

Spatiotemporal trends in mean temperatures and aridity index over Rwanda

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Abstract This study aims at quantifying the trends in mean temperatures and aridity index over Rwanda for the period of 1961–1992, based on analysis of climatic data (temperatures, precipitations, and potential evapotranspiration). The analysis of magnitude and significance of trends in temperatures and aridity index show the degree of climate change and mark the level of vulnerability to extreme events (e.g., droughts) in different areas of the country. The study reveals that mean temperatures increased in most parts of the country, with a significant increase observed in the eastern lowlands and in the southwestern parts. The highlands located in the northwest and the Congo-Nile crest showed a nonsignificant increase in mean temperatures. Aridity index increased only in March, April, October, and November, corresponding with the rainy seasons. The remaining months of the year showed a decreasing trend. At an annual resolution, the highlands and the western region showed a rise in aridity index with a decreasing pattern over the eastern lowlands and the central plateau. Generally, the highlands presented a nonsignificant increase in mean temperatures and aridity index especially during the rainy seasons. The eastern lowlands showed a significant increase in mean temperatures and decreasing trends in aridity index. Therefore, these areas are bound to experience more droughts, leading to reduced water and consequent decline in agricultural production. On the other hand, the north

highlands and southwest region will continue to be more productive.

1 Introduction

Recent scientific evidence suggests a global increase in temperatures and more incidences of droughts (Boko et al. 2007; Trenberth et al. 2007; Vincent 2007; Hahn et al. 2009). The projected increase in temperatures in the twenty-first century is likely to be greater than any rate in the past 10,000 years particularly in sub-Saharan Africa (Parry et al. 2007). Consequently, the analysis of past and present climatic conditions at various levels is important for better projection of climatic scenarios. Recent progressive increase in temperature results from global warming caused by increased concentrations of greenhouse gases in the atmosphere. (Nicholls et al. 1997; Jones et al. 1997; Boko et al. 2007; Vincent 2007; Hahn et al. 2009).

The rise of carbon dioxide (CO₂) in the atmosphere from about 280 ppm in the pre-industrial era to about 364 ppm in 1997 (Keeling and Whorf 1999) has resulted in the increase in global mean annual surface temperature ranges of between 0.3 and 0.6 °C (Nicholls et al. 1997; Jones et al. 1997 and Duncan et al. 2009). On May 9, 2013, the daily mean atmospheric concentration of carbon dioxide (CO₂) of Mauna Loa, Hawaii, surpassed 400 ppm for the first time since measurements began in 1958 (NOAA 2013). This was bound to result in increases of temperature of between 0.5 and 1 °C (for the period of 1958–2013) (Keeling 2013).

An increase in atmospheric concentrations of greenhouse gases equivalent to a doubling of carbon dioxide (CO₂) would force a rise in global average surface temperature of 2 to 4 °C by 2100 (Parry et al. 2007; Duncan et al. 2009; Davies et al. 2010). The atmospheric concentration of nitrous oxide (N₂O) and methane (CH₄) in 2010 was about 323.2 and 1808 ppb or

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20 and 158 % higher than in the pre-industrial level, respectively. The impact of nitrous oxide (N₂O) on climate, over a 100-year period, is 298 times greater than equal emissions of carbon dioxide. This shows the degree to which the world is exposed to global warming (WMO 2013a; WMO 2013b).

The global mean surface temperatures shot up by 0.74 °C between 1901 and 2005 (Trenberth et al. 2007). The period of 2001–2010 was the warmest decade since 1850 (WMO 2013a) with the largest decadal increase in mean temperature of 0.21 °C from 1991–2000 to 2001–2010. The warmest year ever recorded was 2010 (WMO 2013a). An increase in monthly temperature has been observed as recently as June and July 2012, which was 0.63 and 0.92 °C, respectively, above last century's (twentieth century) average of 15.5 °C on land and ocean. This was ranked as the fourth warmest June and July since 1880. June 2012 was at the same time the all-time warmest June globally (on land surface) with a temperature of 1.07 °C above average. September 2012 was ranked the third warmest September globally, with a temperature of 1.02 °C above average (NOAA 2012a, b, c).

Although increases in temperature have been observed since the last century (twentieth century), the patterns and trends are not uniform across Africa. Tropical rainforest regions have experienced a rise of 0.05 to 0.26 °C per decade (Malhi and Wright 2004) and 0.1 to 0.3 °C in South Africa (Engelbrecht et al. 2002; Kruger and Shongwe 2004), while it ranged between 0.2 and 0.3 °C in the Nile Basin countries (Eriksen et al. 2008). The minimum temperatures rose faster than the maximum or mean temperatures for South Africa and Ethiopia (Conway et al. 2004; Kruger and Shongwe 2004). Similar observations have been made not only over Europe where annual minimum temperature increased by between 0.1 °C and 0.2 °C per decade with annual maximum temperature increasing by 0.1 °C–0.15 °C per decade by the end of the past century (1985–2000), but also over most other areas of the world (Vose et al. 2005; Alexander et al. 2006 and Easterling et al. 2006). Between 1961 and 2000, this gradual heating over Africa meant more warm spells (days) and fewer cold days across the continent (New et al. 2006 and Boko et al. 2007).

The last decade of the twentieth century witnessed decreasing trends in temperature over the regions close to the coast or major inland lakes (King'uyu et al. 2000; Funk and Brown 2006), and increasing in the rest of the region. The highest increase in temperatures ranging from 0.7 to 0.9 °C has been observed over Rwanda (Ruosteenoja et al. 2003; Eriksen et al. 2008). Arising from these observations, it is estimated that temperatures will rise by 2.5 °C in the 2050s and 4 °C between 2080 and 2099 over East Africa (Parry et al. 2007). Droughts have mainly affected the Sahel, the Horn of Africa, and southern Africa, particularly since the end of the 1960s (Richard et al. 2001; L'Hôte et al. 2002; Brooks 2004;

Christensen et al. 2007; Trenberth et al. 2007) and the projections suggest that the semi-arid areas will become more arid (Druryan et al. 2008).

Since 1902, a series of famines occasioned by prolonged droughts have been registered in Rwanda (Bart 1993; CAMCO 2011; David et al. 2011) notably in the eastern, southeastern, and central parts of the country (e.g., Umutara and Kibungo in the east, Bugesera in the southeast, Mayaga, Nyaruguru, Muhanga in the central region) (Bart 1993; CAMCO 2011). The prolonged droughts occurred in 1910 (followed by a famine called “Kazuba”), 1917–1918 (followed by a famine called “Rumanurimbaba”), 1925–1926 (followed by a famine called “Gakwege”), 1928–1929 (followed by a famine called “Rwakamigabo”), 1942–1944, 1962–1963, 1981–1984, 1989–1992 (followed by a famine called “Ruringaniza”), 1996, 1998–2000, and 2004–2005 (Bart 1993; MINITERE 2006). However, there is no published data showing the extent of these droughts, the relationships between changes in temperatures, rainfall and food insecurity. It is for this reason that a conclusion linking food insecurity to droughts during the abovementioned periods has been made using common and popular knowledge about climatic conditions.

It is worth noting that the changes in mean temperatures and aridity indices impact on crop production depending on location (Ramankutty et al. 2008). For instance, whereas an increase in temperatures of between 1 and 3 °C may be beneficial to crops in temperate regions, it may be harmful to those in tropical and seasonally dry regions. An increase of more than 3 °C is expected to have negative impacts on crop production in all regions (Parry et al. 2007), while the occurrence of weather extreme events like droughts is likely to cause failure and destruction of crops.

An analysis of mean temperatures and aridity trends over Rwanda is important as it helps in understanding the link between changes in mean temperatures and aridity indices, with a view to predicting their impacts on agricultural productivity in the country. The results arrived at can also be used in further exploration of the matter. This study seeks to bring to light the dangers of increasing occurrences of droughts so that appropriate measures are taken to counter them. This phenomenon has negative impact on not just agriculture, but availability of water as well (Chamchati and Bahir 2011). Notwithstanding the importance of analyzing the mean minimum and maximum temperature trends, this has not been adequately done due to lack of representative minimum and maximum long-term data set.

2 Study area

Rwanda is a small landlocked country located in East Africa (Fig. 1). It lies between 1° 4' and 2° 51' South and 28° 53' and

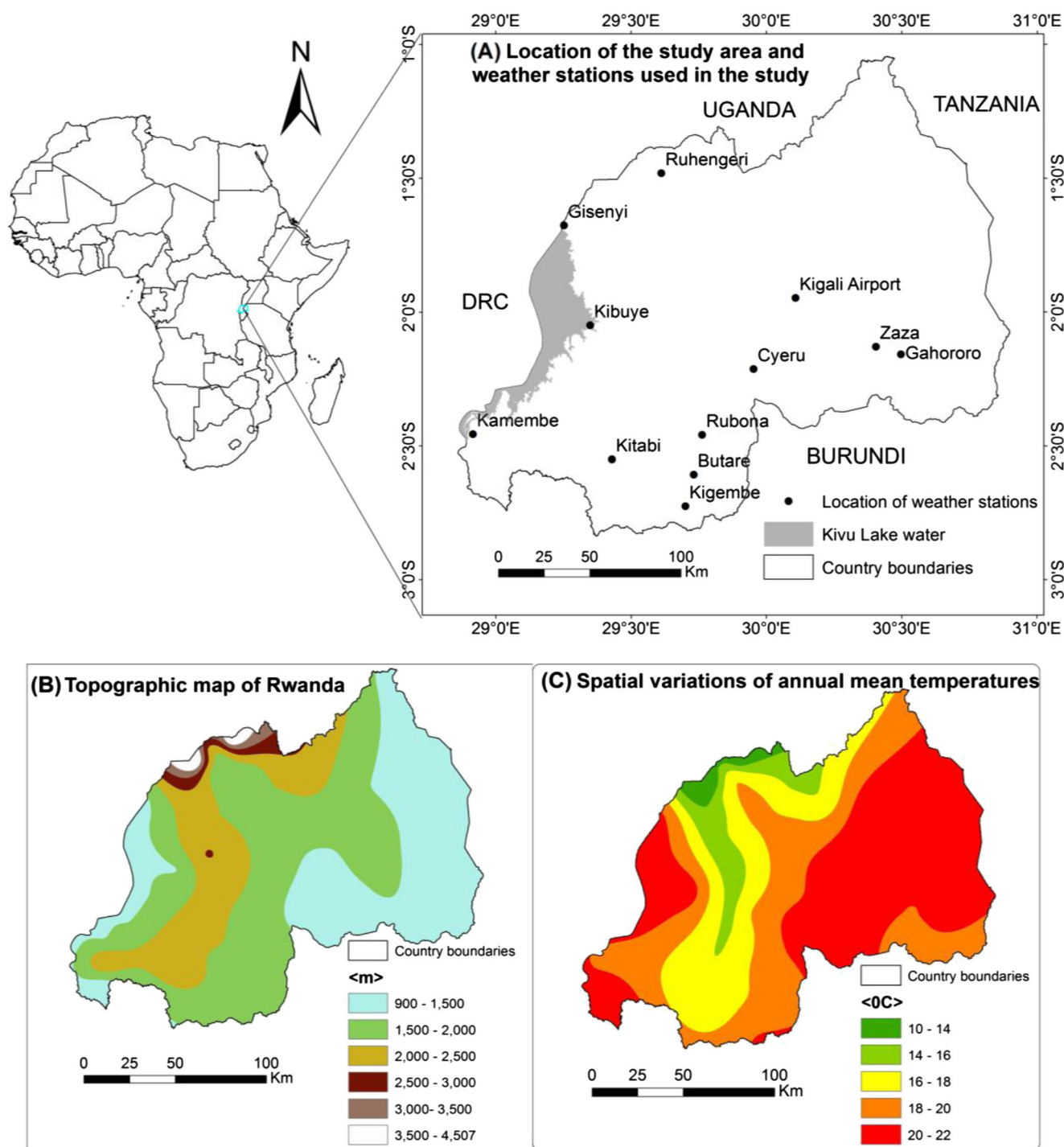


Fig. 1 Location of weather stations used in the study and spatial variations of annual mean temperatures in Rwanda (1961–1992)

30° 53' East, and it covers an area of 26,338 km² (Sirven et al. 1974; MINERENA 2010).

The ascending topography of the country, varying between 900 and 4507 m and stretching from east to west, gives rise to a spatial variability of temperatures (Fig. 1) (Sirven et al. 1974; Ilunga et al. 2004; REMA 2009). Mean annual temperatures range between 19 and 22 °C in the eastern lowlands lying between 1000 and 1500 m, while they vary between 18

and 20 °C in the central plateau region located between 1500 and 2000 m. The regions around Kivu Lake and Bugarama plains, sitting on 900–1800 m have mean annual temperature of between 19 and 22 °C with the mean temperatures fluctuating between 14 and 18 °C in the northern highlands and over the Congo-Nile crest sitting on 2000–3000 m (Ilunga et al. 2004; REMA 2009). The volcanic region, with height varying between 3000 and 4500 m has mean annual temperature of

between 10 and 14 °C. However, there is not enough information for estimating the mean temperature in the highlands especially in volcanic region.

Apart from the highlands, the rest of the country enjoys mean annual temperatures ranging between 18 and 22 °C. The annual temperature range oscillates between 2 and 6 °C, which is a typical characteristic of tropical regions (REMA 2009; MINERENA 2010; CAMCO 2011).

It is worth mentioning that the temperatures vary slightly throughout the year during four climatic seasons in which the long rains (March–April–May) and short rains (September–October–November) seasons alternate with long-dry (June–July–August) and short-dry seasons (December–January–February) (Sirven et al. 1974; Ilunga et al. 2004; Ilunga et al. 2008). That means in essence that the seasons in Rwanda are differentiated based on temporal variations of precipitation regardless of the fact that the onset and offset of each season vary from one year to the next, and from region to region.

3 Data set and methods

3.1 Data set

This study is carried out with the use of temperature, rainfall, and evapotranspiration data sets. Monthly data was collected from the Rwandan Meteorological Center based in Kigali. Length and completeness of records were the basic criteria used to select weather stations in order to have the most complete dataset. The missing values in monthly station records were estimated by interpolating values from the complete nearby weather stations if the missing values are less than 3 % of the total weather station's records for the whole study period as has been used by Türkeş et al. (1996), Türkeş et al. (2002), and Del Río et al. (2012).

Temperatures and rainfall were analyzed for the period of 1961–1992 using raw monthly values collected from 12 weather stations from which seasonal and annual mean temperatures and precipitation records were derived. The period of 1993–2012 has not been taken into consideration in the study owing to the fact that many weather stations were destroyed between 1990 and 1994 during war and genocide period. This makes it quite difficult to get a complete long-term data set covering the country to an acceptable level. It is for this reason that the present study used only 12 weather stations' records to analyze trends in mean temperatures and aridity index. For that reason, spatial distribution of the weather stations across the country is not uniformly distributed, and that might have slight negative impacts on the exactness of spatial interpolation of results.

3.2 Methods

Statistical techniques were applied (Del Río et al. 2012) for each of the 12 weather stations to determine the trends in mean temperatures and in aridity index at monthly, seasonal, and annual resolution (Parry et al. 2004; Agustin 2006; Rodrigo and Trigo 2007; Del Río et al. 2012). The linear trends values represented by the slope of the simple least-square regression line provided the rate of rise/fall in mean temperature and aridity index (Jain and Kumar 2012). The magnitude of the trends derived from linear regression analysis (Sene and Farquharson 1998) and their statistical significance at 95 % level were calculated (Horton et al. 2001; Partal and Kahya 2006; Peterson et al. 2008; Kizza et al. 2009; Karpouzou et al. 2010; Olofintoye and Sule 2010; Del Río et al. 2012) using Stata software 10 (StataCorp 2007; Christopher 2011). The trends were considered as significant if P is ≤ 0.05 . Arc Map 10 software (ESRI 2011) was used to generate magnitude, significance, and direction of mean temperatures and aridity index trends maps respectively. Spatially, the results were first presented in vector form that was interpolated by performing “topo to raster analyst” and the magnitude of trends was shown with contours, while the significance and direction of trends were presented with grey colors as used by Del Río et al. (2012).

Biot, Gausson, De Martonne, and Thornthwaite indices were applied for monthly and annual dryness analysis before proceeding to the study of aridity trends (Thornthwaite and Mather 1957; Allen et al. 1998; Türkeş et al. 2002; Právělie 2013).

Biot's (1959) monthly aridity index (Biot and Gabert 1964 and Daget 1977) is

$$P/4T \quad (1)$$

Gausson's monthly aridity index (Gausson 1954) is

$$P/2T \quad (2)$$

De Martonne's annual aridity index (1926) is

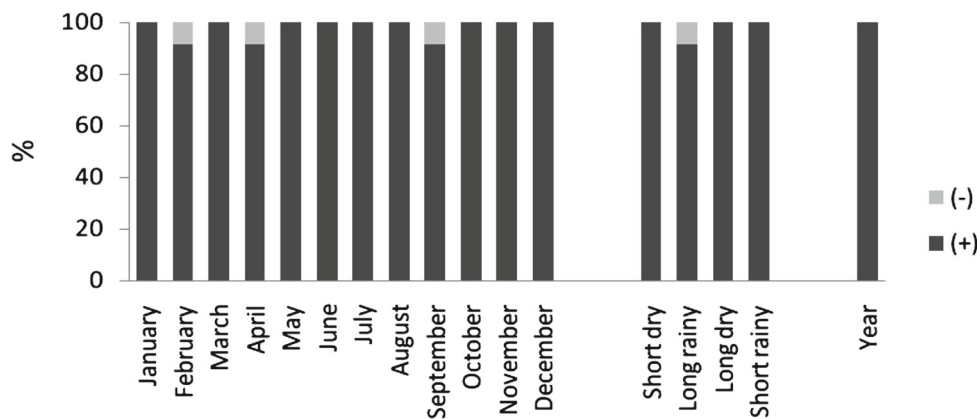
$$P/T + 10 \quad (3)$$

De Martonne's monthly aridity index is

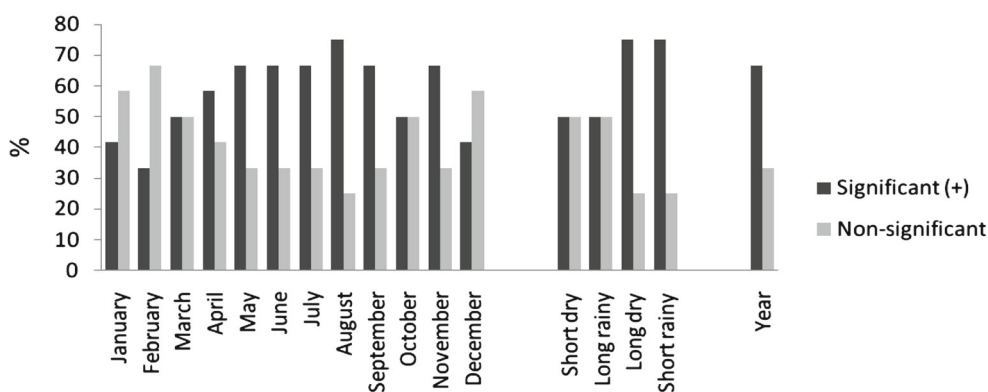
$$12P/T + 10 \quad (4)$$

where P =average precipitation in millimeters (mm) and T =mean temperature in degrees Celcius (°C). The arid, semi-arid, and moderately arid months and years were considered as the period in which $P/T+10$ and $12P/T+10$, respectively fall between 0 and 30 (where arid (A) aridity index (AI) <15 , semi-arid (SA) $15 < AI \leq 24$, and moderately arid (MA) month and year $24 < AI \leq 30$) and above that limit characterizing

Fig. 2 a Percentages of weather stations with positive and negative temperature trends. **b** Percentages of weather stations showing the significance and non-significant trends of temperatures



(a) :Percentages of weather stations with positive and negative temperature trends



(b) :Percentages of weather stations showing the significance and non-significant trends of temperatures

humid months and years (where slightly humid (SH) $30 < AI \leq 40$, humid (H) $40 < AI \leq 50$, very humid (VH) $51 < AI \leq 60$, and excessively humid (EH) month and year $61 < AI \leq 187$) as used by Práválie (2013).

The Thornthwaite aridity index is calculated using P/PET , where P =precipitation and PET =potential evapotranspiration.

$$PET = 16 \left(\frac{(10t)^a}{I} \right); \tag{5}$$

where PET =monthly potential evapotranspiration, t =mean monthly air temperature in $^{\circ}C$; I =the heat index for the year, which is equal to $\sum_1^{12} i$ and $i = \left(\frac{t}{5}\right)^{1.514}$ and “ a ” is the cubic function of I ; $a = 6.75 \times 10^{-7} \times I^3 - 7.71 \times 10^{-5} \times I^2 + 1.79 \times 10^{-2} \times I + 0.49239$. Both a and I can be found from the tables (Thornthwaite and Mather 1957; Allen et al. 1998; Türkeş et al. 2002). The arid, semi-arid, and dry sub-humid months and years were considered as months and years in which the ratio of monthly and annual precipitations to potential evapotranspiration respectively falls within the range from 0.03 to

0.65 (where hyper arid: Thornthwaite aridity index (TAI) < 0.05 , arid (A) $0.05 < TAI < 0.20$, semi-arid (SA): $0.20 < TAI < 0.50$ and dry sub-humid (DSH) month $0.50 < TAI < 0.65$) and above that limit characterizing humid months (wet sub-humid (WSH) $0.65 < TAI < 0.75$ and humid (H) month $TAI \geq 0.75$) as used by Türkeş et al. (2002). The monthly and annual amount of water deficit or surplus, calculated as the numerical difference between rainfall amount and potential evapotranspiration, was done to evaluate monthly and annual moisture balance at weather stations used in this study.

The calculation of the abovementioned monthly aridity indices have been performed to characterize each month in terms of aridity to select the appropriate index to use in analyzing aridity index trends. Birot, De Martonne, and Thornthwaite indices gave almost the same results. De Martonne aridity index has been used in aridity trend analysis in this study for being simpler than the Thornthwaite index in calculating monthly and annual aridity indices. De Martonne index gives more a detailed index than Birot’s index, which determines only a dry or humid month or year without specifying the degree of dryness or wetness.

4 Results and discussion

4.1 Trends in mean temperature

Analysis of trends in mean temperatures is important in estimating warming trends. The increase in temperatures plays an essential role in the increasing of intensity of aridity leading to more occurrences of droughts episodes, along with land

degradation (Liu et al. 2008), reduction of water resources (Chamchati and Bahir 2011) and a decline of agricultural production resulting from the failure and destruction of crops. Figure 2a, b shows the direction (positive or negative) and significance of trends in mean temperatures, respectively.

Figure 2a shows an increasing trend in mean annual temperatures throughout the year for all stations across the country. Only one station (Ruhengeri), located in the northwestern

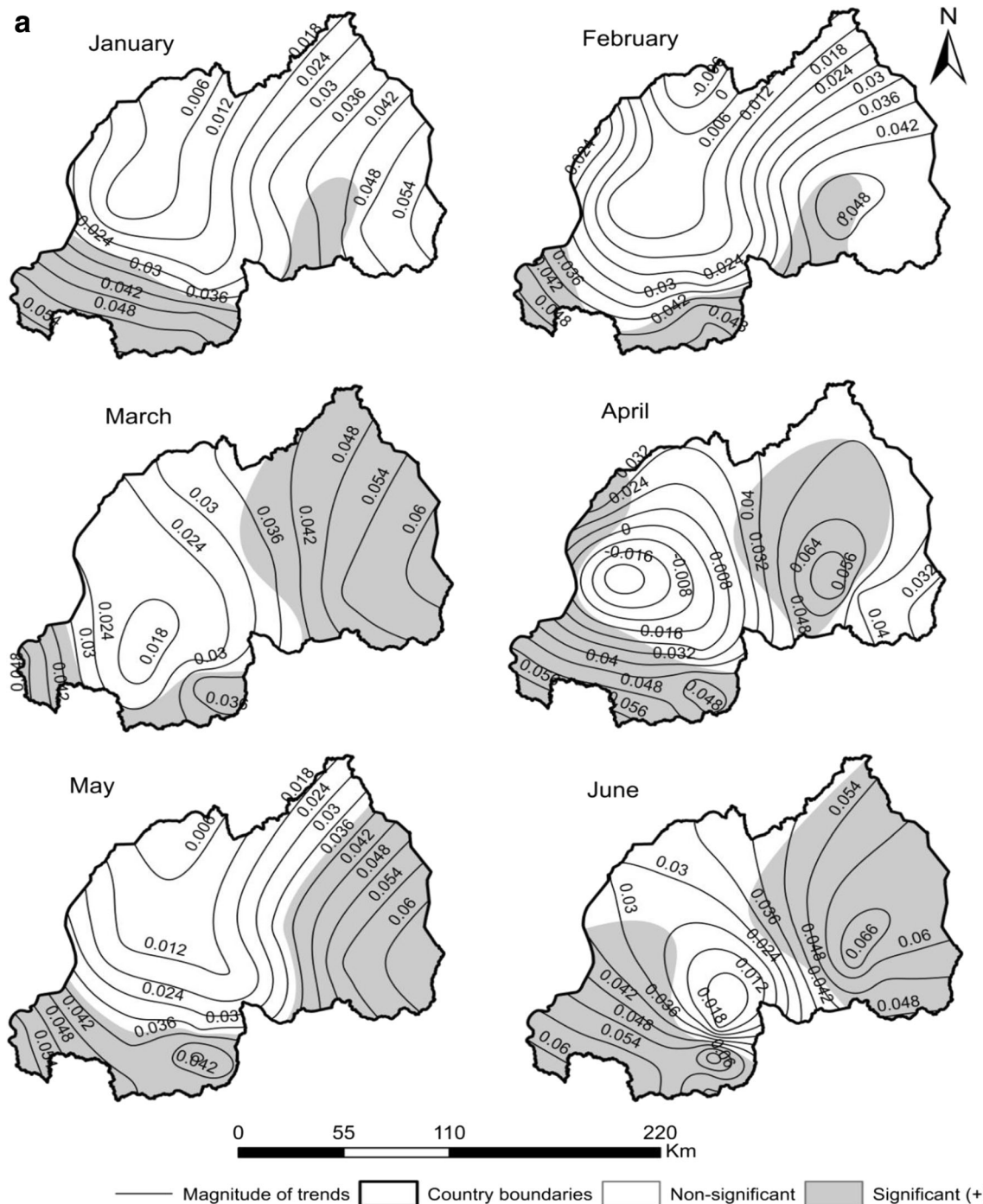


Fig. 3 a Magnitude (in °C/year) and significance in mean temperature trends (January–June). b Magnitude (in °C/year) and significance in mean temperature trends (July–December). c Magnitude (in °C/year) and significance in mean seasonal and annual temperature trends

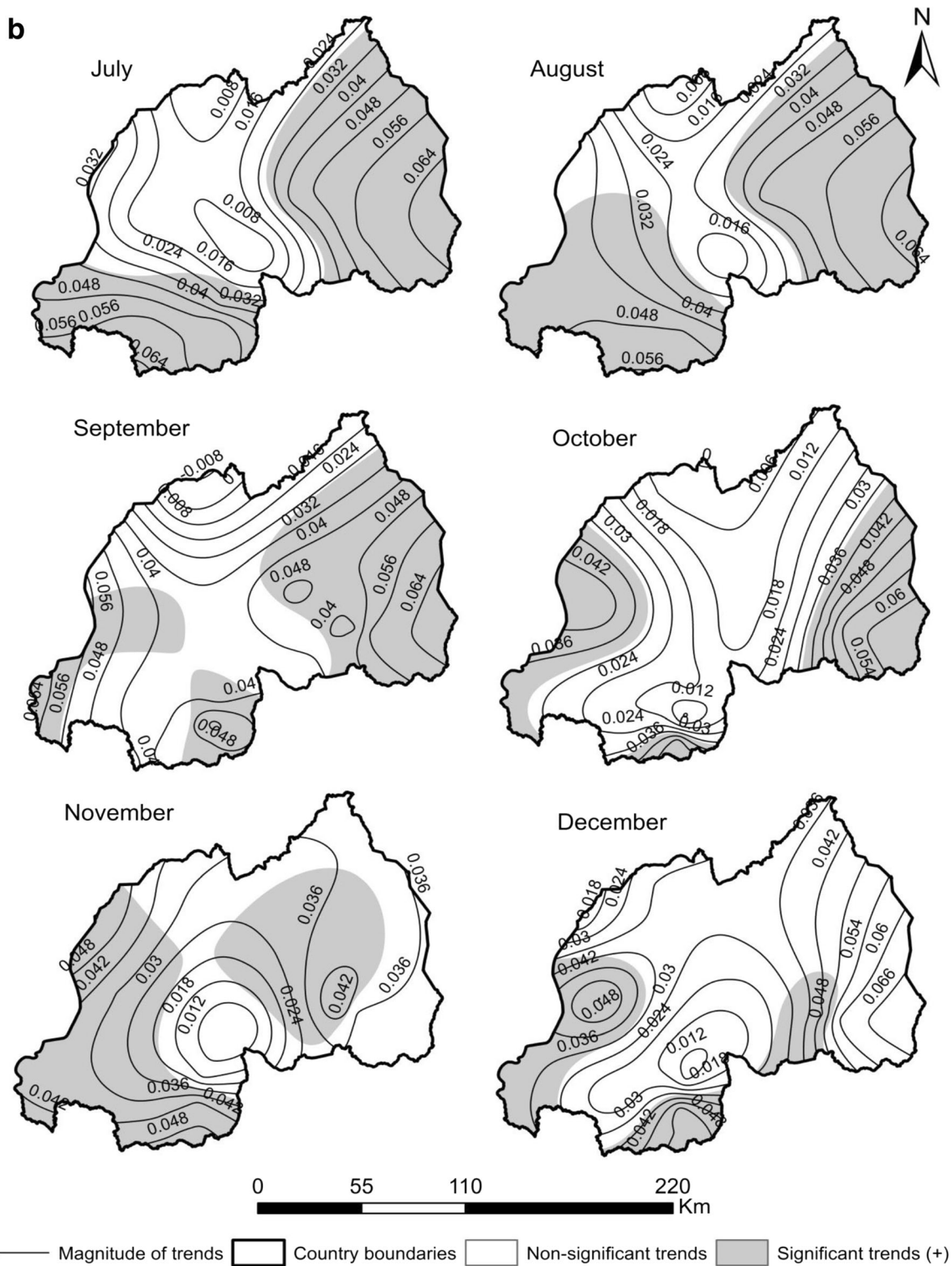


Fig. 3 (continued)

highlands, registered a decreasing trend in February, April, and October. A high significant increasing trend was observed from March to November, while a low significant increasing trend was observed from December to February (Fig. 2b). At seasonal time scale, the high significant increase is observed

during the long dry season (June–July–August), which is characterized by the lowest rains and during the short rainy season (September–October–November) corresponding with the overhead position of solar radiation over Rwanda in March and April. The nonsignificant increase in mean

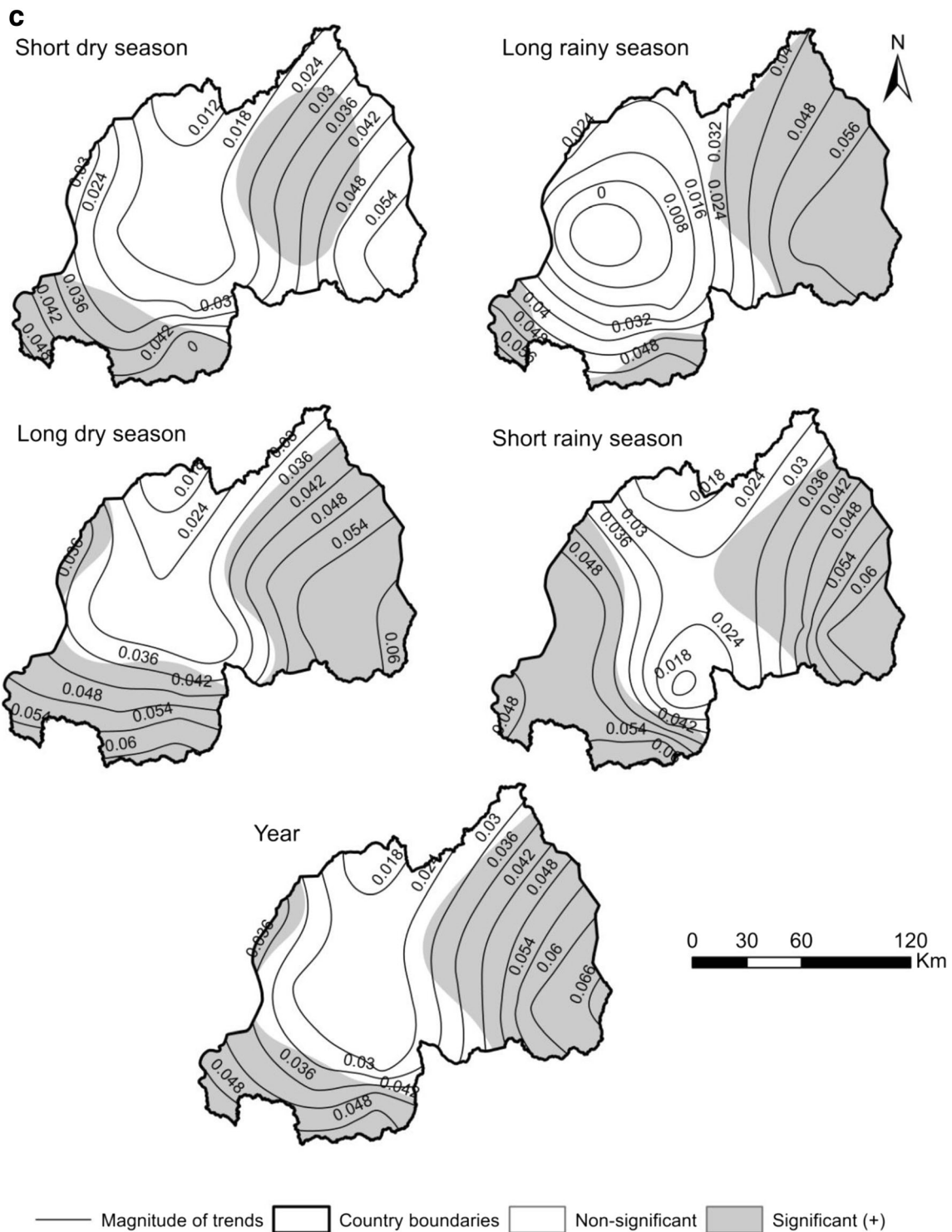


Fig. 3 (continued)

temperature at most parts of the country has been mainly observed during the short dry season (December–January–February), which can be attributed to the fact that solar radiation is overhead on the Tropic of Capricorn during this period. At an annual resolution, the significant

increase in mean temperatures is recorded at 70 % of the weather stations.

The spatial distribution of the magnitude (in $^{\circ}\text{C}/\text{year}$) and significance of mean temperature trends are shown in Fig. 3.

Table 1 Characteristics of the months and years according to Birot's aridity index (12 weather stations for the period 1961–1992)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Butare	H	H	H	H	H	D	D	D	D	H	H	H	H
Cyeru	H	H	H	H	H	D	D	D	H	H	H	H	H
Gahororo	H	H	H	H	H	D	D	D	D	H	H	H	H
Gisenyi	D	H	H	H	H	D	D	D	H	H	H	H	H
Kamembe	H	H	H	H	H	D	D	D	H	H	H	H	H
Kibuye	H	H	H	H	H	D	D	D	H	H	H	H	H
Kigali	D	H	H	H	H	D	D	D	D	H	H	H	H
Kigembe	H	H	H	H	H	D	D	D	H	H	H	H	H
Kitabi	H	H	H	H	H	D	D	D	H	H	H	H	H
Rubona	H	H	H	H	H	D	D	D	D	H	H	H	H
Ruhengeri	H	H	H	H	H	D	D	D	H	H	H	H	H
Zaza	D	H	H	H	H	D	D	D	D	H	H	H	H
Average	H/D	H	H	H	H	D	D	D	H/D	H	H	H	H

H humid, *D* dry

The spatiotemporal presentation of trends in mean temperatures (Fig. 3) indicates significant rises in temperature in the eastern lowlands and the regions around Lake Kivu in the southwest of the country where the monthly and annual mean temperatures are above 18 °C. The highlands to the northwest and Congo-Nile crest show a nonsignificant increase in mean temperatures.

The mean temperatures increased by between 0.018 and 0.066 °C per year over Rwanda with a decreasing trend in February and September at Ruhengeri weather station located in the northwest region, and in April at Kibuye weather station, located in the western region of the country around Kivu Lake. The highest increase of between 0.044 and 0.066 °C per year has been observed in the regions to the eastern lowlands. From this observation, it is safe to conclude

that lowlands with higher monthly and annual mean temperatures are warming faster compared to the rest of the country.

The nonsignificant increasing pattern observed mainly from December to February in many parts of the country exhibits almost the same spatial distribution. November and April, the months receiving the highest precipitation in the year, show the same spatial behavior in mean temperature trends. Apart from the abovementioned months, the rest, that is, March, May, June, July, August, September, and October present almost a similar increasing pattern in mean temperatures. Long-dry and short-rainy seasons that are found in most of the country show a significant increase and present relatively the same spatial pattern in mean temperature trends as it is at annual resolution.

Though an increase of between 0.018 and 0.066 °C per year in mean annual temperature was observed over Rwanda,

Table 2 Characteristics of the months and years according to De Martonne aridity index (12 weather stations, 1961–1992)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Butare	H	H	EH	EH	VH	A	A	A	SH	H	VH	H	H
Cyeru	SH	H	VH	EH	H	A	A	MA	SH	SH	VH	SH	SH
Gahororo	SH	H	VH	EH	H	A	A	A	MA	H	EH	H	H
Gisenyi	SH	SH	H	VH	H	MA	A	MA	H	VH	H	SH	SH
Kamembe	VH	EH	EH	EH	SH	A	A	MA	H	EH	EH	VH	VH
Kibuye	H	H	VH	EH	H	A	A	A	SH	SH	H	SH	SH
Kigali	MA	SH	H	EH	H	A	A	A	SH	SH	H	SH	SH
Kigembe	H	VH	EH	EH	VH	A	A	MA	SH	H	VH	H	H
Kitabi	EH	EH	EH	EH	EH	A	A	MA	H	EH	EH	EH	VH
Rubona	H	H	VH	EH	H	A	A	A	MA	H	VH	H	H
Ruhengeri	VH	VH	EH	EH	EH	MA	A	MA	VH	EH	EH	VH	VH
Zaza	SH	SH	VH	EH	H	A	A	A	MA	H	VH	H	SH
Average	H	H	VH	EH	H	A	A	MA	H	H	VH	H	H

A arid or dry, *SA* semi-arid, *MA* moderately arid, *SH* slightly humid, *H* humid, *VH* very humid, *EH* excessively humid

Table 3 Characteristics of the months and years according to Gaussen aridity index (12 weather stations, 1961–1992)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Butare	H	H	H	H	H	D	D	D	H	H	H	H	H
Cyeru	H	H	H	H	H	D	D	D	H	H	H	H	H
Gahororo	H	H	H	H	H	D	D	D	H	H	H	H	H
Gisenyi	H	H	H	H	H	H	D	H	H	H	H	H	H
Kamembe	H	H	H	H	H	D	D	H	H	H	H	H	H
Kibuye	H	H	H	H	H	H	D	H	H	H	H	H	H
Kigali	H	H	H	H	H	D	D	D	H	H	H	H	H
Kigembe	H	H	H	H	H	D	D	D	H	H	H	H	H
Kitabi	H	H	H	H	H	H	D	H	H	H	H	H	H
Rubona	H	H	H	H	H	D	D	D	H	H	H	H	H
Ruhengeri	H	H	H	H	H	H	D	H	H	H	H	H	H
Zaza	H	H	H	H	H	D	D	D	H	H	H	H	H
Average	H	H	H	H	H	D/H	D	D/H	H	H	H	H	H

H humid, *D* dry

the eastern lowlands and the southwest regions, with the highest mean annual temperature varying between 19 and 22 °C are becoming warmer (at the rate of 0.036 to 0.066 °C per year) compared to the rest of the country. However, the spatial pattern in mean temperature trends is changing slightly as a result of low variations in mean monthly temperatures.

4.2 Trends in aridity

Like is the case with other countries of the eastern Africa region, Rwanda is becoming warmer faster (0.018 and 0.066 °C per year) compared to the global average (0.74 °C between 1901 and 2005) (King'uyu et al. 2000; Ruosteenoja et al. 2003; Funk and Brown 2006; Eriksen et al. 2008). A rising trend in temperature of between 0.03 and 0.06 °C per

year has been also observed in African countries like Sudan (North and South), Ethiopia, and Uganda. An annual mean temperature increase of 0.01 to 0.03 °C per year between 1961 and 2000 was observed in the neighboring countries of Burundi, inland Kenya, and Tanzania. Others are Madagascar, Eritrea, and South Africa (Engelbrecht et al. 2002; Kruger and Shongwe 2004; Washington and Pearce 2012).

It is for this reason that an analysis of trends in aridity is critical for timely monitoring of warming and drying of the country. A study of aridity index trends is one of the tools that can be used to project food security situation at national, regional and international levels as crop production depends on available water during growth. This study uses Birot, Gaussen, De Martonne, and Thornthwaite aridity indices to assess the presence of dry months in Rwanda. The first three

Table 4 Characteristics of the months and years according to Thornthwaite aridity index (12 weather stations, 1961–1992)

Station	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Year
Butare	H	H	H	H	H	SA	A	SA	H	H	H	H	H
Cyeru	H	H	H	H	H	SA	A	DSH	H	H	H	H	H
Gahororo	H	H	H	H	H	SA	A	SA	H	H	H	H	H
Gisenyi	H	H	H	H	H	SA	A	SA	H	H	H	H	H
Kamembe	H	H	H	H	H	SA	A	DSH	H	H	H	H	H
Kibuye	H	H	H	H	H	DSH	A	DSH	H	H	H	H	H
Kigali	H	H	H	H	H	SA	A	SA	H	H	H	H	H
Kigembe	H	H	H	H	H	SA	A	DSH	H	H	H	H	H
Kitabi	H	H	H	H	H	DSH	A	H	H	H	H	H	H
Rubona	H	H	H	H	H	SA	A	SA	H	H	H	H	H
Ruhengeri	H	H	H	H	H	H	SA	H	H	H	H	H	H
Zaza	H	H	H	H	H	SA	A	SA	H	H	H	H	H
Average	H	H	H	H	H	SA	A	SA	H	H	H	H	H

H humid, *A* arid, *SA* semi-arid, *DSH* dry sub-humid

indices use temperature and rainfall amounts while the last aridity index uses potential evapotranspiration and precipitation to estimate monthly and annual aridity. The results are presented in tables below (Tables 1, 2, 3, and 4).

It is observed that apart from Gausson aridity index, the other indices show that June–July–August are dry months in most weather stations used in this study. Birot and De Martonne indices show an extension of dryness up to September mainly at weather stations located in the eastern lowlands and the central plateau. These are areas that receive low rains with high temperatures (above 18 °C). Gausson monthly aridity index shows June and August as humid at four stations located around Kivu Lake (e.g., Gisenyi and Kibuye) and in the highlands (at Kitabi and Ruhengeri), respectively. Areas around Kivu Lake have low elevation with high rains and more than 18 °C mean monthly and annual temperature, which is unusual in Rwanda. Thornthwaite aridity index presents June–July–August as dry months at different places save for Ruhengeri weather station (located in the northwestern highlands), where June and August are humid.

Water deficit index, which is the numerical difference between rainfall amounts and potential evapotranspiration (Thornthwaite and Mather 1957; Allen et al. 1998) has shown a deficit ranging between 28.1 and 49.8 mm in June and August at 90 % of the weather stations. The lowest water deficit of 11.4 mm has been registered in the northwestern highlands and highest (70 mm) in the eastern lowlands both in July for the period 1961–1992. This month (July) has shown the water deficit at all weather stations. However, there are water surplus in the remaining months as well as at annual timescale at all weather stations used in this study. Although all climatic regions of Rwanda can be used to grow crops despite the variations in available water, the northwestern highlands have the highest potential for agriculture in Rwanda.

De Martonne aridity index that gives results in mm has been selected to be used in aridity trend analysis in this study

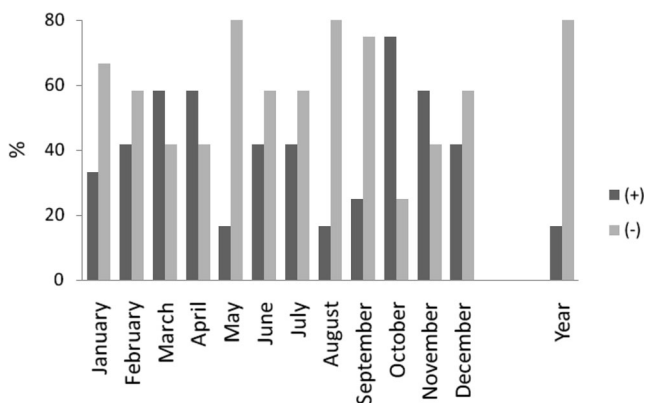


Fig. 4 Percentages of weather stations with positive and negative aridity trends

for being simpler than the Thornthwaite index in calculating monthly and annual aridity indices as it was explained in methodology section. Figure 4 shows a fall/rise in De Martonne monthly and annual aridity index for 1961–1992.

Rise in temperatures plays a critical role in determining the intensity of aridity and crop water deficit. A decrease in the aridity index indicates acceleration in warming while a rise in index shows an increase of water storage resulting from increased rainfall amounts. The annual aridity index showed a decreasing trend in around 80 % at the weather stations. A rising pattern in De Martonne aridity index was observed during the rainy months (March, April, October, and November) at around 60 % of the weather stations with the rest of the year showing a decreasing trend. Therefore, the wet months got wetter while the rest of the year remained dry. The decreasing trends in aridity index are not significant across all parts of the country. This is bound to lead to a shortage of water storage to comfortably sustain the growth of crops. The end result would be decline in crop production. Further studies are recommended to correlate crop yields and aridity index values (Fig. 5a–c).

Though the changes in De Martonne aridity index were nonsignificant throughout the year, it increased in the months of March, April, October, and November. This corresponded with the wet season in most parts of the country where the De Martonne aridity indices vary between 50 and 87 (i.e., very humid and excessively humid: VH and EH, respectively, in Table 2). The remaining period showed a decreasing aridity index over most parts of Rwanda. A high decrease in De Martonne aridity index of around 1.95 per year from an index varying between 40 and 60 (i.e., humid and very humid: H and VH, respectively, in Table 2), has been observed in January and May in the northwest and the southern region, respectively, with a high increase of 1.32 per year in the northern region of the country.

Apart from January and February, the volcanic chains of Birunga located in the northwest region of the country showed a rise in De Martonne aridity index. The southwest region showed a decline in the aridity index during the dry season (June–July–August) with the rest of the year showing a rising trend. These months have De Martonne aridity indices varying between 15 and 30 (i.e. arid and semi-arid: A and SA, respectively, in Table 2). Thus, they are already exposed to dry conditions. The southern and central plateau showed a decreasing trend throughout the year, while the eastern lowlands presented a rise in aridity index only during the rainy months (March, April, October, and November). The only exception was May, whose decrease in aridity index could be the result of the decline in the amount of rainfall (Muhire and Ahmed 2014). Its effect is shortened crop growing period that leads to reduced crop production.

The spatial pattern in De Martonne annual aridity index trend increases at the mean rate of 0 to 0.48 in the northwest

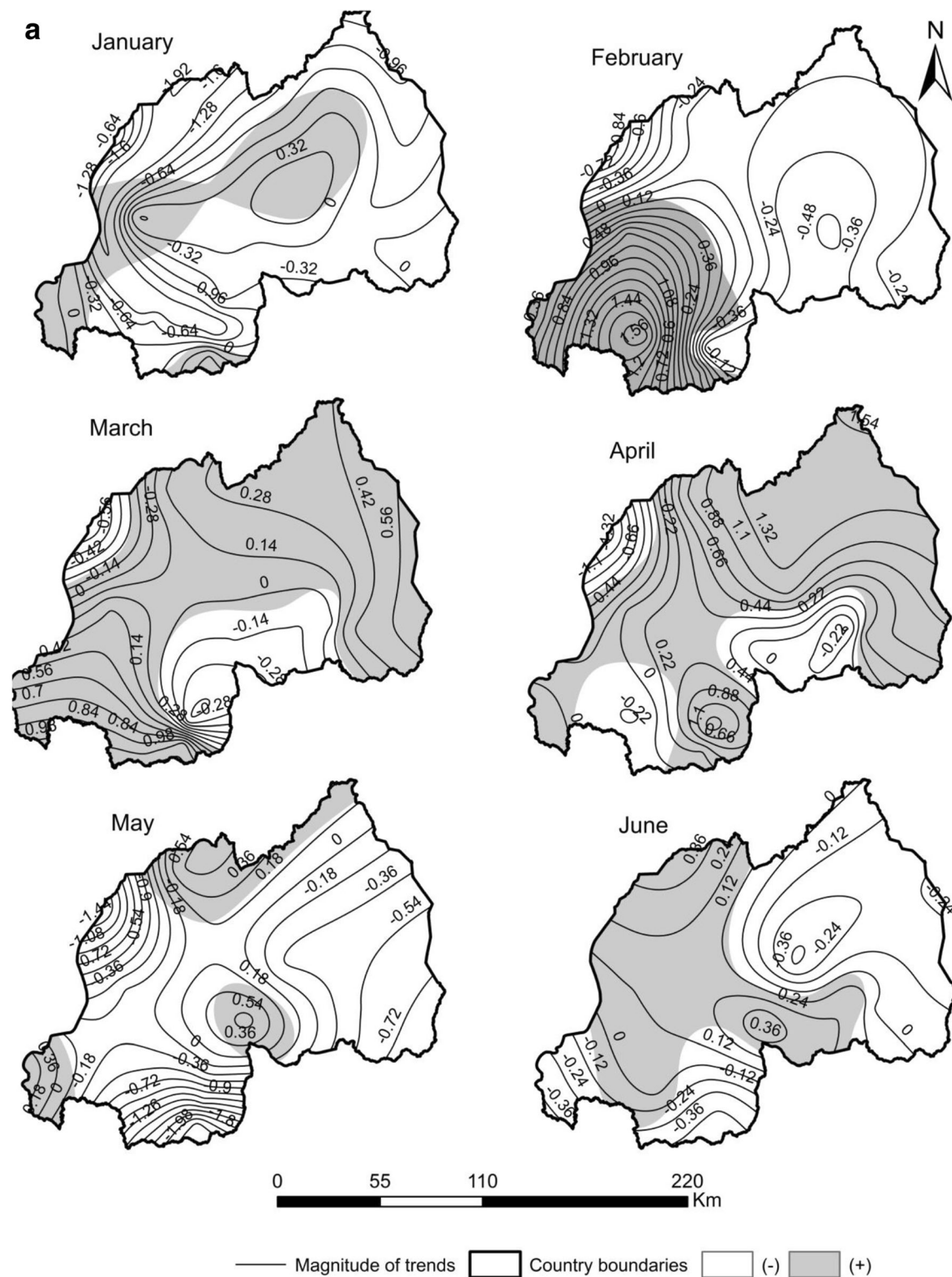


Fig. 5 **a** Magnitude (per year) and direction of De Martonne aridity trends (January–June). **b** Magnitude (per year) and direction of De Martonne aridity trends (July–December). **c** De Martonne annual aridity indices and their trends (per year)

and western regions of the country with the exception of Gisenyi weather station. The remaining parts of the country (central and eastern regions) show a decline in De Martonne aridity index, where a higher decrease rate of 1 to 1.44 per year

is registered in the south. This reveals that the central plateau and eastern lowlands regions having the lowest De Martonne aridity index of between 33 and 45 are becoming warmer compared to the rest of the country.

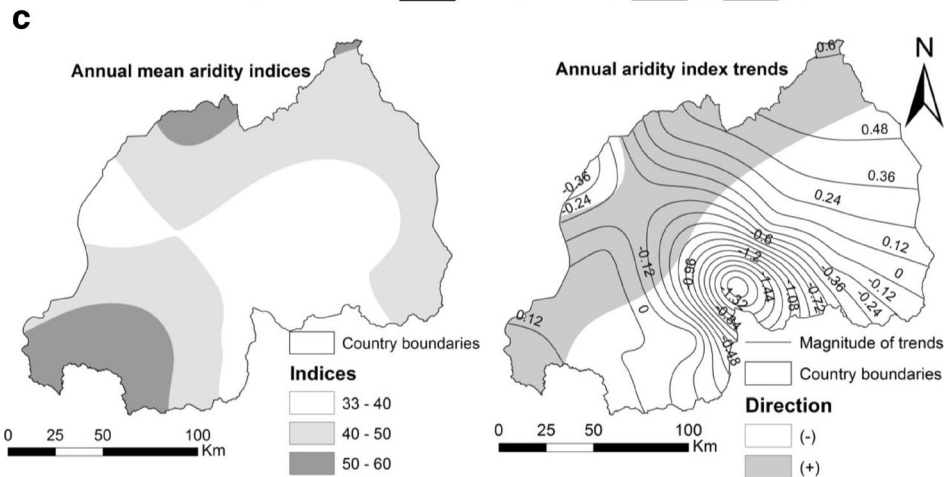
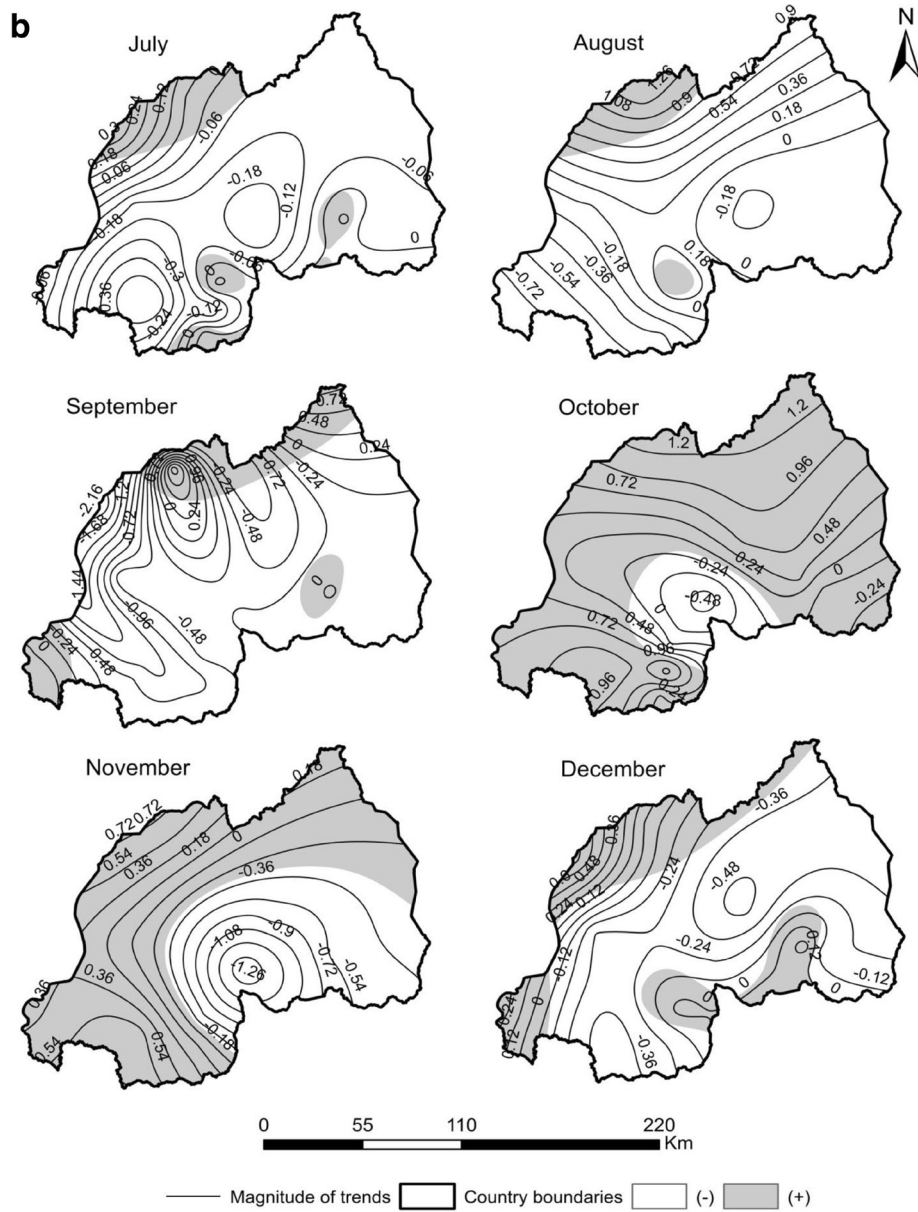


Fig. 5 (continued)

5 Conclusion

The significant increase in mean annual temperatures of between 0.036 and 0.066 °C per year resulted in a high decline of De Martonne aridity index of between 0.12 and 0.36 per year over the southeastern lowlands of Rwanda. The nonsignificant increase in mean annual temperatures of between 0.018 and 0.03 °C followed by a significant increase in precipitation at a rate of between 2 and 6.5 mm per year over the Congo-Nile crest and the northern highlands for the period of 1935–1992 (Muhire and Ahmed 2014) resulted in an increase in De Martonne aridity index of between 0.12 and 0.6 per year for the period of 1961–1992. Though the central region of the country showed a nonsignificant increase in mean seasonal and annual temperatures, it presents the highest decreasing trend in De Martonne aridity index of between 0.6 and 1.44 per year for the period of 1961–1992.

It is worth noting that increasing temperature trends accompanied by a decreasing pattern in De Martonne aridity index especially during the drier months in regions receiving low amounts of rainfall especially over the eastern lowlands and the south of the country, is likely to cause a progressive increase in potential evapotranspiration (Ilunga and Tsinda 2004), leading to reduced water storage. Hence, this decrease in De Martonne aridity index with an increase in potential evapotranspiration is bound to cause crop water deficit, leading to failure of crops or decline of crops production.

A nonsignificant increase in annual mean temperatures with an increasing De Martonne aridity index trend over northwest highlands make this region to continue to have enough water storage to support crops. Hence, the northwest highlands and southwest region might remain the most productive region of the country. Further investigation on the correlation between mean temperatures and aridity index trends with crop production will help to enlighten Rwandans on the ongoing changes in order to lessen and prevent food insecurity in the country. Therefore, a study on the temperature and aridity indices trends in the coming years is recommended.

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