showed that the minimum air temperatures increased about twice as fast as the maximum temperatures over global land areas since 1950, resulting in a broad decline in the diurnal temperature range (DTR: difference of maximum and minimum air temperature). Among the factors that could affect the minimum air temperature, we note changes in cloud cover, precipitation, soil moisture, and atmospheric circulation likely accounted for much of the trend differential during a given period for example [25–28]. Changes in land use also impacted the difference in maximum and minimum air temperature in some areas [29–32].

As indicated by Christy [29], there are differences between *Tx* and *Tn* trends, especially recently, as they may reflect a response to complex changes in the boundary layer dynamics. They added that the *Tx* represents the significantly greater daytime vertical connection to the deep atmosphere, whereas *Tn* represents only a shallow layer whose air temperature is more dependent on the turbulent state than on the temperature in the upper atmosphere and this turbulent state in the stable boundary layer is highly dependent on local land use and perhaps locally produced aerosols, and the significant human development of the surface may be responsible for the rising *Tn* while having little impact on *Tx*. Byamukama [16] indicated that land use change in Rwanda (forest, grass, and wetlands conversion to arable land) is also the contributors to GHGs (Green House Gas) emissions. This may affect the real and natural patterns of air temperature trends in Rwanda, especially minimum air temperature. For both monthly maxima and minima of air temperature analysed, it was noticeable that the air temperature trends for Kigali Aero meteorological station indicated positive and significant trends with a greater coefficient of determination (R^2). This may be related to the level at which urbanization involves artificial changes to the land surface and increases energy consumption.

It indicated that urbanization affects the surface energy budget and land-atmosphere interaction, resulting in the 'urban heat island' effect (UHI) [23,33]. Parker [34] argued that urbanization usually induces a warming trend in the observed surface air temperature series, in a way similar to that of the increasing concentration of atmospheric greenhouse gases, however, the effect of urbanization has become a matter of concern in the field of climate change detection. Some authors highlighted that the urban influence on the global air temperature series is negligible [24,34], but the urbanization-induced warming in local (or regional) air temperature observations could be considerable [35,36]. For example, Portman [37] showed that urban meteorological stations in North China experienced an urban-induced warming trend of 0.15–0.26 °C/30 years during 1954–1983.

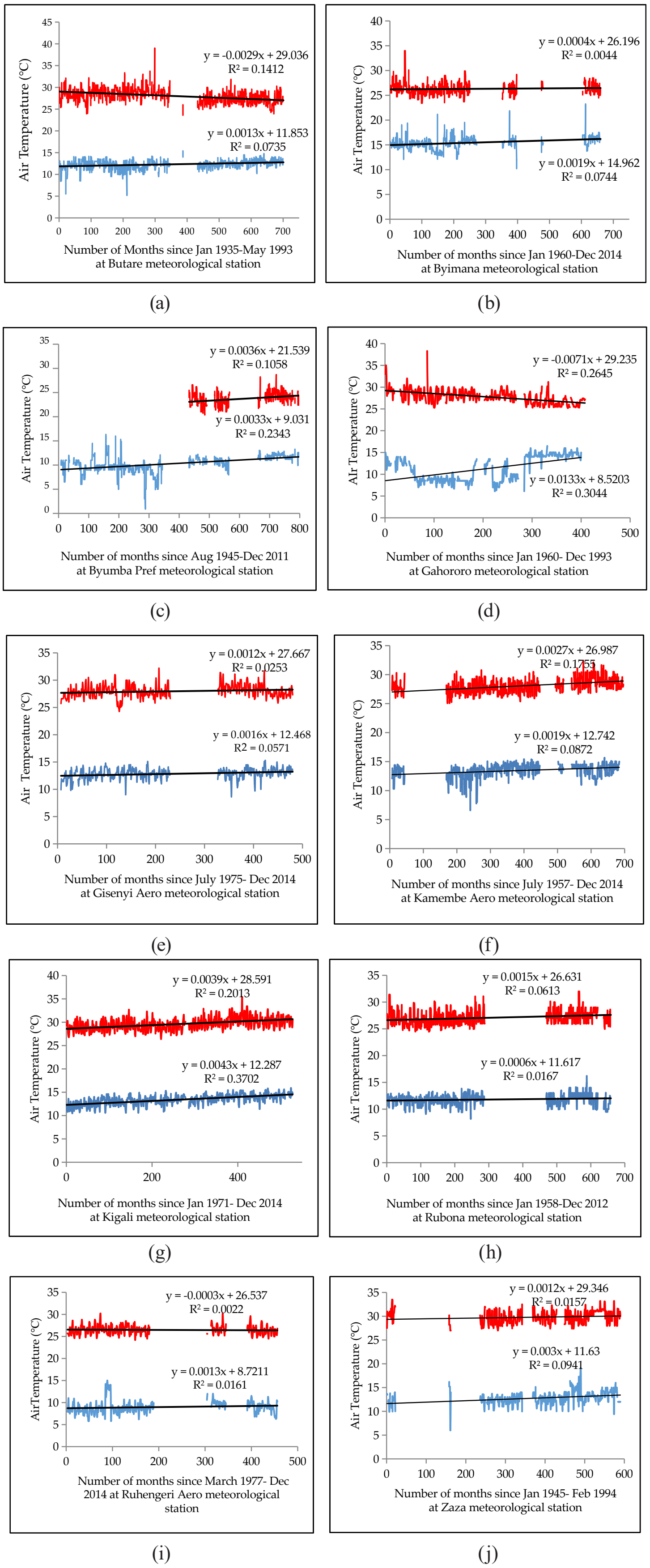


Figure 3. Trends of monthly maxima and minima in air temperature at 10 meteorological stations.

Although Safari [17] worked on annual mean air temperature in Rwanda, his findings in the 19-year sub-period (1958–1977) showed that Kigali Aero meteorological station (capital city of Rwanda) has a positive trend with a very high coefficient of determination (R^2 = 0.67). He also concluded that the observed warming is most likely explained by the growing population accompanied by the increasing emission of greenhouse gases, and the growing urbanization and industrialization the country has experienced, especially the city of Kigali, during some last decades.

Table 4 clearly indicates the aspect, regression coefficients and the significance of trends for both maximum and minimum air temperature. At each meteorological station, the hottest and coldest days and nights have been summarized according to the periods of observation.

Table 4 shows that half of the meteorological stations presented their highest extremes of monthly maximum air temperature in the year 2005. In fact, as noted by Byamukama [16], the year 2005 was among the hottest years in Rwanda, such as 1999, 2000, and 2006. This high level of recorded air temperature created severe droughts in some regions of the country, particularly in the east (Bugesera, Umutara, and Mayaga regions), where agricultural production has been undermined. Nash and Ngabitsinze [13], also noted that the year 2005 was marked with severe drought in Rwanda. The studies show that the period 2001–2010 was the warmest decade on record since modern meteorological records began around the year 1850 [38,39]. The report indicates that the year 2005 was hotter above the land in the southern hemisphere whereas it was hotter above the ocean in the northern hemisphere.

The analysis of minimum air temperature indicated that Byumba Pref meteorological station showed the lowest extremes of monthly minimum air temperature. This may be due to the fact that Byumba Pref (Byumba Province) meteorological station is located in the region with the highest altitude (2235 m, ASL) considering other meteorological stations used in this study.

Table 4. Regression analysis of monthly extreme air temperature at 10 meteorological stations.

Meteo-Station	Extremes of Air Temperature	Trend	R-Square	P-Value	Remark
Butare	Minimum of minimum	*Positive*	0.07	0.000	Significant
	Maximum of maximum	*Negative*	0.14	0.000	Significant
Byimana	Minimum of minimum	*Positive*	0.07	0.000	Significant
	Maximum of maximum	*Positive*	0.00	0.215	Non-Significant
Byumba pref	Minimum of minimum	*Positive*	0.23	0.000	Significant
	Maximum of maximum	*Positive*	0.11	0.000	Significant
Gahororo	Minimum of minimum	*Positive*	0.30	0.000	Significant
	Maximum of maximum	*Negative*	0.26	0.000	Significant
Gisenyi Aero	Minimum of minimum	*Positive*	0.06	0.000	Significant
	Maximum of maximum	*Positive*	0.03	0.002	Significant
Kamembe Aero	Minimum of minimum	*Positive*	0.09	0.000	Significant
	Maximum of maximum	*Positive*	0.18	0.000	Significant
Kigali Aero	Minimum of minimum	*Positive*	0.37	0.000	Significant
	Maximum of maximum	*Positive*	0.20	0.000	Significant
Rubona	Minimum of minimum	*Positive*	0.02	0.005	Significant
	Maximum of maximum	*Positive*	0.06	0.000	Significant
Ruhengeri Aero	Minimum of minimum	*Positive*	0.02	0.032	Significant
	Maximum of maximum	*Negative*	0.00	0.432	Non-Significant
Zaza	Minimum of minimum	*Positive*	0.09	0.000	Significant
	Maximum of maximum	*Positive*	0.02	0.022	Significant

Table 5 indicates that 5 of 10 meteorological stations (Rubona, Kamembe Aero, Kigali Aero, Byumba Pref and Ruhengeri Aero) presented their maximum air temperature in 2005, whereas the remaining 5 meteorological stations their maximum air temperatures were distributed in various years. The month of February hosted a large number of maxima throughout various years but mostly in 2005 for Rubona, Kamembe Aero, Kigali Aero, Byumba Pref (Byumba Prefecture) and Ruhengeri Aero whereas for Gahororo it was in 1967 and lastly Zaza in 1946. The highest maximum of maximum air temperature that has been ever measured at the 10 meteorological stations was 39 °C, recorded at Butare parish meteorological station in November 1959. The minimum of maximum temperatures has been varying in different years and months with the lowest value of 12.8 °C recorded at Byumba Pref meteorological station in April 2000.

The minimum of minimum air temperature also showed a varying pattern with air temperature ranging between 10.5 °C and 1 °C. This lowest value was measured at Byumba Pref meteorological station in December 1968. Generally, the month of December 1968 at Byumba Pref meteorological station indicated lower air temperature values compared to other months for air temperature measurements.

3.2 Variability in hot and cold days and nights

The analysis of 10 meteorological stations showed that there was variability in trends of hot days (HD), cold days (CD), hot nights (HN) and cold nights (CN) as well.

As it is visible in **Figure 4**, the trends of daily and night extreme air temperatures were displayed in the following way: Gahororo meteo-station presented negative trends for cold days and nights as well as for hot days and nights. Butare meteo-station showed only a positive trend for cold days whereas a positive trend was noticed for hot days at Byumba meteo-station. On the other hand, at Gisenyi Aero, Kamembe Aero, Kigali Aero, Rubona, and Zaza meteorological stations, the number of hot days and nights was increasing contrary to cold days and nights.

Table 6 gives more details about the trends and significance of daily and night extreme air temperatures at the 10 meteorological stations under study.

Table 5. The hottest and coldest days and nights as indices of extreme air temperatures.

Meteorological Stations	Maximum of Maximum air Temperature		Minimum of Maximum Air Temperature		Maximum of Minimum Air Temperature		Minimum of Minimum Air Temperature	
	Value (°C)	Month and Year	Value (°C)	Month and Year	Value (°C)	Month and Year	Value (°C)	Month and Year
Butare (Parish)	39	Nov. 1959	15	Apr. 1950	20.5	Jul. 1935	5.2	Nov. 1936
Rubona	32	Feb. 2005	16	Mar. 2005	16.6	Aug. 1967	8.2	Jul. 1978
Byimana	34	Dec. 1963	12.9	Dec. 1963	23.1	Jan. 2011	4.7	Jul. 1973
Kamembe Aero	32.3	Feb. 2005	16.3	Aug. 1978	19.9	Nov. 2007	7	Jan. 1977
Gisenyi Aero	32.2	Mar. 1992	16.1	Dec. 2014	19.2	Mar. 1992	9	Aug.1986
Kigali Aero	35.4	Feb. 2005	17	Sep. 2014	20.5	Jan. 2013	10.5	Feb. 1972
Gahororo	38.3	Feb.1967	14	Nov. 1963	27; 26.5	Feb. 1960; Nov. 1961	6.1; 6.3	Aug.; Nov. 1978
Zaza	33.5	Feb. 1946	15	Oct. 1959	23.2	May 1983	6	May 1958
Byumba Pref	28.7	Feb. 2005	12.8	Apr. 2000	20.5	Apr. 1964	1	Dec. 1968
Ruhengeri Aero	30.2	Feb. 1983; 2005	15.8	Sep. 2014	19.2	Dec. 1987	5.8	Jan. 1985

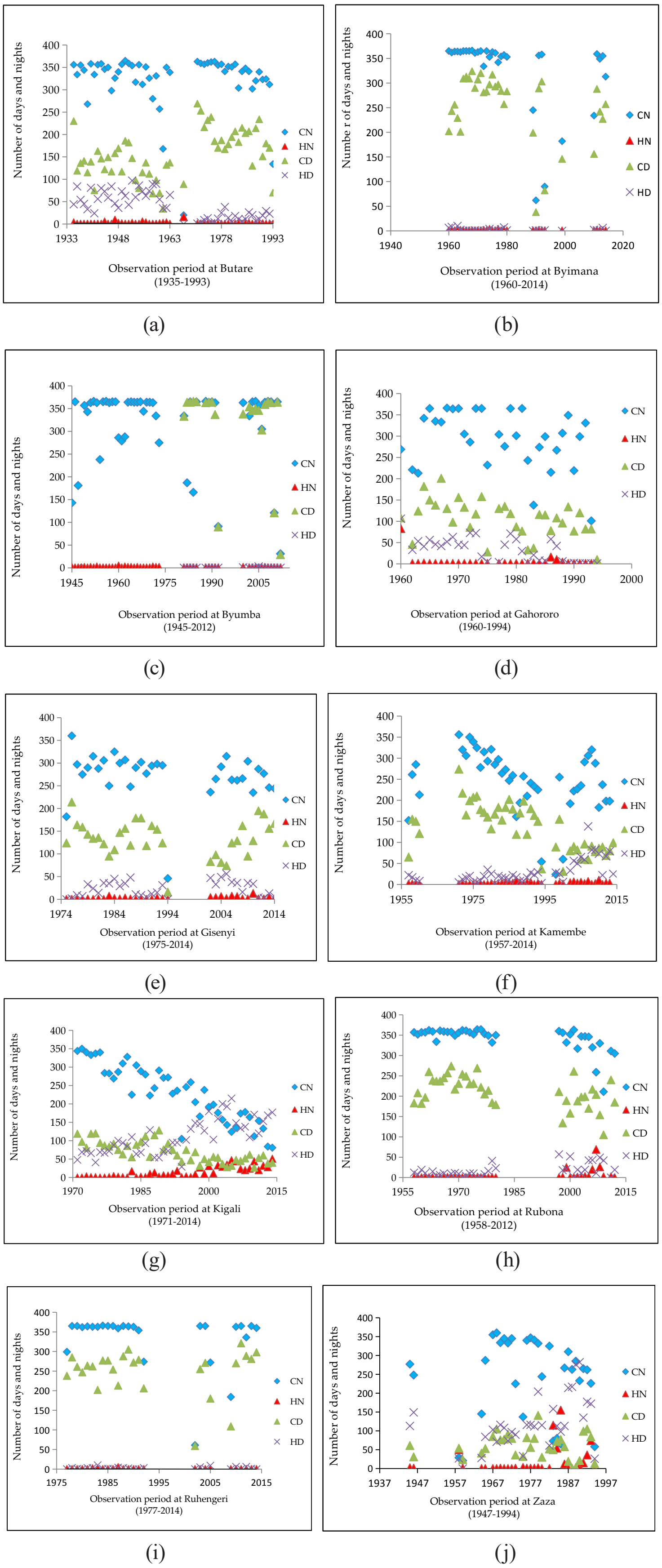


Figure 4. Trends of daily and night extreme air temperatures at 10 meteorological stations.

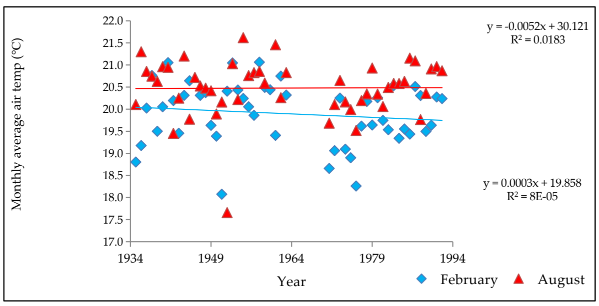
Table 6. Regression analysis of daily and night extreme air temperature at 10 meteorological stations.

Meteo Station		Trend	R-Square	P-Value	Remark
Butare	CN	*Negative*	0.015	0.374	Non-Significant
	HN	*Negative*	0.014	0.405	Non-Significant
	CD	*Positive*	0.157	0.003	Significant
	HD	*Negative*	0.495	0.000	Significant
Byimana	CN	*Negative*	0.160	0.023	Significant
	HN	*Negative*	0.007	0.639	Non-Significant
	CD	*Negative*	0.120	0.052	Significant
	HD	*Negative*	0.029	0.348	Non-Significant
Byumba pref	CN	*Negative*	0.000	0.931	Non-Significant
	HN	*Negative*	0.063	0.075	Non-Significant
	CD	*Negative*	0.095	0.163	Non-Significant
	HD	*Positive*	0.029	0.452	Non-Significant
Gahororo	CN	*Negative*	0.089	0.097	Non-Significant
	HN	*Negative*	0.065	0.159	Non-Significant
	CD	*Negative*	0.186	0.012	Significant
	HD	*Negative*	0.457	0.000	Significant
Gisenyi Aero	CN	*Negative*	0.030	0.333	Non-Significant
	HN	*Positive*	0.213	0.007	Significant
	CD	*Negative*	0.009	0.608	Non-Significant
	HD	*Positive*	0.021	0.416	Non-Significant
Kamembe Aero	CN	*Negative*	0.092	0.048	Significant
	HN	*Positive*	0.209	0.002	Significant
	CD	*Negative*	0.354	0.000	Significant
	HD	*Positive*	0.410	0.000	Significant
Kigali Aero	CN	*Negative*	0.833	0.000	Significant
	HN	*Positive*	0.646	0.000	Significant
	CD	*Negative*	0.570	0.000	Significant
	HD	*Positive*	0.573	0.000	Significant
Rubona	CN	*Negative*	0.330	0.000	Significant
	HN	*Positive*	0.158	0.014	Significant
	CD	*Negative*	0.234	0.002	Significant
	HD	*Positive*	0.264	0.001	Significant
Ruhengeri Aero	CN	*Negative*	0.064	0.212	Non-Significant
	HN	*Negative*	0.041	0.321	Non-Significant
	CD	*Negative*	0.007	0.687	Non-Significant
	HD	*Positive*	0.005	0.735	Non-Significant
Zaza	CN	*Negative*	0.001	0.882	Non-Significant
	HN	*Positive*	0.069	0.145	Non-Significant
	CD	*Negative*	0.001	0.875	Non-Significant
	HD	*Positive*	0.207	0.009	Significant

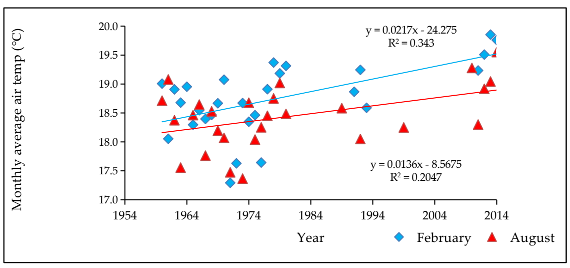
The trends of daily and night extreme air temperatures were obtained in a varying pattern, where HD represents hot days, CD stands for cold days, HN represents hot nights and CN represents cold nights. The majority of the trends showed an increasing number of hot days and nights but not always significant (**Table 6**). Regardless of the non-significance of trends in hot days and nights, on the other hand, they show a picture of the warming that has been occurring in Rwanda over time.

3.3 Change in average seasonal air temperature

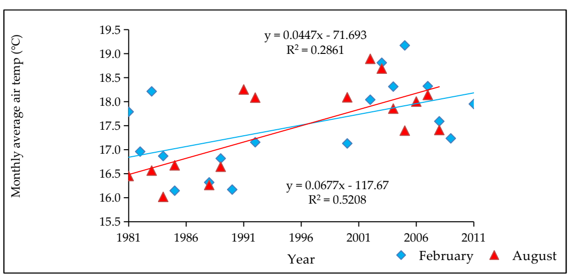
The analysis assessed the similarity and difference in air temperature trends for one month belonging to a short dry season (February) and another belonging to a long dry season (August). As indicated in **Figure 5**, except Butare which showed a negative trend for the short dry season, other meteorological stations presented an increase in trends of monthly mean air temperature for both short dry and long dry seasons.



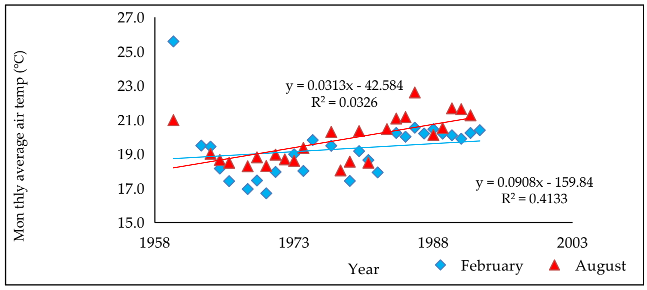
(a) Air temperature trends at Butare Aero meteorological station.



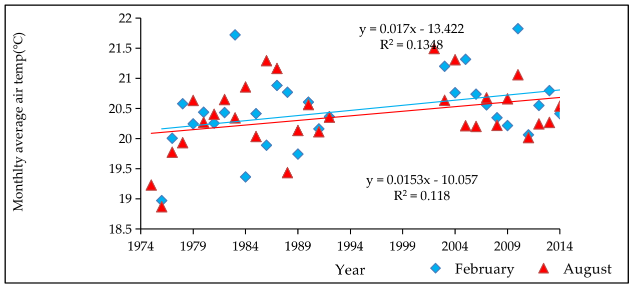
(b) Air temperature trends at Byimana meteorological station.



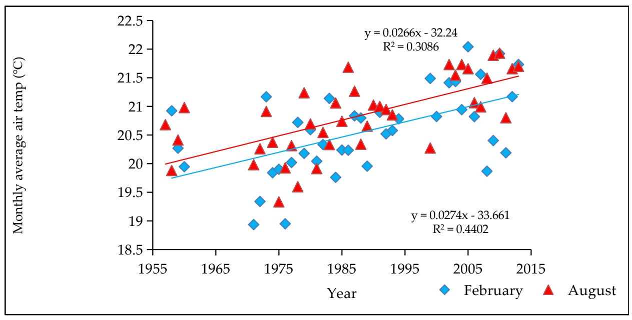
(c) Air temperature trends at Byumba pref meteorological station.



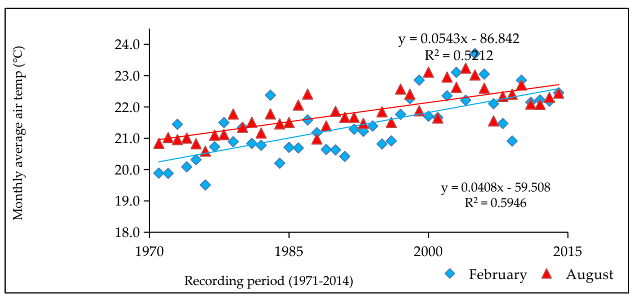
(d) Air temperature trends at Gahororo meteorological station.



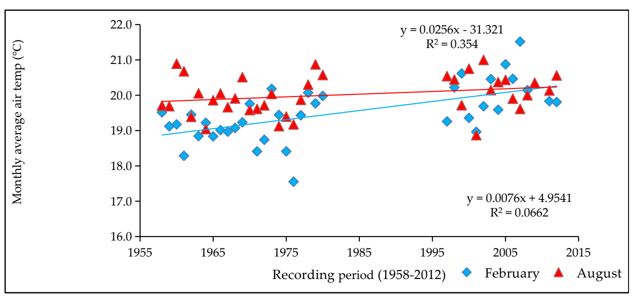
(e) Air temperature trends at Gisenyi Aero meteorological station.



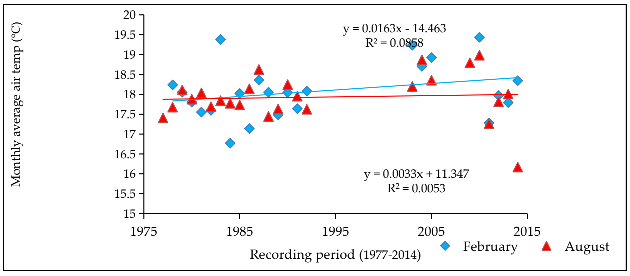
(f) Air temperature trends at Kamembe Aero meteorological station.



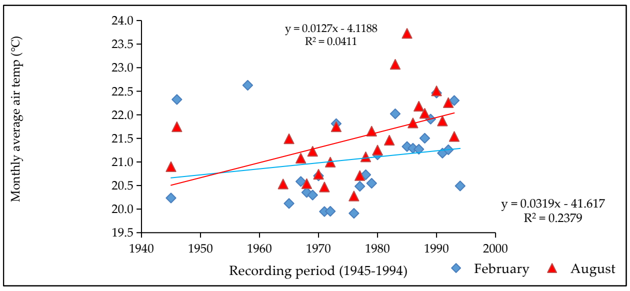
(g) Air temperature trends at Kigali Aero meteorological station.



(h) Air temperature trends at Rubona meteorological station.



(i) Air temperature trends at Ruhengeri Aero meteorological station.



(j) Air temperature trends at Ruhengeri Aero meteorological station.

Figure 5. Trends of monthly average air temperature in February and August at 10 meteorological stations.

The output of regression analysis for the 10 meteorological stations showed that the trend of seasonal air temperature was much positive and highly significant at Kigali Aero meteorological station compared to the remaining meteo-stations (**Table 7**). According to the same results the trends for both short and long dry seasons at Ruhengeri meteo-station were in no case significant even though they were positive. The trends of seasonal air temperature were negative for the short dry season and positive for the long dry season but both were not significant.

The analysis of average seasonal air temperature showed almost similar trends even though not all were significant (**Table 7**). For the trends of short and long dry seasons at the 10 meteorological stations, only Butare presented a negative and non-significant trend for the short dry season. Most of the trends were statistically significant and very few were not. The similarity of these trends described above is due to the fact that the months of February and August belong to the periods that intersect with rainfall time in Rwanda.

3.4 Impacts of observed warming in Rwanda

A number of studies conducted recently in Rwanda have recognized that climate variability and change were happening and were coupled with significant impacts on the country's natural resources including agriculture, which is the main source of livelihood in rural areas [38]. It was indicated that the climate variability in Rwanda was expressed in the occurrence of higher changes in frequency, intensity, and persistence of extremes such as drought [40]. For example, MINITERE [41] reported that the eastern region of the country has been experiencing severe rainfall deficits over the last decades with the high vulnerability of the population in the region. It also noted that the observation made from 1961 to 2005 showed that the period between 1991 and 2000 has been the driest since 1961. These observations showed a marked prolonged drought in 1992, 1993, 1996, 1999, and 2000. Similar results were obtained by Nash and Ngabitsinze [13] and included the years 2005 and 2006 on the list of years with severe droughts in Rwanda. They indicated that these temperature extremes seriously affected Bugesera, Umutara and Mayaga regions. In addition, REMA [42] reported that the eastern province especially Bugesera region experienced severe droughts in 1999, 2006, and 2008. The length and intensity of land degradation have also weakened the lands' resilience; and when it comes to be combined with overgrazing and poor cultivation practices, drought has led to deterioration in pasture and arable land to the point where they have been abandoned. In the report, it was indicated that a decline in food crop production because of low moisture content was no doubt associated with changing climatic conditions in Rwanda.

Table 7. Regression analysis for seasonal air temperature.

Meteo-Station	Season	Trend	R-Square	P-Value	Remark
Butare	Short dry	*Negative*	0.018	0.349	Non-Significant
	Long dry	*Positive*	0.000	0.950	Non-Significant
Byimana	Short dry	*Positive*	0.343	0.001	Significant
	Long dry	*Positive*	0.205	0.018	Significant
Byumba	Short dry	*Positive*	0.286	0.022	Significant
	Long dry	*Positive*	0.521	0.002	Significant
Gahororo	Short dry	*Positive*	0.033	0.367	Non-Significant
	Long dry	*Positive*	0.413	0.001	Significant
Gisenyi Aero	Short dry	*Positive*	0.135	0.050	Significant
	Long dry	*Positive*	0.118	0.058	Non-Significant
Kamembe Aero	Short dry	*Positive*	0.309	0.000	Significant
	Long dry	*Positive*	0.440	0.000	Significant
Kigali Aero	Short dry	*Positive*	0.521	0.000	Significant
	Long dry	*Positive*	0.595	0.000	Significant
Rubona	Short dry	*Positive*	0.354	0.000	Significant
	Long dry	*Positive*	0.066	0.119	Non-Significant
Ruhengeri Aero	Short dry	*Positive*	0.086	0.175	Non-Significant
	Long dry	*Positive*	0.005	0.730	Non-Significant
Zaza	Short dry	*Positive*	0.041	0.311	Non-Significant
	Long dry	*Positive*	0.238	0.011	Significant

4. Conclusions and recommendations

This study shows that generally, the analysis of both daily maximum and minimum air temperatures indicated visible patterns of climate variability in Rwanda. The analysis of monthly extreme air temperatures showed that the year 2005 hosted a higher number of hottest days mostly observed in February. On the other hand, the minima (coldest days) in air temperature were recorded in Byumba, a region with higher altitude compared to the locations of meteorological stations used for this study. Throughout this study, it was noticed that the number of hot days and nights increased for the majority of analysed meteorological stations and consequently the reduction in the number of cold days and nights. The trends of seasonal air temperatures were not far different, and this is due to the short and long dry seasons intercepted with rainfall in Rwanda. Impacts of warming have been observed in Rwanda since a long time ago. Various researchers argued that these impacts expressed in the form of severe droughts were observed especially in the eastern part of the country affecting massive people who had to rely on external supply because of the failure in crop production. This past climate variability, which has been accompanied by various catastrophic impacts in Rwanda, should trigger further and deeper researches for forecasting purposes. The development of early meteorological warning systems will help Rwandan people, especially farmers, and policy makers to change the way things used to be and cope with this changing climate.

Author Contributions

Protais Seshaba: Conceptualization (lead); data curation (equal); formal analysis (equal); investigation (lead); methodology (equal); project administration (lead); resources (equal); software (lead); supervision (equal); validation (equal); visualization (equal); writing the original draft (lead), writing, review and editing (lead).

Edouard Singirankabo: Conceptualization (supporting); data curation (equal); formal analysis (equal); investigation (supporting); methodology (equal); project administration (supporting); resources (supporting); supervision (equal); validation (equal); visualization (equal); writing the original draft (supporting), writing, review and editing (supporting).

Donat Nsabimana: Conceptualization (supporting); data curation (equal); formal analysis (equal); investigation (supporting); methodology (supporting); project administration (equal); resources (supporting); supervision (lead); validation (lead); visualization (equal); writing the original draft (equal), writing, review and editing (equal).

Conflict of Interest

There is no conflict of interest.

Funding

No funding.

Acknowledgments

We are grateful to Meteo Rwanda for allowing us to have access to its meteorological dataset for responding to the questions of the current research.

References

[1] World Meteorological Organization, 1992. Measurement of temperature and humidity (Technical Note No. 194). WMO: Geneva.

[2] Enz, J.W., Hofman, V., Thostenson, A., 2014. Air temperature inversions causes, characteristics and potential effects on pesticide spray drift. NDSU Extension Service.

[3] Lobell, D.B., Schlenker, W., Costa-Roberts, J., 2011. Climate trends and global crop production since 1980. Science. 333(6042), 616–620. DOI: https://doi.org/10.1126/science.1204531

[4] IPCC, 2007. Climate change 2007: Impacts, adaptation and vulnerability. Cambridge University Press: Cambridge.

[5] GISS surface temperature analysis. NASA Goddard Institute for Space Studies and Columbia University Earth Institute: New York.

[6] IPCC, 2007. Climate change 2007: The physical scientific basis. Cambridge University Press: Cambridge.

[7] Katz, R.W., Brown, B.G., 1992. Extreme events in a changing climate: variability is more important than averages. Climatic Change. 21, 289–302. DOI: https://doi.org/10.1007/BF00139728

[8] Nicholson, S.E., Kim, J., 1997. The relationship of the El Niño—Southern oscillation to African rainfall. International Journal of Climatology. 17(2), 117–135. DOI: https://doi.org/10.1002/(SICI)1097-0088(199702)17:2<117::AID-JOC84>3.0.CO;2-O

[9] Hulme, M., Doherty, R., Ngara, T., et al., 2001. African climate change: 1900–2100. Climate Research. 17(2), 145–168. DOI: https://doi.org/10.3354/cr017145

[10] IPCC, 2001. Climate change 2001: The scientific basis. Cambridge University Press: Cambridge.

[11] Niang, I., Ruppel, O.C., Abdrabo, M.A., et al., 2014. Africa. Climate change 2014: Impacts, adaptation, and vulnerability. Cambridge University Press: Cambridge. pp. 1199–1265.

[12] DFID, 2009. Economic impacts of climate change: Kenya, Rwanda, and Burundi. Oxford Office: Oxford.

[13] Nash, E., Ngabitsinze, J.C., 2013. Low-carbon resilient development in Rwanda. International Institute for Environment and Development (IIED): London.

[14] WWF, 2006. Climate change impacts on East Africa. World Wide Fund: Gland.

[15] Fischlin, A., Midgley, G.F., Price, J.T., et al., 2007. Ecosystems, their properties, goods, and services. Climate change 2007: Impacts, adaptation and vulnerability. Cambridge University Press: Cambridge. pp. 211–272.

[16] Byamukama, B., Carey, C., Cole, M., et al., 2011. National strategy on climate change and low carbon development for Rwanda. Univer-

sity of Oxford: Oxford.

[17] Safari, B., 2012. Trend analysis of the mean annual temperature in Rwanda during the last 52 years. Journal of Environmental Protection. 3(6), 20077.
DOI: https://doi.org/10.4236/jep.2012.36065

[18] Habiyaremye, G., Jairu, N.D., de la Paix Mupenzi, J., et al., 2012. Statistical analysis of climatic variables and prediction outlook in Rwanda. East African Journal of Science and Technology. 1(1), 27–34.

[19] Singirankabo, E., Iyamuremye, E., Habineza, A., et al., 2023. Statistical modelling of maximum temperature in Rwanda using extreme value analysis. Open Journal of Mathematical Sciences. 7, 180–195.
DOI: https://doi.org/10.30538/oms2023.0206

[20] Mutabazi, A., 2010. Assessment of operational framework related to climate change in Rwanda. REMA: Kigali.

[21] Downing, T., Watkiss, P., Dyszynski, J., et al., 2009. Economics of Climate change in Rwanda. Stockholm Environment Institute: UK Oxford Office.

[22] Stott, P.A., Gillett, N.P., Hegerl, G.C., et al., 2010. Detection and attribution of climate change: A regional perspective. Wiley Interdisciplinary Reviews: Climate Change. 1(2), 192–211.
DOI: https://doi.org/10.1002/wcc.34

[23] Collier, C.G., 2006. The impact of urban areas on weather. Quarterly Journal of the Royal Meteorological Society. 132(614), 1–25.
DOI: https://doi.org/10.1256/qj.05.199

[24] Folland, C.K., Vose R.S., Easterling D.R., et al., 2001. Observed climate variability and change. Climate change 2001: The scientific basis. Cambridge University Press: Cambridge. pp. 108–109.

[25] Przybylak, R., 2000. Diurnal temperature range in the Arctic and its relation to hemispheric and Arctic circulation patterns. International Journal of Climatology. 20(3), 231–253.
DOI: https://doi.org/10.1002/(SICI)1097-0088(20000315)20:3<231::AID-JOC468>3.0.CO;2-U

[26] Braganza, K., Karoly, D.J., Arblaster, J.M., 2004. Diurnal temperature range as an index of global climate change during the twentieth century. Geophysical Research Letters. 31(13).
DOI: https://doi.org/10.1029/2004GL019998

[27] Flannigan, M.D., Stocks, B.J., Wotton, B.M., 2000. Climate change and forest fires. Science of the Total Environment. 262(3), 221–229.
DOI: https://doi.org/10.1016/S0048-9697(00)00524-6

[28] Foden, W., Mace, G., Vié, J.C., et al., 2008. Species susceptibility to climate change impacts. IUCN: Gland, Switzerland.

[29] Balling Jr, R.C., Klopatek, J.M., Hildebrandt, M.L., et al., 1998. Impacts of land degradation on historical temperature records from the Sonoran Desert. Climatic Change. 40, 669–681.
DOI: https://doi.org/10.1023/A:1005370115396

[30] Bonan, G.B., 2001. Observational evidence for reduction of daily maximum temperature by croplands in the Midwest United States. Journal of Climate. 14(11), 2430–2442.
DOI: https://doi.org/10.1175/1520-0442(2001)014<2430:OEFROD>2.0.CO;2

[31] Small, E.E., Sloan, L.C., Nychka, D., 2001. Changes in surface air temperature caused by desiccation of the Aral Sea. Journal of Climate. 14(3), 284–299.
DOI: https://doi.org/10.1175/1520-0442(2001)014<0284:CISATC>2.0.CO;2

[32] Stott, P.A., Jones, G.S., Christidis, N., et al., 2011. Single-step attribution of increasing frequencies of very warm regional temperatures to human influence. Atmospheric Science Letters. 12(2), 220–227.
DOI: https://doi.org/10.1002/asl.315

[33] Arnfield, A.J., 2003. Two decades of urban climate research: A review of turbulence, exchanges of energy and water, and the urban heat island. International Journal of Climatology. 23(1), 1–26.
DOI: https://doi.org/10.1002/joc.859

[34] Parker, D.E., 2010. Urban heat island effects on estimates of observed climate change. Wiley Interdisciplinary Reviews: Climate Change. 1(1), 123–133.
DOI: https://doi.org/10.1002/wcc.21

[35] Lin, X.C., Yu, S.Q., 2005. Interdecadal changes of temperature in the Beijing region and its heat island effect. Chinese Journal of Geophysics. 48(1), 47–54.
DOI: https://doi.org/10.1002/cjg2.624

[36] Yan, Z., Li, Z., Li, Q., et al., 2010. Effects of site change and urbanisation in the Beijing temperature series 1977–2006. International Journal of Climatology. 30(8), 1226–1234.
DOI: https://doi.org/10.1002/joc.1971

[37] Portman, D.A., 1993. Identifying and correcting urban bias in regional time series: Surface temperature in China's northern plains. Journal of Climate. 6(12), 2298–2308.
DOI: https://doi.org/10.1175/1520-0442(1993)006<2298:IACUBI>2.0.CO;2

[38] WFP/FEWS-NET, 2003. Rwanda vulnerability baseline report. World Food Programme of the United Nations (WFP)/Famine Early Warning Systems Network (FEWS-NET): Kigali.

[39] World Meteorological Organization, 2013. The global climate 2001–2010: A decade of climate extremes. World Meteorological Organization: Geneva.

[40] Climate Risk Country Profile: Rwanda [Internet]. World Bank Group; 2021. Available from: https://climateknowledgeportal.worldbank.org/sites/default/files/2021-09/15970-WB_Rwanda%20Country%20Profile-WEB.pdf

[41] MINITERE, 2006. National adaptation programmes of action (NAPA) to climate change. Ministry of Lands, Environment, Forestry, Water and Mines (MINITERE): Kigali.

[42] REMA, 2007. Pilot integrated ecosystem assessment of Bugesera. United Nations Development Programme (UNDP), United Nations Environment Programme (UNEP) and Rwanda Environment Management Authority (REMA): Kigali.