How future climatic uncertainty and biotic stressors might influence the sustainability of African vegetable production

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Abstract

The study was conducted to determine whether likely global climatic uncertainty in the future will pose substantive risk to small-scale vegetable producers in Africa, and to consider whether climate change threatens the development and sustainability of improved vegetable horticultural systems in Africa. Annual average air temperature and rainfall totals were assessed over the period 1975-2014 or, where possible, for rainfall for longer periods approaching 100 years; the trends in these data sets were determined through linear regression techniques. Predictions of the likely values of annual average air temperatures in the next 25, 50, 75 and 100 years were made. Considerable variability in trends is reported ranging from extremely fast warming in Tunis, Tunisia contrasting with slight cooling in Bamako, Mali. Annual variability in rainfall was substantive but there were no long-term trends of consequence, even when considered over the last 100 years. Consequently, the sustainability of vegetable production will be threatened mostly by changes in pest (e.g., weeds, insects, fungi, bacteria and viruses) damage to crops in small-scale production systems. A call is made for national governments to give these issues enhanced priority in the distribution of future research and capacity-building resources, as most of these production stressors are under-researched and evident solutions to such problems are not currently available.

Keywords: annual temperature, rainfall variability, diseases, pests, horticultural systems

INTRODUCTION

The potential for smallholder horticulturalists in Africa, very often women, to grow themselves out of poverty and to provide better nutrition for their families is greatly increased when they are able to practice effective vegetable production and marketing from their smallholdings and kitchen gardens. (Afari-Sefa et al., 2012). Climate uncertainty and its implications for changing potential biotic and abiotic stressors across the continent are poorly understood (Bebber, 2015; Ebert et al., in press) and the literature concerning future projections for vegetables is sparse. This issue is addressed for some specific locations (Keatinge et al., 2013) but the paucity of sites providing data cannot be deemed to be continentally appropriate (Keatinge et al., 2014, 2015a). It has been suggested that the majority of small-scale farmers agree the climate in Africa is changing for the worse (Rao et al., 2011) and there have been few attempts to intensify horticulture sustainably except on kitchen garden scale landholdings (Pretty et al., 2011). We hypothesize that climate change threatens the development and sustainability of improved vegetable horticultural systems in Africa (Ebert et al., in press), as well as other crops (Challinor et al., 2007; Paeth et al., 2009).

For trends in maize (*Zea mays*) production and other staples, the issue of climate change is well-addressed. A highly detailed analysis employing data from more than 20,000

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historical maize trials has been reported (Lobell et al., 2011). Their paper indicates a non-linear relationship between temperature and yield; for each degree day above 30°C, the final yield falls by 1% even under optimal rain-fed conditions, and losses are further exacerbated to 1.7% by a greater incidence of drought. Several papers call for adaptation of farming systems to address future climate scenarios based on the general circulation models promulgated by the Intergovernmental Panel on Climate Change (IPCC, 2007, 2013) which suggest at least 2°C global climate warming over the next 100 years with mixed variations in annual rainfall. In the case of both maize and beans (*Phaseolus vulgaris*) in scenarios modeling a 4°C increase in annual average temperature, continent-wide yield reductions across Africa were substantive – in the 10-25% category for maize and greater than 50% for beans – which would have negative consequences for smallholder farmers (Thornton et al., 2011) and food security on the continent. Similar studies on sorghum, millet, ground nut and cassava production report predicted yield changes of around minus 10-20% by the mid-21st century (Schlenker and Lobell, 2010). An increased likelihood of severe drought and flooding events that would impact farmers severely has been discussed (Shongwe et al., 2009, 2011; Rao et al., 2015).

Southern Africa is projected to be vulnerable to increasing pressure of drought by 2030 (Lobell et al., 2008) while the long term sustainability of the maize-based agro-ecosystem is called into question and a shortening of the growing season is projected for the western parts of southern Africa (Shongwe et al., 2009). Likewise, increased temperatures and reduced rainfall in the Highveld region of South Africa may seriously undermine the long term productivity of maize (Walker and Schulze, 2008). Reductions in yields of more than 10% may be experienced across southern Africa in the medium term (Zinyengere et al., 2013). These concerns for southern African farming systems are also reported generally and for Zambia specifically by Twomlow et al. (2008), who call for immediate and intensive training of smallholder farmers to supplement their adaptive capacity to weather variation and thus to cope better with future climate change. An examination of long term trends in rainfall data (Stern and Cooper, 2011) concluded over 89 years (excluding the four principal dry season months) at Moorings Station in southern Zambia did not identify any simple trends. Yet, when the years were split between El Niño, ordinary, and La Niña events, then the daily probability of rain was lower in El Niño years than in other years. The importance of El Niño years and their variability in terms of precipitation in the Mara-Serengeti area of Kenya and Tanzania has been highlighted by Ogutu et al. (2008), who observed that greater rainfall was experienced in colder El Niño-Southern Oscillation (ENSO) events and less rainfall in warmer ENSO event years, thus demonstrating the extreme difficulty in determining specific trends in African rainfall resulting from overall global warming. Likewise, in terms of air temperature for this region, monthly minimum temperatures were seen to increase substantially at Nakuru, Kenya, yet no change was discernible in monthly maximum temperatures (Ogutu et al., 2012). Similarly, somewhat contradictory results in temperature trends are evident elsewhere, such as in Asia (Keatinge et al., 2014) and Mesoamerica (Keatinge et al., 2016).

In the case of eastern Africa, an increase in mean precipitation rates is projected in the long term and there may be a greater number of storms of high intensity (Shongwe et al., 2011). Studies modeling climate scenarios up to 2050 with maize and bean crops suggest that local topographic variations may play a substantive role in the relative sustainability of farming systems, with sites at higher elevation showing more yield gains than losses resulting from climate change (Thornton et al., 2009). Yet, in common with earlier papers, the importance of generating local, community-based efforts to increase the adaptive capacity of smallholder farmers is stressed if the resource-poor are not to incur additional hardship. Studies on maize (Cooper and Coe, 2011) represent the position of rain-fed agriculture in eastern Africa, specifically at Makindu, Kenya, where with a 3°C projected rise in air temperature, most (80%) of growing seasons would still show the same amount of variability in length of growing season that farmers currently experience. Thus, helping farmers to develop resilient systems today would be a good strategy to ensure sustainability of their enterprises in the future. A clear, increasing trend in maximum and minimum air temperatures since 1990 was observed for Embu in Kenya (Rao et al., 2015). At this location average annual air temperature increased significantly by around 0.4°C when the 1980-89 period was contrasted with 2001-2010, but no clear trend was observed in the amount of rainfall either annually or seasonally from 1980-2010.

For west Africa, specifically for the Cameroonian Sahelian zone, a rising trend in air temperature was observed between 1960 and 2008 but no such trend was evident in the precipitation data, which was highly variable (Yengoh, 2013). Analyzing the results of 16 studies it is concluded (Roudier et al., 2011) that yield reduction will be highly variable across a range of staple crops, including cereals, roots and tubers, but is generally likely to be large (averaging >10% yield loss) across a range of medium-term time horizons (2030-2050 onwards) with the negative effects of increased temperature being much larger than the consequences of projected reductions in rainfall. Yet, a very substantial variability in annual rainfall over the last 100 years or so in the Sahel has been reported (Sissoko et al., 2011). This may make any determination of future trends in rainfall exceedingly difficult, though these authors suggest that the drying trend of the late 20th century might have been related to natural and human-produced greenhouse gas emissions and human use of aerosols.

Although it may not be easy to identify clear trends in future projected temperatures and rainfall across Africa, the possibility of increased rainfall by 2050 in some areas such as the East African highlands has been suggested (Cooper et al., 2009), as well as increased air temperature (Rao et al., 2015). A combination of higher temperatures and increased moisture would not only affect crop growth but perhaps more importantly may influence the behavior of the major biotic constraints to production. Farrow et al. (2011) indicate that root rot (*Pythium* spp.) would be a more severe constraint to production of beans with increased rainfall in eastern Africa – particularly for the highland areas surrounding the Lake Victoria basin. Ground-truthing to prove this point was not accomplished by the authors as there was an insufficient density of rainfall recording stations in their region, yet logic suggests that this potential scenario must have some considerable validity for vegetables such as the *Solanaceae* (Boland et al., 2004; Luck et al., 2011), which are highly susceptible to soil-borne diseases. Farrow et al. (2011) reviewed historical work and cite examples of some very serious diseases in Africa that may become much more damaging in hotter and wetter conditions. This list includes diseases such as late blight (*Phytophthora infestans*) and cassava mosaic viruses, which are highly damaging to leafy vegetables. The effects of plant pests exacerbated by climate change will be difficult to determine (Bebber, 2015); considerable additional research investment will be required to untangle these highly complex relationships effectively, and then to design the appropriate coping amendments for farming systems (Garrett et al., 2011).

Authors from AVRDC - The World Vegetable Center have reported that, as a result of likely climate change, additional heat, drought and pest tolerance will be required from current and future vegetable breeding programs for global species in Africa (De la Peña and Hughes, 2007; Keatinge et al., 2009; De la Peña et al., 2011) such as tomatoes (*Solanum lycopersicum*) (Fufa et al., 2011) and other exotic *Solanaceae* such as capsicums and chillis (*Capsicum annuum*) (Hanson et al., 2011). The selection and breeding of hardy indigenous species with tolerance to biotic and abiotic constraints needs to be a mainstream research effort if sustainable and resilient vegetable production systems are to be developed in Africa (Keatinge et al., 2015b; Dinssa et al., 2016).

MATERIALS AND METHODS

For temperature data the sites were selected for the quality and length of available data in those areas where vegetable horticulture is presently practiced and with data exceeding 30 years in length. Effort was made to ensure site selection was widely distributed across Africa (Table 1; Figure 1). Annual mean temperatures were computed based on monthly averages per year. In rare cases where some months have missing data, the monthly averages of the same months from five immediately previous years were used to fill in the gaps (Environment Canada, 2012). Data were collected from multiple sources, including some used in previous studies (Keatinge et al., 2013, 2014, 2015a).

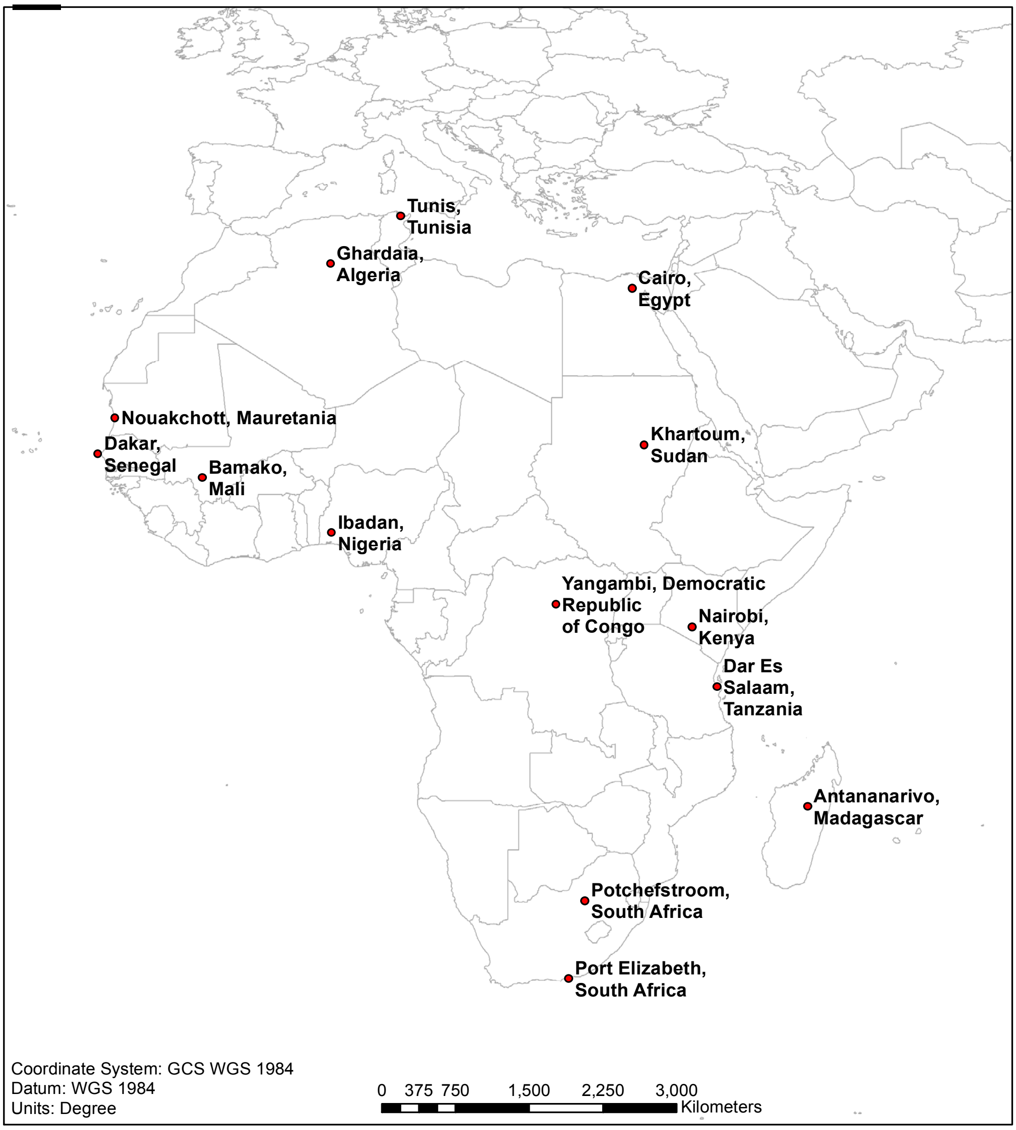


Figure 1. Location of African meteorological sites employed in the analysis.

Data for annual average air temperature were downloaded from the UK Meteorological Office global database and accessed through http://datamarket.com. If there were minor examples of missing data in the recent past from this data source, these were determined from other records for the specific sites such as from http://www.tutiempo.net/en/climate and http://www.wunderground.com. All data were carefully examined for anomalies and missing values before sites were accepted for inclusion. At each site, linear regression lines were fitted to the data for the periods 1975-2014 as further described (Keatinge et al., 2014). The possibility of curvilinear fits for the data was initially considered, but linear fits were the most appropriate solution in terms of fit (Figures 2-11; Tables 2 and 3).

Table 1. Location, elevation and years of temperature (T) and rainfall (R) data used for analysis of long term records at meteorological stations in Africa.

Meteorological station location	Latitude	Longitude	Elev. (m)	Data run	T or R T and R
Antananarivo, Madagascar	-18.00	+047.48	1279	1975-2014	T only
Bamako (Sénou airport)[1], Mali	+12.53	-007.95	0380	1975-2014	T and R
Bamako (old airport), Mali	+12.65	-008.00	0350	1919-1974	R only
Cairo Airport, Cairo, Egypt	+30.13	+031.40	0064	1975-2014	T only
Dakar (Yoff), Dakar, Senegal	+14.73	-017.50	0027	1975-2014	T only
Dar Es Salaam (Julius Nyerere airport, Tanzania)	-06.87	+39.20	0055	1975-2014	T only
Ghardaia, Algeria	+32.40	+003.81	0450	1975-2014	T only
Ibadan, Nigeria (IITA)	+07.43	+003.90	0227	1975-2014	T and R
Ibadan, Moor Plantation[2]	+07.38	+003.93	0198	1901-1998	R only
Khartoum, Sudan	+15.60	+032.54	0382	1975-2013	T only
Nairobi (Jomo Kenyatta airport), Kenya	-01.31	+036.91	1624	1975-2014	T only
Nouakchott, Mauretania	+18.10	-015.95	0002	1975-2014	T only
Port Elizabeth, South Africa	-33.98	+025.60	0061	1975-2013	T and R
Port Elizabeth, South Africa	-33.98	+025.60	0061	1867-2010	R only
Potchefstroom, NW University, S. Africa	-26.74	+027.08	1349	1975-2014	T only
Tunis, Carthage, Tunisia	+36.83	+010.23	0003	1975-2014	T and R
Tunis, Carthage, Tunisia	+36.83	+010.23	0003	1895-2014	R only
Yangambi (INERA), DR Congo	+0.82014	+24.45627	0458	1912-2010	T and R

[1]Sénou is 15 km south of central Bamako which was the site of the old airport.
[2]21 km apart with Moor Plantation west of Ibadan city and IITA north of Ibadan city.

Table 2. Trend analysis in annual average air temperature (°C) for African meteorological stations 1975-2014.

Meteorological station location	Intercept	Slope	R^2	Significance
Antananarivo, Madagascar	-034.59	+0.027	0.45	P<0.01
Bamako (Sénou), Mali	+059.83	-0.016	0.18	P<0.01
Cairo Airport, Cairo, Egypt	-066.78	+0.044	0.56	P<0.01
Dakar (Yoff), Dakar, Senegal	-038.89	+0.032	0.43	P<0.01
Dar es Salaam airport, Tanzania	-007.42	+0.017	0.32	P<0.01
Ghardaia, Algeria	-084.83	+0.054	0.61	P<0.01
IITA, Ibadan, Nigeria	+004.59	+0.011	0.11	P<0.05
Khartoum, Sudan	-033.95	+0.032	0.36	P<0.01
Nairobi (Jomo Kenyatta), Kenya	-013.63	+0.016	0.23	P<0.01
Nouakchott, Mauretania	-000.81	+0.013	0.06	ns
Port Elizabeth, South Africa	+019.89	-0.001	0.00	ns
Potchefstroom, NW Uni. S. Africa	-003.21	+0.010	0.03	ns
Tunis, Carthage, Tunisia	-117.90	+0.069	0.80	P<0.01
Yangambi (INERA), DR Congo[1]	-11.946	+0.0186	0.32	P<0.01

[1]To 1975-2010 only.
ns = no significant difference.

Table 3. Long term trend analysis in annual rainfall totals for selected African meteorological stations (years variable between stations).

Meteorological station location	Intercept	Slope	R^2	Significance
Bamako (Old airport + Sénou), Mali (1919-2014)	+6829.06	-2.98	0.16	P<0.01
Bamako (Old Airport), Mali (1919-1974)	-0959.77	+1.03	0.00	ns
Bamako Sénou, Mali (1975-2014)	+4380.14	-1.77	0.00	ns
Ibadan (Moor Plantation + IITA), Nigeria (1901-2014	-1843.79	+1.58	0.03	ns
Moor Plantation, Ibadan, Nigeria (1901-1998)	-0359.47	+0.820	0.00	ns
IITA, Ibadan, Nigeria (1975-2014)	-8140.02	+4.748	0.02	ns
Port Elizabeth, South Africa (1867-2014)[1]	+0569.63	+0.009	0.00	ns
Port Elizabeth, South Africa (1975-2014)[1]	+9926.26	-4.69	0.11	ns
Tunis Carthage, Tunisia (1895-2014)[2]	-1057.47	+0.768	0.05	ns
Tunis Carthage, Tunisia (1975-2014)[2]	-0135.65	+0.300	0.00	ns
Yangambi (INERA), DR Congo (1912-2010)[3]	-505.702	+1.147	0.01	ns

[1]2011 missing value; [2]2000 and 2001 missing values; [3]individual missing months replaced by long-term mean of the respective month.
ns = no significant difference at P=0.01.

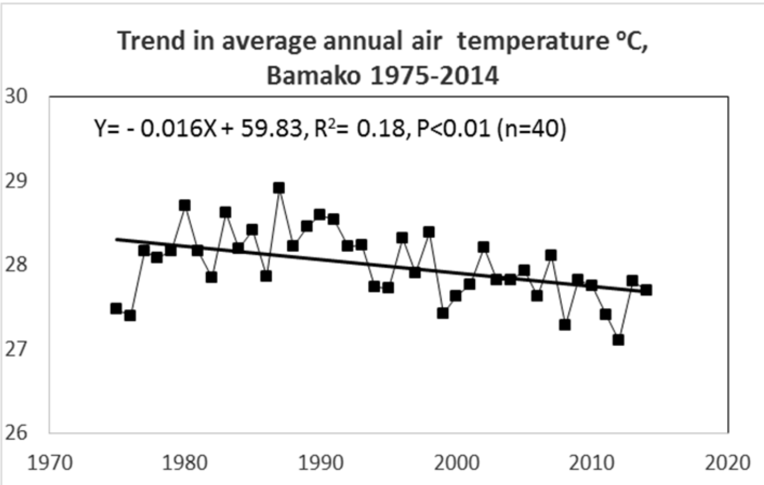


Figure 2. The trend in annual average air temperature (°C) at Bamako (Sénou) 1975-2014.

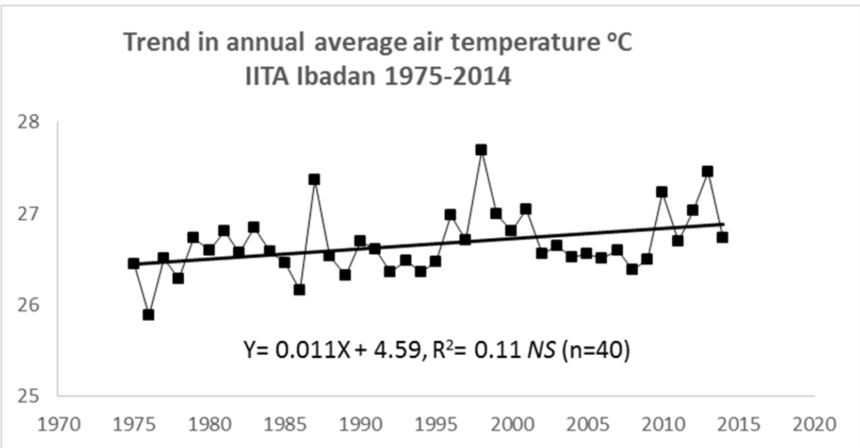


Figure 3. The trend in annual average air temperature (°C) at Ibadan (IITA) 1975-2014.

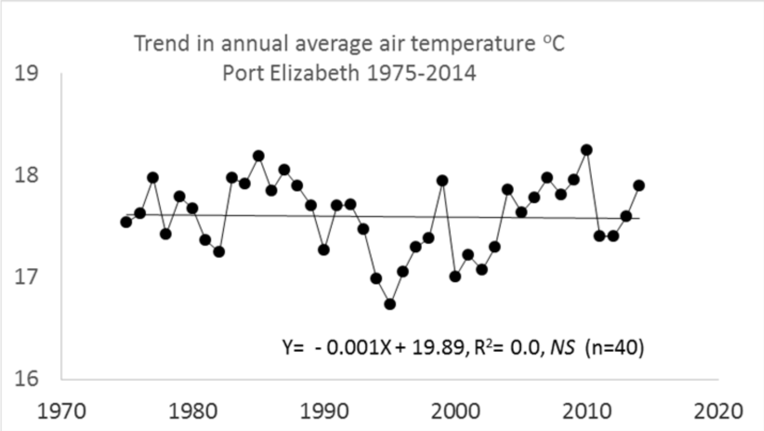


Figure 4. The trend in annual average air temperature (°C) at Port Elizabeth 1975-2014. *NS* = no significant difference at P=0.01.

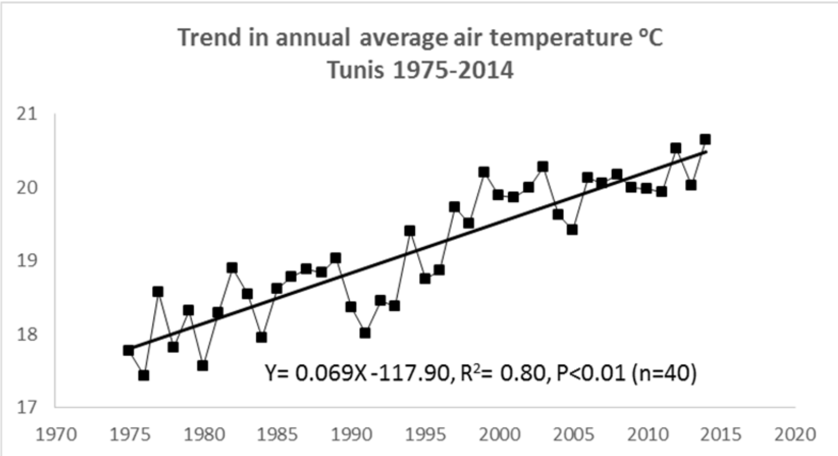


Figure 5. The trend in annual average air temperature (°C) at Tunis Carthage 1975-2014.

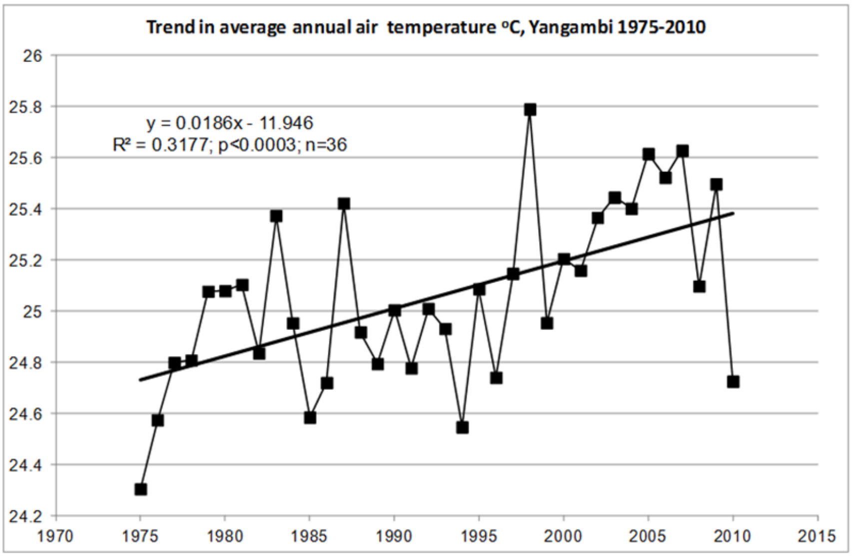
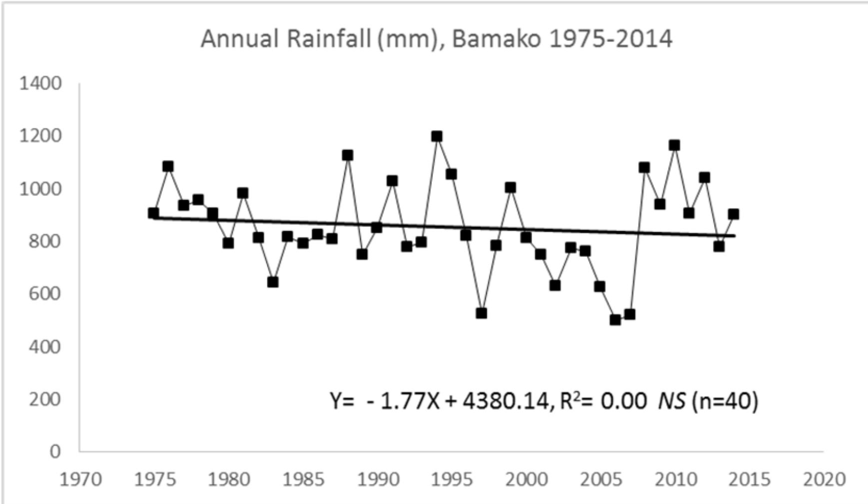
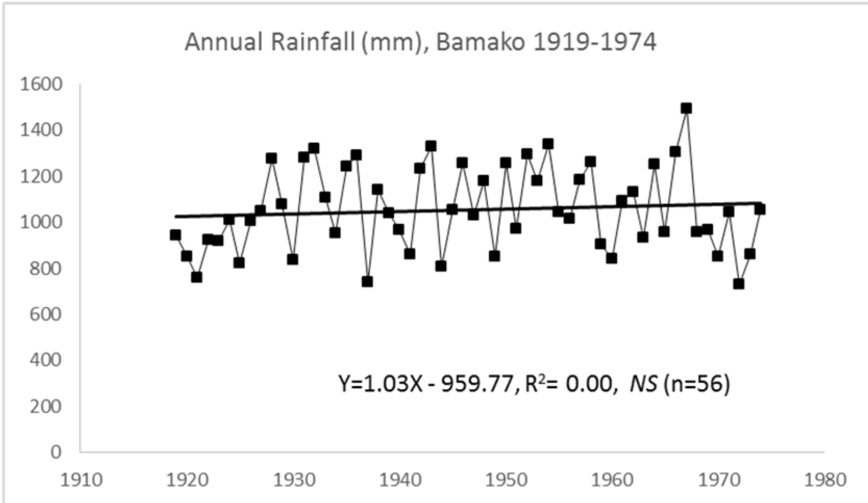


Figure 6. The trend in annual average air temperature (°C) at Yangambi 1975-2010.



A



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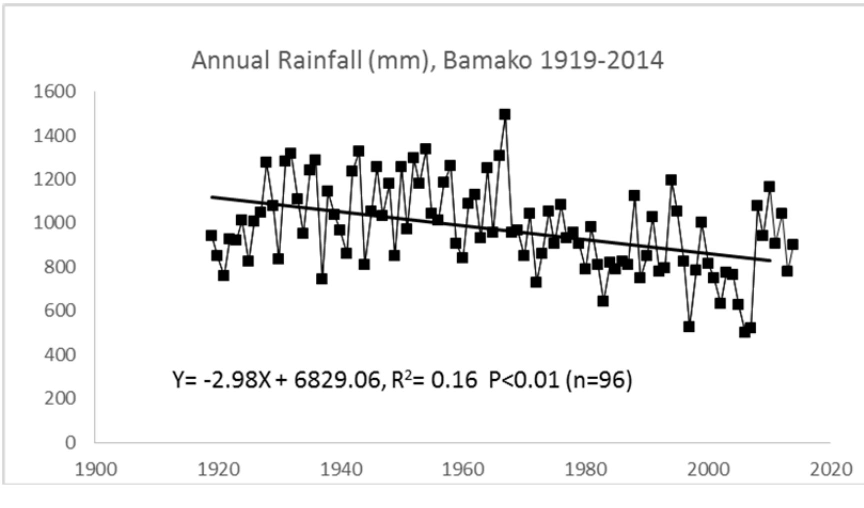


C

Figure 7. A) Annual rainfall totals (mm) 1975-2014 at Bamako (Sénou); B) Annual rainfall totals (mm) 1919-1974 at Bamako (Old airport); C) Annual rainfall totals (mm) 1919-2014 at Bamako (Old airport + Sénou).

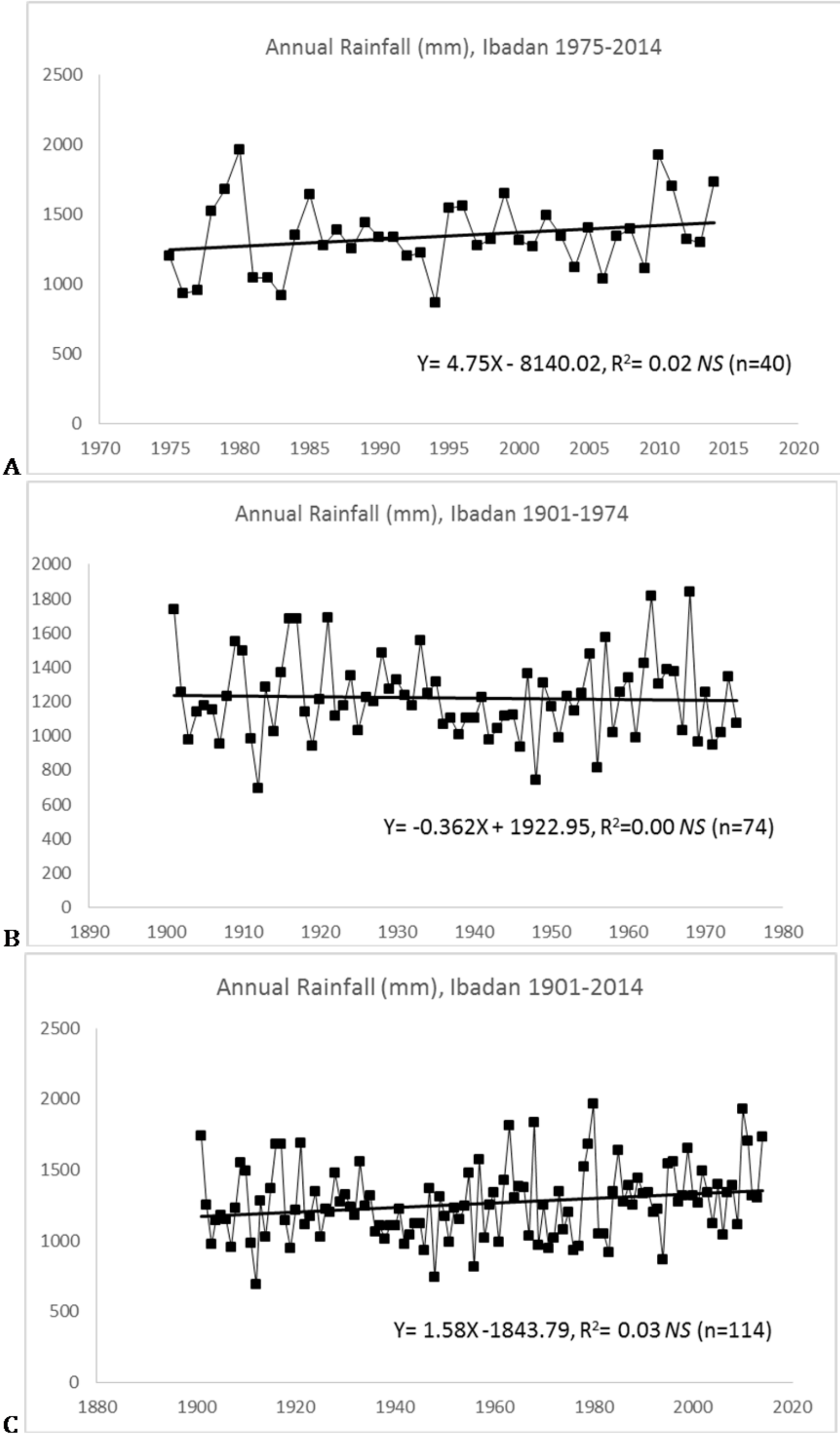
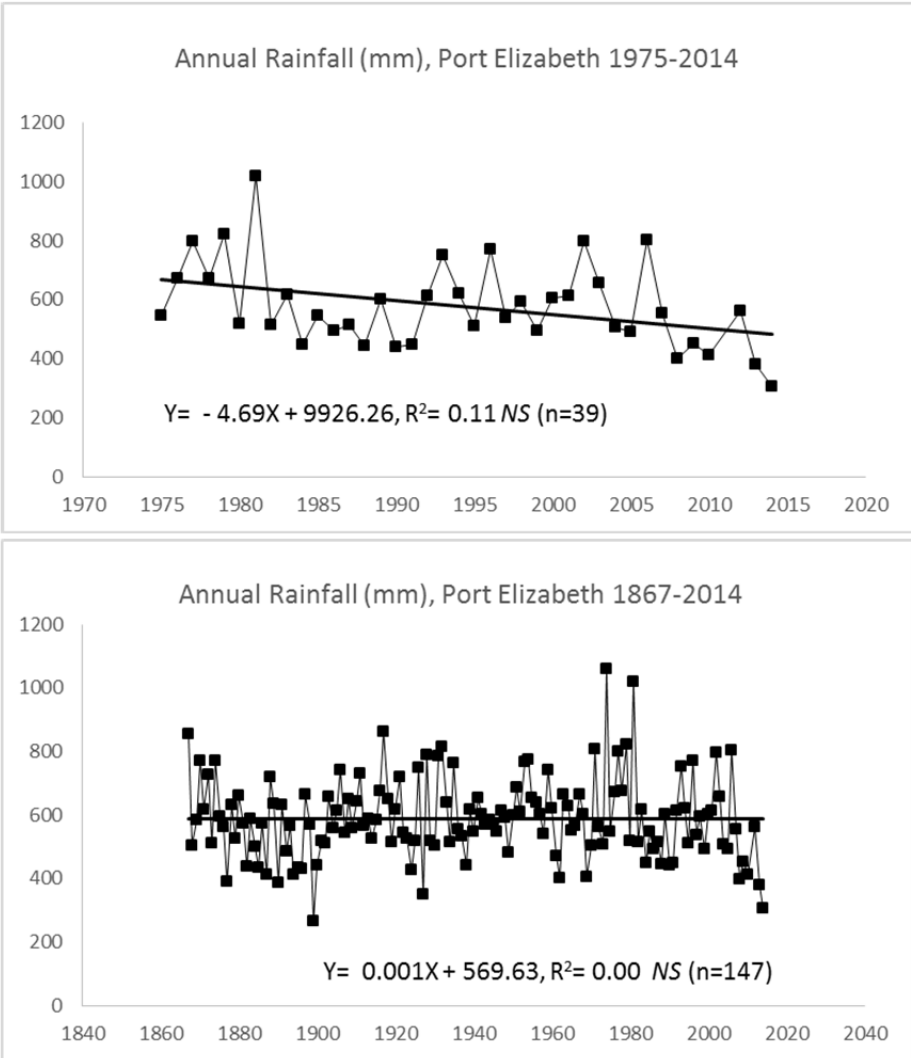


Figure 8. A) Annual rainfall totals (mm) 1975-2014 at Ibadan (IITA); B) Annual rainfall totals (mm) 1901-1974 at Ibadan (Moor Plantation); C) Annual rainfall totals (mm) 1901-2014 at Ibadan (Moor Plantation + IITA).



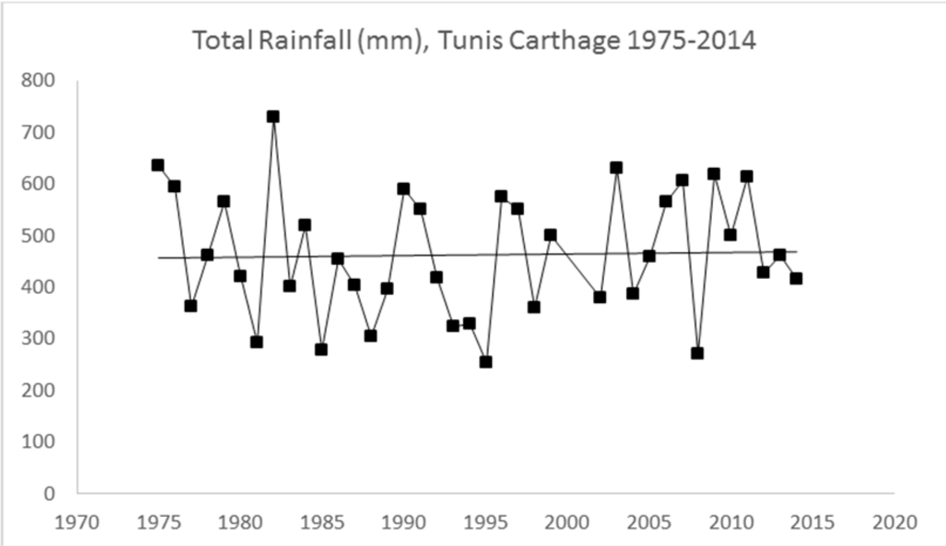
A

B

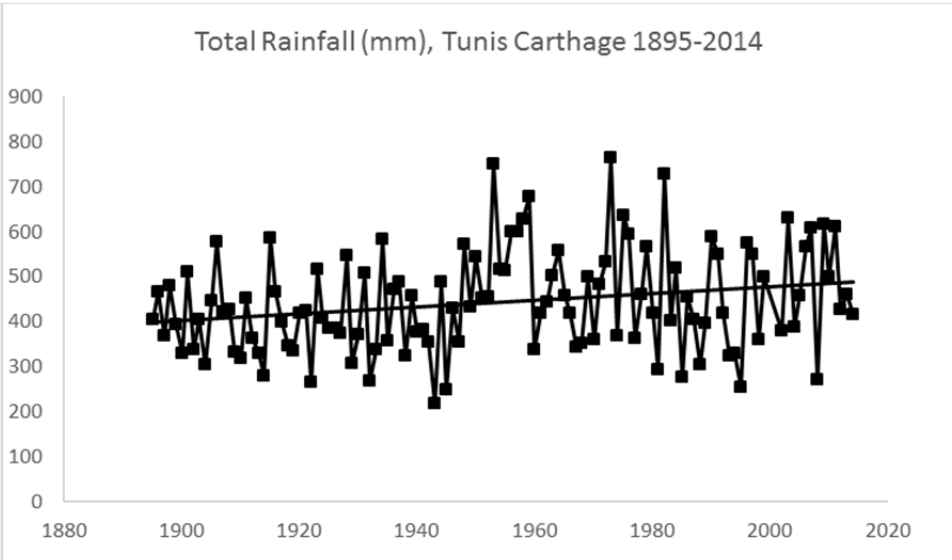
Figure 9. A) Annual rainfall totals (mm) 1975-2014 at Port Elizabeth; B) Annual rainfall totals (mm) 1867-2014 at Port Elizabeth.

For rainfall data, the literature suggested that trends at all levels from continental, regional, national and individual sites are very hard to determine with any real confidence (Thomas et al., 2007; Sissoko et al., 2011). As a result, only individual locations with long records of high quality (longer than 90 years) were selected for illustrative purposes of the variability in this critical parameter. These data sets were made available from the directly collected and locally acquired records of international agricultural research institutes including IITA (the International Institute of Tropical Agriculture), ICRISAT (the International Crops Research Institute for the Semi-Arid Tropics), ICARDA (the International Center for Agricultural Research in the Dry Areas), INERA (Institute National pour les Etudes et Recherche Agricole) and from the website http://geekwright.com/modules/gwreports/index.php. For two of these sites (Bamako and Ibadan) it was necessary to combine the data from two closely associated sites to create a sufficiently long data run to realistically examine the trends in rainfall. Thus, at Bamako, data from the sites of the old (1919-1974) and new airports (1975-2014) were amalgamated. Similarly, at Ibadan the records from Moor Plantation (1901-1974) were added to those of the headquarters of IITA (1975-2014). Linear regression analysis was carried out on both the amalgamated and non-amalgamated data sets for these locations (Table 3) to demonstrate the potential legitimacy of the amalgamations. The quality of the other data sets at most of the other locations shown in

Table 1 were generally too poor for inclusion in the analysis, thus reducing the number of active sites used for rainfall trend analysis.



A $Y = -135.65 + 0.30X$, $R^2 = 0.00$, *NS* (n=38)



B $Y = -1057.47 + 0.768X$, $R^2 = 0.05$, *NS* (n=118)

Figure 10. A) Annual rainfall totals (mm) 1975-2014 at Tunis Carthage (missing 2000 and 2001); B) Annual rainfall totals (mm) 1895-2014 at Tunis Carthage (missing 2000 and 2001).

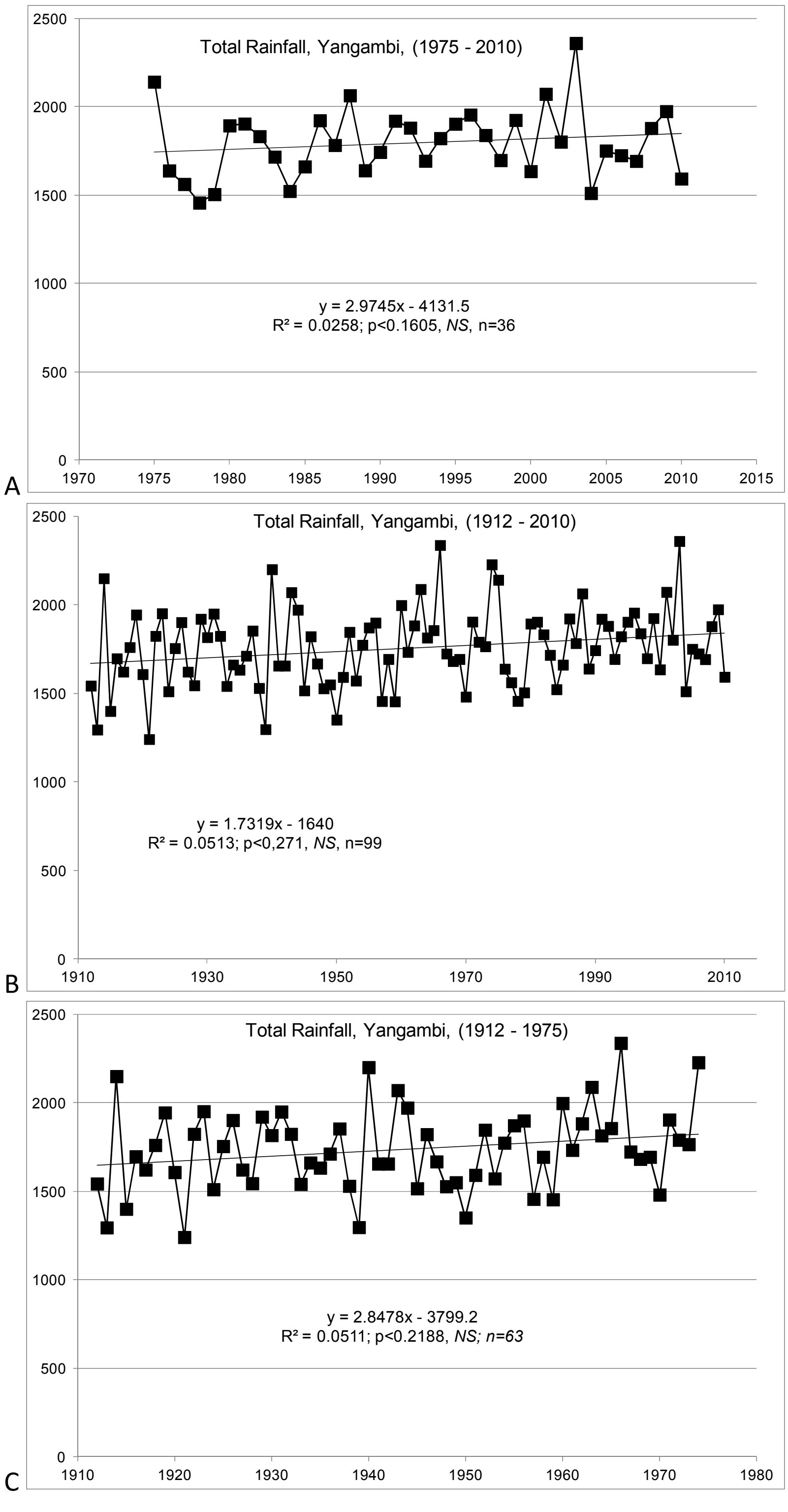


Figure 11. A) Annual rainfall totals (mm) 1975-2010 at Yangambi, province oriental, DR Congo; B) Annual rainfall totals (mm) 1912-2010 at Yangambi, province oriental, DR Congo; C) Annual rainfall totals (mm) 1912-1974 at Yangambi, province oriental, DR Congo.

RESULTS

The variability and trends in average annual air temperature 1975-2014 are shown in

Table 2 for 14 sites. A very large variability in trends and R^2 values was observed (Figures 2-6). Sites such as Tunis and Ghardia in North Africa had data trends indicating extremely rapid increases in temperature. Sites including Cairo, Khartoum, Dakar and Antananarivo showed positive but lesser increases in temperature trends. The data for Nairobi, Dar es Salaam, Ibadan (IITA) and Yangambi indicated small positive trends. Results for Nouakchott, Potchefstroom and Port Elizabeth showed no significant trends and Bamako had a small significant negative trend. R^2 values ranged from a very close linear fit (0.8) at Tunis to a very poor fit (0.0) at Port Elizabeth but there was no suggestion from visual inspection of these data that other non-linear models would have been more appropriate (Figures 5 and 4, respectively).

Using the trends presented in Table 2 (1975-2014) projections were made for periods of 25, 50, 75 and 100 years into the future assuming that the trends remained constant for the projected time period (Table 4). The figures are presented as a clearer way to compare the results at different locations in the terms usually presented by major global modeling efforts (IPCC, 2007). A very substantial variation was evident, ranging from 6.9°C per 100 years (2015-2115) at Tunis, to 4.5°C in Cairo, and 1.1°C at Ibadan (IITA). For Port Elizabeth the trend was not significant and thus the projection is for no change; at Bamako the trend was negative, and the projected change in 100 years was -1.6°C.

Table 4. Increases in average annual air temperature (°C) projected by 25, 50, 75 and 100 years up to 2115 assuming that the trends presented in Table 2 remain constant.

Meteorological station location	2015-2040	2015-2065	2015-2090	2015-2115
Antananarivo, Madagascar	+0.66	+1.33	+1.99	+2.65
Bamako (Sénou), Mali	-0.40	-0.80	-1.20	-1.60
Cairo Airport, Cairo, Egypt	+1.11	+2.23	+3.34	+4.45
Dakar (Yoff), Dakar, Senegal	+0.79	+1.59	+2.38	+3.17
Dar es Salaam airport, Tanzania	+0.42	+0.84	+1.26	+1.68
Ghardaia, Algeria	+1.34	+2.68	+4.02	+5.36
IITA, Ibadan, Nigeria	+0.28	+0.55	+0.83	+1.11
Khartoum, Sudan	+0.80	+1.61	+2.41	+3.21
Nairobi (Jomo Kenyatta), Kenya	+0.41	+0.83	+1.24	+1.65
Nouakchott, Mauretania	0	0	0	0
Port Elizabeth, South Africa	0	0	0	0
Potchefstroom, NW Uni. S. Africa	0	0	0	0
Tunis, Carthage, Tunisia	+1.72	+3.44	+5.15	+6.87
Yangambi (INERA), DR Congo	+0.46	+0.93	+1.40	+1.86

Rainfall trends are shown in Table 3 and Figures 7-11. Records created by local station combinations were deemed to be legitimate as there were few differences observable between the trends shown at the various locally adjacent sites (Figures 6a-c and 7a-c). All sites examined in the standard recording period for this paper 1975-2014 showed no significant trends, with relatively high annual variability and thus very low R^2 values. When extended periods greater than 90 years were examined, the same results were observed (Figures 7c, 8c, 9b, 10b, 11b) with the minor exception of Bamako, which showed a significant but very slightly negative trend. This might have been due to the splitting of the two airport sites, as neither site when taken alone showed a significant trend (Figures 7a-c). The R^2 in this instance (Figure 7c) was also quite low (0.16). As R^2 values were generally low, the likelihood of spurious significant results is recognized as possible. Thus the rigorous statistical confidence requirement of $P<0.01$ was used to confirm the significance of the trends.

DISCUSSION

Future climatic uncertainty and its influence on biotic stressors will be profound

(Boland et al., 2004; Garrett et al., 2006). Such factors may compromise the sustainability of African vegetable production. This influence on productivity will come from considerable and unpredictable, usually positive, variation in long term temperature trends in different locations. There is continuing large inter-year variability in rainfall totals that show no significant long-term trends in the modern era (1975-2014) or even when viewed over much longer spans of over 100 years.

Increased air temperatures and uncertain rainfall will cause additional difficulties for small-scale vegetable producers due to likely increases in weed growth, in pest numbers and their epidemiology, changes in disease spectra, in greater pathogenicity, and in increased aggressiveness and greater viral virulence and mutation. These complex interactions between weeds, insects, pathogens and climate are currently poorly understood (Scherm, 2004; Gregory et al., 2009). Major insect pests, such as pod borers that infest legume and fruit vegetables, will be able to complete additional generations in a season. This will also be true for major viral vectors such as whiteflies, aphids and thrips (Hanson et al., 2011). The impact will occur not only on global vegetables such as tomato, eggplant, cabbages and green beans but also on a wide range of African indigenous/traditional vegetables (Keatinge et al., 2016). Furthermore, the impact will include damage to African staple crops of which part can be used as secondary vegetables, such as cowpea leaves and green pods (Yang and Keding, 2009), cassava leaves (Ufuan Achidi et al., 2005), pigeon pea as green peas and even green maize for roasting (McCann, 2001).

Temperature and rainfall trends

The considerable variability in temperature trends shown between locations in Africa (1975-2014) was not unexpected as such variability has been shown to have existed globally for the period 1975-2011 (Keatinge et al., 2014). In addition, a historical study involving locations distributed globally with at least 100 years of data (Keatinge et al., 2015a) demonstrated similar results. Furthermore, in a study of locations in a much more concentrated geographic area – Mesoamerica – such differences in temperature at nearly adjacent locations have been reported (Keatinge et al., 2015b). The causes of such variability are not well understood, but factors influencing rural albedo and heat diffusivity such as increased urbanization or the growing extent of high-albedo structures at airports (Keatinge et al., 2013), extreme changes in land use such as deforestation in Central and Northwest Africa (Paeth et al., 2009), the introduction of major irrigation schemes (Baigorria et al., 2007), localized high concentrations of air pollution (Keatinge et al., 2015a), and elevation and aspect within the context of mountain chains (Keatinge et al., 2015b) have all been considered, without any fully satisfactory explanation emerging from the different analyses.

The results in this paper do not contradict studies by other authors predicting temperature increases in the future, such as at Embu in Kenya (Rao et al., 2015), or temperature variability in years associated with the El Niño-Southern oscillation (Ogutu et al., 2008). However, the existing literature does not highlight the inter-location variability, which is clearly evident. When large-scale modeling is applied to larger numbers of data sets in Africa, and globally, such local variability is averaged out and this then results in the 2+°C increases per 50-100 years predicted by the working groups of the IPCC (IPCC, 2007, 2013). Even in this very small sample of 13 locations the average increase predicted per 100 years is in the same 2-3°C range. However, whether such averages are now germane to the future plans of vegetable breeders and crop protection specialists remains a moot point. For example, should vegetable breeders in Potchefstroom ignore the need for specific extra heat tolerance in their cultivars over the next 25 years, as no increase in annual average air temperature is predicted? Should those in Tunis be ultra-aware of this factor as increases in temperature are predicted to be large (Table 4)? The results given in this paper suggest that just such policies would be logical, although if overall warming drivers are to operate on a consistent global scale then perhaps less variability between sites might be the future outcome. However, there is no evidence to suggest that to be the case in Africa.

The rainfall results presented in this paper offer a much clearer picture. The conclusion that no significant differences were observed in seasonal long-term trends at

Moorings Station in Zambia with 89 years of data (Stern and Cooper, 2011) and likewise for stations around Nakuru in the Masai Mara/Serengeti game reserves region of Kenya/Tanzania but for a quite short run of data (Ogutu et al., 2008, 2012) are confirmed continentally for the few stations with good long-term records of consistent quality. Given the clear annual variability in rainfall totals at all the locations examined, it would probably require a much longer data set (>200 years) to ascertain historical trends and such data sets are not available. Therefore, for purposes of this paper we assume there is no substantive trend in total annual rainfall discernible in any location in Africa, but farmers need to be very concerned about rainfall variability on a year-to-year basis. This assumption would be supported by the analysis of long term Sahelian data (Sissoko et al., 2011). This, of course, does not rule out the likelihood of an increase in extreme drought and flooding weather events in a warming world predicted by Shongwe et al. (2009, 2011) and Rao et al. (2015) for Southern and Eastern Africa.

Implications for biotic stressors and the sustainability of African vegetable production

Although annual average air temperature is a very blunt instrument for the prediction of plant growth/pest interactions (Scherm and van Bruggen, 1994), it is still one of the most conservative/reliable meteorological variables (which is freely available) for reflecting change within systems. Temperature is recognized as a critical climate variable determining insect pest-crop interactions (Boland et al., 2004). Given the variation between temperature trends shown at different locations (Table 4) and that plant breeding programs, where possible, will be aiming at more than small niche environments, it is necessary to target higher levels of resistance to expected plant stressors than was previously considered acceptable in a variety suitable for release (Afari-Sefa et al., 2012). For example, 'Tengeru 97' is an open pollinated fresh market tomato (*Solanum lycopersicum*) line bred by AVRDC - The World Vegetable Center and released as a variety by the Tanzanian government 20 years ago (Ojiewo et al., 2010). It is now commonly grown throughout East Africa from Ethiopia to Zimbabwe and sold by a range of private sector seed companies. However, its eventual successors with the potential to follow in the 'Tengeru' series must incorporate new material from the AVRDC breeding pipeline, which is designed to have further improved, pyramided resistance to pathogens. These include early and late blight (*Alternaria solani* and *Phytophthora infestans*, respectively), *Tomato yellow leaf curl virus* (TYLCV; *Begomovirus*), anthracnose fungal diseases (*Colletotrichum* spp.) and bacterial wilt (*Ralstonia solanacearum*). Farmers will also need to adopt better, safe agricultural practices, which, in the case of tomato, will include the use of grafted seedlings, integrated pest management practices, and if possible, sufficient protection measures such as net houses to prevent virus vectors coming into contact with the plants. Increasing annual temperatures have the potential to magnify the risk of yield reduction (Sheu et al., 2009; Tsai et al., 2011), particularly when it is appreciated that whitefly (*Bemisia tabaci*) – the insect vector for TYLCV – can produce an extra three generations in seasons when average air temperatures increase by 1°C (Hanson et al., 2011). Likewise, such increased temperatures can extend or modify the geographic and altitudinal range of pests (Jaramillo et al., 2011), or advance the timing of aphid migrations into crops (Scherm, 2004).

Other insect species severely damaging to important vegetables in Africa, and which may become more numerous and more destructive with increased temperatures, include spider mites (*Tetranychidae* spp.; Rosenzweig et al., 2001), pod borers (*Maruca vitrata*, *Heliocoverpa armigera*; Sharma et al., 2010), leaf miners (*Liriomyza* spp. and *Tuta absoluta*; Allache et al., 2015), diamondback moth (*Plutella xylostella*; Grzywacz et al., 2010) and many others. All these species are capable of very substantive damage to field and greenhouse vegetable yields either directly or indirectly through virus transmission from insects such as thrips (*Thysanoptera* spp.), which transmits *Tomato spotted wilt virus* in a range of vegetables (Moritz et al., 2004).

Concern over stressors encouraged by higher air temperatures should include major weed species. These are both native and invasive in Africa such as *Imperata cylindrica*

(MacDonald, 2004); *Striga* and *Orobanche* spp. (Parker, 2009), and *Chromolaena odorata* (Kriticos et al., 2005; Norgrove and Hauser, 2015). These major weed species are already extremely difficult to control under small-scale farmer conditions in Africa and higher temperatures and CO_2 levels in a warming continent could easily exacerbate these chronic problems.

We believe our hypothesis that climate change threatens the development and sustainability of improved vegetable horticultural systems in Africa is supported by the evidence presented in this paper. Plant breeders, entomologists and plant pathologists will now need to give careful attention to whether local climate uncertainty and weather events are an increasingly significant factor across the broad locations at which they are aiming their improved vegetable lines for release. Consideration needs to be given to breeding for drought, flooding and salinity tolerance. Vigilance will be needed to monitor for the emergence of adapted pests and mutated pathogens, with new viruses being a particular case in point as vegetables are particularly sensitive to these stressors. Thus, it is vital for all national governments in Africa to take the potential risk to their horticultural industries as a serious matter of national priority. They must be more generous and consistent in their support of horticultural research and capacity building in horticulture. No action in this regard can only lead to increased poverty, malnutrition, and failure to attain the targets outlined in UN Sustainable Development Goal 2 (Improving Agricultural Systems and Reducing Rural Poverty).

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