Temperature Variability over Africa

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(Manuscript received 26 March 2010, in final form 2 March 2011)

ABSTRACT

The variation of near-surface air temperature anomalies in Africa between 1979 and 2010 is investigated primarily using Microwave Sounding Unit (MSU) total lower-tropospheric temperature data from the Remote Sensing Systems (RSS) and the University of Alabama in Huntsville (UAH) datasets. Significant increasing temperature trends were found in each of the following regions examined: all of Africa, Northern Hemisphere Africa, Southern Hemisphere Africa, tropical Africa, and subtropical Africa. Considering the months June–August, regions in both North and South Africa saw significantly warmer temperatures in the most recent period 1995–2010 than in the period 1979–94. However, for the months December–February, the significant warming was concentrated in the north of Africa. When the two most recent decades are compared with the period 1979–90, warming is observed over these same regions and is concentrated in the most recent decade, from 2001 to 2010. The results presented here indicate that the climate change over Africa is likely not predominantly a result of variations in the El Niño–Southern Oscillation (a teleconnection that has been previously shown to affect climate in some parts of Africa). Instead the climate changes likely occur owing to other natural variability of the climate and/or may be a result of human activity. However, even without ascertaining the specific causes, the most important finding in this work is to demonstrate that a significant rise in African temperatures occurred between 1979 and 2010.

1. Introduction

The Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (Pachauri and Reisinger 2007) considered that progress in understanding of how climate is changing in space and in time has been gained through improvements and extensions of numerous datasets and data analyses, broader geographical coverage, better understanding of uncertainties, and a wider variety of measurements. However, data coverage remains limited in some regions. The AR4 report shows, through the use of station data, that the warming of the climate system is unequivocal, with 11 of the last 12 years (1995–2006) ranking among the 11 warmest years in the instrumental record of global surface temperatures since 1850 (Trenberth et al. 2007). The report also notes that the total temperature increase from the period 1850–99 to the period 2001–05 is 0.76°C (Trenberth et al. 2007). The main conclusion of AR4 is that most of the observed increase in globally averaged temperatures since the midtwentieth century is very likely due to the observed increase in anthropogenic greenhouse gas emissions (Hegerl et al. 2007). Brown et al. (2008) also indicate that extreme daily maximum and minimum temperatures have warmed for most regions of the world since 1950 and that the total area exhibiting positive trends is significantly greater than that which can be attributed to natural variability.

Difficulties remain in reliably simulating and attributing observed temperature changes at smaller scales. On these scales natural climate variability is relatively larger, making it harder to distinguish changes expected due to external forcings. Uncertainties in local forcings and feedbacks also make it difficult to estimate the contribution of greenhouse gas increases to observed small-scale temperature changes (Hegerl et al. 2007).

Africa is unique in that it is the only continent that, almost symmetrically, straddles the equator, and hence experiences such a varied climate with both Northern and Southern Hemispheric climatic influences (Odada and Olago 2005). Africa is about 8000 km in length from northern Tunisia to the southern tip of the country of South Africa. In addition, Africa encompasses more
than 20% of the world’s total land area and has a population of greater than 1 billion. Due in part to its location, vast size, and varying topography (Fig. 1), Africa has eight climate zones according to the Köppen climate classification system. The northern half of Africa is primarily desert or arid, while the central and southern areas contain savanna and rain forest regions. Some of the extreme temperature variations that have been experienced in Africa include a high of 57.8°C (136°F) at El Aziza, Libya, on 13 September 1922 and a low of −23.9°C (−11°F) at Ifrane, Morocco, on 11 February 1935.

There have been few studies about climate change focusing on temperature that consider the whole of Africa. Part of the reason for this may be that, as Frich et al. (2002) note, there are large regions in the world where no digital data are readily available for analysis. Caesar and Alexander (2006) also emphasize this point regarding the sparse data coverage of freely available station data for Africa. Desanker and Magadza (2001) discuss some of the problems in trying to establish a weather station network that includes the technological and scientific underdevelopment of many African countries exacerbated by civil war, extensive poverty, and political instability. In addition, Lamptey (2009) notes that Africa has been underrepresented in international efforts to improve research capabilities, observing facilities, operational forecasting, and meteorological education. This is in spite of the fact that sub-Saharan countries are especially vulnerable to weather and climate variation, and that Sahelian weather directly affects the United States in the form of hurricanes and dust clouds.

Nicholson (2001) notes that weather stations first emerged in the south of Africa and then along the coasts. These locations would therefore have the longest records. Figure 2 taken from Eischeid et al. (1995) illustrates the lack of temperature measurements in Africa (and other locations such as South America) in comparison to North America and Europe. This is reinforced by Washington et al. (2004) who reported that the network of 1152 World Meteorological Organization (WMO) World Weather Watch (WWW) stations in Africa has an average density of weather stations of just one per 26,000 km² (this is 8 times lower than the minimum recommended level given by the WMO). The location of these weather stations is also unevenly distributed.

Of the operational weather stations, some do not have long climate records and some are not publically available. Easterling et al. (2003) discuss a workshop that was held in 2001 bringing together scientists from 23 African countries to address some of the issues of data availability and data analysis in Africa. They note that, “further effort is required to encourage continued collaboration, data exchange, and analysis . . .” (Easterling et al. 2003, p. 1407). Despite this in 2009, the author of this paper had great difficulty obtaining publically available weather station data at no cost.

Of the few studies that are available on climate change in Africa, many focus on rainfall. Hulme et al. (2001) note that good databases exist with regard to rainfall (although they do note some areas such as the Congo basin have extremely patchy and limited coverage). Nicholson (2000, 2001) has well documented the long-term reduction in rainfall in the semiarid regions of West Africa. New et al. (2006) identified significant trends in some southern Africa precipitation indices. In particular, a spatially coherent increase in consecutive dry days was found over much of southern Africa in the last decades of the twentieth century. Kruger (2006) analyzes rainfall data in South Africa because of the longer dataset there. Landman and Mason (1999) also examined rainfall in South Africa and Namibia as they looked at the association of sea surface temperatures (SSTs) of the Indian Ocean and their effect on the rainfall. Reason and Mulenga (1999) analyzed rainfall in the southwestern Indian Ocean. Rowell et al. (1995) also examined rainfall trends but focused on northern Africa.
Those studies that focus on temperature changes in Africa often concentrate on individual countries or a small area, however, climate varies considerably across the continent. Muhlenbruch-Tegen (1992) selected 18 weather stations in South Africa to analyze during the time period of 1940–89. His analysis showed that the coastal stations had significant increasing temperature trends, which he attributed to increases in SSTs, but the inland stations had no significant temperature changes.

Hulme et al. (2001) noted that throughout the twentieth century, Africa has warmed at a rate of 0.5°C century\(^{-1}\) and from 1987 to 1998, the six warmest years in Africa’s temperature record occurred with increasing intensity making 1998 the warmest. From 1901 to 1995, they report that the Mediterranean coastal countries in northwestern Africa and inland southern Africa warmed at 2°C century\(^{-1}\). However, over the same time period, a few regions such as Nigeria–Cameroon and Senegal–Mauritania actually cooled. Hulme et al. (2001) note that there is slightly larger warming in the June–August and September–November seasons than in December–February and March–May. The Sahel, the Mediterranean coast, and significant portions of Botswana, Zimbabwe, and the Transvaal have dried by about 25% century\(^{-1}\). Meanwhile, eastern and equatorial Africa have seen wetting at around 10% century\(^{-1}\).

Brown et al. (2008) indicate that extreme daily maximum and minimum temperatures have warmed for most regions of the world since 1950. However, for South Africa, Muhlenbruch-Tegen (1992) found that several stations had an increasing trend in their minimum temperature, while in other cases trends in minimum and maximum temperatures counteracted each other. His conclusion indicates that the data are inconclusive as to whether South Africa was warming or cooling for the duration of his study. In support of this, Kruger and Shongwe (2004) found that for annual mean minimum temperature, 21 stations showed positive trends, with 86% of them being statistically significant. Four stations had negative trends, but none of them were statistically significant. They also found that, “days and nights with relatively high temperatures have increased, while days and nights with relatively low temperatures have decreased” (Kruger and Shongwe 2004, p. 1929). Christy et al. (2009) analyzed temperature trends in the eastern part of Africa. They used data that included 60 weather stations in Kenya and 58 in Tanzania and concluded that there appears to be little change in East Africa for the maximum temperatures. Defining eastern Africa as 19 countries located on the eastern part of the African continent and extending from the sub-Saharan Sudan and Ethiopia to the Horn of Africa, East Africa, and central and southern Africa, King’uyu et al. (2000) studied data from 71 weather stations from 1939 to 1992. More specifically, the 19 countries are located inside the latitudes of 25°–30°S and longitudes of 20°–60°E. King’uyu et al. (2000) concluded that nighttime temperatures are increasing, but that this trend is not spatially uniform over the given study area. This again has been confirmed recently by Aguilar et al. (2009) who conducted a study on the regions of west central Africa, Guinea Conakry, and Zimbabwe. They deduced that the areas are warming, with hot extremes increasing, while there are fewer cold extremes. This is consistent with literature focusing on other areas of the world. For instance, Vincent et al. (2005) examined trends over the period 1960–2000 in the
indices of daily temperature extremes for South America and found that there were no consistent changes in the indices based on daily maximum temperature. However, significant trends were observed when considering minimum temperature. They found significant increasing trends in the percentage of warm nights and decreasing trends in the percentage of cold nights at many stations. However, other parts of the world have shown more record daily high maximum temperatures than record low minimum temperatures and this ratio has been increasing in recent decades (United States, Meehl et al. 2009; Australia, Trewin and Vermont 2010).

Another paper by Hughes and Balling (1996) referencing Jones’ (1994) dataset noted that South Africa saw a cooling in mean temperature from 1885 to 1915, a warming from 1915 to 1945, a slight cooling from 1945 to 1970, and rapid warming from 1970 onward. Much of this warming has occurred in the last 30 years, but they conclude that urban growth may have compromised the data records since their examination of 19 nonurban weather stations in South Africa indicated no significant warming during this recent period. Adding to this body of research, Kruger and Shongwe (2004) completed a study of temperature trends in Africa using 26 weather stations between 1960 and 2003. They did not go back further in time because the data before 1960 is not sufficiently quality controlled. These stations had not changed location nor had any changes in their surrounding area. Of those 26 stations, only 3 of them did not show a positive trend in annual mean maximum temperatures and the trend in 57% of these stations were statistically significant. They noted, contrary to Muhlenbruch-Tegen (1992), that stations which were located inland had higher trends than the ones located near the coast.

Hulme et al. (2001) note that ENSO is a potentially important driver on future African climate. Kruger and Shongwe (2004) examined whether ENSO had any effects on the trends in temperature, specifically for the late austral summer period of January–March. They concluded that increases in late summer temperatures are not forced by the occurrence of El Niño and La Niña events. However, Klopper et al. (1998) examined data from 77 weather stations located in South Africa. They used a method called singular value decomposition to see if they could find any relevant correlation between ocean temperatures and South African seasonal temperature and conclude that ENSO-related features resemble an important influence on the seasonal temperature of South Africa with the warm ocean surface temperatures in the equatorial Pacific corresponding to warm temperatures in South Africa (with the opposite occurring for cool ocean surface temperatures).

The IPCC regional climate projections for Africa suggest that for West Africa, East Africa, South Africa, and the Sahara, regardless of the season, the predicted average increase in temperature for 1900–2100 ranges from 3°C to 4°C (Christensen et al. 2007). This amount is about 1.5 times the projected global mean temperature increase for 1900–2100 when compared with one of the more conservative cases of the Special Report on Emissions Scenarios (SRES). The 3°C rise pertains to coastal and equatorial areas of Africa, while the larger 4°C change is projected to occur in the western Sahara region. In addition, Christensen et al. (2007) note that it is possible, further along in this century, that there will be a significant increase in the effect that land use changes will have on climate. Paeth et al. (2009) set out to produce climate simulations that included land use change. By 2050, the strongest warming in their model occurs in sub-Saharan Africa. Paeth et al. (2009) conjecture that a possible reason for this is that the changes in land cover are also heavily responsible for climate trends and hence they note that protecting land cover is just as important as reducing greenhouse gas emissions in order to mitigate future climate change. Carto (2009) points out that due to marine pollen records, we can deduce whether the rain forests were in fact more extensive than they are today and that from the point of rain forest decrease the temperature began to rise as well. This mechanism being that reduced vegetation cover leads to decreasing evapotranspiration, such that more energy is available for near-surface heating. Christy et al. (2009) note that changes in the observation sites in East Africa, replacing vegetation with concrete, likely accounts for some warming. Hulme et al. (2001) note that, much like other climate change studies/projections have shown, the Sahara (interior) and central-southern Africa will experience the greatest warming, while equatorial and coastal regions of Africa will experience the least warming.

Although Hulme et al. (2001) note that no simple correlation exists between temperature and rainfall in the Sahel, East Africa, and southeastern Africa, Hulme (1996) does assert that drying in the Sahel was associated with a moderate warming trend. Glantz (1992) discusses the importance of temperature changes as he notes the indirect role that temperature plays on evaporation rates and hence water availability, particularly in areas where there is a delicate balance between evaporation and precipitation. As increasing evidence grows on temperature controls of important physiological processes in insects, plants, and crops, the topic of climate change in Africa, specifically temperature, becomes imperative.

In this work mean near-surface air temperatures in Africa are investigated for the most part utilizing the mean total lower-tropospheric temperature profiles.
from Remote Sensing Systems (RSS; Mears et al. 2003) and the University of Alabama in Huntsville (UAH; Christy et al. 2000) datasets. Supplementary data for comparative purposes are drawn from the National Centers for Environmental Prediction (NCEP)–National Center for Atmospheric Research (NCAR) reanalysis (NNR; Kalnay et al. 1996) and from the 40-yr European Centre for Medium-Range Weather Forecasts (ECMWF) reanalysis (ERA-40; Uppala et al. 2005). All datasets are analyzed from 1979 to 2010. As Hulme et al. (2001) point out, such a historical perspective is essential if the simulated climates of the next century are to be put into their proper context.

2. Methodology

Mean total lower-tropospheric temperature variability above the earth’s surface over Africa between 1979 and 2010 is investigated. Data (to the nearest grid point) are considered for the following regions: the whole of Africa, Northern Hemisphere (NH) Africa, Southern Hemisphere (SH) Africa, tropical Africa (23.5°N–23.5°S), subtropical Africa (north of 23.5°N and south of 23.5°S), Northern Hemisphere tropical Africa (0°–23.5°N), Southern Hemisphere tropical Africa (0°–23.5°S), Northern Hemisphere subtropical Africa, and Southern Hemisphere subtropical Africa. Because of the difficulties in obtaining accurate meteorological and climatological records in continental Africa highlighted above, which include a lack of funding in the countries, topography, and remoteness of areas, this, in addition to the fact that station data is not freely available, leads to the use primarily of satellite instead of station data. Two satellite datasets are available, from RSS (Mears et al. 2003) and from UAH (Christy et al. 2000), each at 2.5° × 2.5° resolution. Statistical analysis of both datasets is included, while spatial plots draw solely from the RSS dataset.

Other studies such as Collins et al. (2009) for South America have utilized the Climate Research Unit’s (CRU) Global Temperature version 3 (CRUTEM3) dataset, which consists of land air temperature anomalies available on a 5° × 5° gridbox basis (Brohan et al. 2006). However, while the use of this dataset may be appropriate for other areas of the world, it did not have good spatial coverage over Africa, particularly the Sahara. In lieu of data-sparse surface observational datasets, the satellite data are also compared statistically to two reanalysis datasets, the NNR reanalysis (Kalnay et al. 1996) and the ERA-40 reanalysis (Uppala et al. 2005).

Temperatures used in the NNR are at the 2-m level, with T62 Gaussian grid resolution. Temperature is classified as a B category variable in the NNR. This designation indicates that, although there are observational data that directly affect the value of the variable, the model also has a very strong influence on the analysis value (Kalnay et al. 1996). The NNR is available from 1948; however, only data from 1979 is considered in this study since there has been substantial evolution of the observing system since 1948. Kistler et al. (2001) note three major phases: the first from the 1940s to 1957 when the first upper-air observations were established, the second from 1958 to 1978 with the modern rawinsonde network, and the third from 1979 to the present. Trenberth et al. (2001) also give caution to potential artificial jumps and trends in the NNR as a result of changes in the observing systems when using the data back to 1948. This study therefore considers the more reliable post-1979 period, which coincides with the availability of satellite data.

Temperatures used in the ERA-40 are also at the 2-m level, with 2.5° × 2.5° resolution in the ERA-40 until 2002 and 1.5° × 1.5° resolution after 2002 in the ERA-interim dataset. Bengtsson et al. (2004) examined the viability of assessing climate trends through reanalysis data and concluded that while the temperature trends in the ERA-40 were slightly higher than that of the satellite

FIG. 3. Difference of the mean RSS total lower-tropospheric temperatures (K) between the periods 1979–94 and 1995–2010 in (a) DJF and (b) JJA. The shaded areas represent statistical significance at the 5% level.
data they did fall within estimated error limitations. All dataset analyses are considered over the same period, from 1979 to 2010, and temperature anomalies are used to facilitate intercomparison. Washington et al. (2006) comment on the problem of the poor level of peer-reviewed journal publications in Africa, which is among the lowest anywhere in the world and the limited extent of international engagement, which they note severely isolates African climate science. However, the use of freely available global datasets such as the ones used in this study does facilitate an increased understanding of Africa's climate.

Trends are examined by examining the slope of the best-fit linear trend from an ordinary least squares (OLS) regression, and the trend is determined to be significant at the 5% level ($\alpha < 0.05$). It should be noted that the Durbin–Watson statistic was calculated to analyze autocorrelation in the yearly averaged time series. No correction was deemed necessary based on the results of this analysis such that each yearly averaged time series has a Durbin–Watson test statistic around 2, suggesting that the null hypothesis that there is no autocorrelation would not be rejected. The nonparametric Mann–Kendall test (described by Onoz and Bayazit 2003) has been used for temperature trend detection in other studies, for example, Collins et al. (2009) who used it particularly for considering station data in South America. However, for the Africa data used here, OLS regression is the appropriate and more robust methodology because all mean temperatures in Africa are considered with residuals that are normally distributed. In addition, the coefficients of skewness and kurtosis are all less than the absolute value of 1 following the $Z$ distribution for normally distributed data.

### Table 1. Temperature trends (slope and significance obtained from a linear regression). Data obtained from the RSS and UAH satellite datasets.

<table>
<thead>
<tr>
<th>Region of Africa</th>
<th>Slope RSS</th>
<th>Significance RSS</th>
<th>Slope UAH</th>
<th>Significance UAH</th>
</tr>
</thead>
<tbody>
<tr>
<td>All</td>
<td>0.016</td>
<td>0.001</td>
<td>0.010</td>
<td>0.035</td>
</tr>
<tr>
<td>Tropical</td>
<td>0.015</td>
<td>0.003</td>
<td>0.008</td>
<td>0.111</td>
</tr>
<tr>
<td>Subtropical</td>
<td>0.020</td>
<td>0.001</td>
<td>0.019</td>
<td>0.003</td>
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<tr>
<td>Subtropical NH</td>
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<td>0.001</td>
<td>0.019</td>
<td>0.015</td>
</tr>
<tr>
<td>Subtropical SH</td>
<td>0.013</td>
<td>0.036</td>
<td>0.018</td>
<td>0.001</td>
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<tr>
<td>Tropical NH</td>
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<td>0.023</td>
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<tr>
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</tr>
<tr>
<td>NH</td>
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<td>0.010</td>
<td>0.051</td>
</tr>
<tr>
<td>SH</td>
<td>0.011</td>
<td>0.080</td>
<td>0.003</td>
<td>0.533</td>
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</table>
The means and standard deviations of the RSS temperature are determined for all months of the year for the periods 1979–94 and 1995–2010 and the results presented in this paper are the average of December–February (DJF), June–August (JJA), September–November (SON), and March–May (MAM). To evaluate the temperature variability in recent decades, the data is further subdivided into 1991–2000 and 2001–10 and a similar analysis is conducted. The temperatures of the last 10 years (2001–10) are also considered since in the recent period there is a marked temperature increase starting at the beginning of this century in Africa and globally. The statistical significance determined to the 5% level (\( \alpha < 0.05 \)) of the difference between the composites, for the different periods considered in this work, is calculated from the OLS regression applying the Student’s two-tailed \( t \) test, where a significant \( t \) value is noted at more than 2.04.

The results shown in this paper could be associated with natural and anthropogenic variability; therefore, the occurrence of all ENSO events is verified based on the current National Oceanic and Atmospheric Administration (NOAA) operational index, the Oceanic Niño Index (ONI), by considering the three-month seasonal values. To examine the ENSO effect, in addition to examining the periods 1979–94 and 1995–2010, the differences in temperature between these periods after the El Niño and La Niña seasons identified above have been removed (i.e., just considering the neutral years) is then examined. In addition, the periods were then also investigated solely analyzing El Niño and La Niña years separately in each period.

3. Results

a. Africa compared with other continents

When considering the temperature change in the DJF season between the earlier period 1979–94 with the most recent period 1995–2010 (Fig. 3a), only Africa shows significant temperature increases across much of the continent [(data are unavailable for both polar regions and elevations above 3000 ft (900 m)]. When considering the JJA season (Fig. 3b), considering continents within the low and middle latitudes, both Africa and South America show significant temperature increases over the majority of their areas. This highlights the need to study temperature change in Africa in more detail.

b. Annual mean temperature: NNR

Figure 4 compares annual mean near surface air temperature anomalies across all four datasets between 1979 and 2010 for the whole of Africa, Northern Hemisphere subtropical Africa, and Northern Hemisphere tropical Africa as these are the regions with the most notable trends. It should be noted that while some differences exist in the datasets, they do compare reasonably well regarding the interannual variability and general trends. Table 1 provides a summary of the slope (and significance) from a linear regression for this period for all these regions utilizing the satellite data. It can be seen that increasing trends were observed in both satellite datasets with most regions experiencing significant trends to the 1% level with the RSS data. While the Southern Hemisphere regions had slightly lower significance values, they were still high (subtropical and tropical Southern Hemisphere having a significance value greater than 5% and Southern Hemisphere Africa having a significance greater than 10%). The IPCC AR4 reported that the period between 2000 and 2006 is considered the globally warmest of the last 100 years (Trenberth et al. 2007). In the African regions investigated (as noted above), it was also noted that the temperatures have increased since 2000.

Considering the RSS data for Africa over the period 1979–2010, there is a significant (to the 1% level) upward linear trend noted with an estimate of 0.16°C decade⁻¹ based on the results of the regression. This increase is larger than that noted for South America (0.09°C decade⁻¹) by Collins et al. (2009), although it should be noted that the Collins et al. (2009) analysis did not utilize the RSS dataset.
The temporal series of annual mean temperature anomalies over Northern Hemisphere Africa is similar to the series for the whole of Africa. Over the period 1979–2010, there is a significant (to the 1% level) upward linear trend noted with an estimate of $0.18^\circ$C decade$^{-1}$ based on the results of the regression. The temporal series of the annual mean temperature anomalies over Southern Hemisphere Africa shared some of the similarities of the other two African series described above. The results from the OLS regression show a trend also with an estimate of $0.11^\circ$C decade$^{-1}$ significant to the 10% level.

Now just considering tropical Africa, again the increasing trend looks similar to the other regions examined with a significant (to the 1% level) upward linear trend noted with an estimate of $0.15^\circ$C decade$^{-1}$ based on the results of the regression. Separating the tropics into

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**Fig. 7.** Difference of the mean RSS total lower-tropospheric temperatures (K) in DJF and JJA between (a),(c) 2001–10 and 1979–90, and between (b),(d) 1991–2000 and 1979–90. The shaded areas represent statistical significance at the 5% level.
Northern Hemisphere tropical Africa and Southern Hemisphere tropical Africa, both of these regions show an increasing trend (0.19°C decade\(^{-1}\) and 0.11°C decade\(^{-1}\), respectively) indicative of the overall tropical situation described here.

The temporal series of the annual mean temperature over subtropical Africa shows a significant upward linear trend with an estimate of 0.2°C decade\(^{-1}\) based on the results of the regression. As expected, due to the larger African subtropical landmass in the Northern Hemisphere, when dividing the sub-tropics into Northern Hemisphere and Southern Hemisphere sub-tropics, the Northern Hemisphere sub-tropics looks more akin to the overall sub-tropical situation. The results from the OLS regression show a trend with an estimate of 0.23°C decade\(^{-1}\) for the Northern Hemisphere sub-tropics but only 0.13°C decade\(^{-1}\) for the Southern Hemisphere sub-tropics.

It should be noted that for every region examined, the trend in the Southern Hemisphere (whole of Southern Hemisphere, tropical and subtropical Southern Hemisphere) was always smaller than the Northern Hemisphere counterpart. This is consistent with previous work by Jones et al. (1994) among others who note that globally the Northern Hemisphere is warming faster than the Southern Hemisphere.

c. December–February

The spatial patterns of the temperature during December–February in Africa are strikingly similar in both periods, 1979–94 and 1995–2010 (Figs. 5a,b). However, there are some notable differences, for example, in the period 1979–2010 a change in the temperature pattern in Africa is observed, with enlargement of the area enclosed by the 280-K isotherm around the coast of Kenya and Tanzania (Fig. 5b). The temperature differences between the two periods are shown in Fig. 5c (with significant results shown to the 5% level in gray). It can be seen that significant warming occurs over much of the tropical region of the Northern Hemisphere between the period 1979–94 and the period 1995–2010. The observed warming in South Africa occurs largely on parts of the southern and eastern coast. This is in agreement with Muhlenbruch-Tegen (1992) studying the period 1940–1989 using station data who noted that only the coastal stations of South Africa had significant increasing temperature trends.

To evaluate temperature variability in the recent decades only, the data are further subdivided: 1991–2000 and 2001–10 (Fig. 6a). The spatial patterns of the temperature are similar in both periods (figure not shown). The area over the northern Sahara, which previously showed warming in the recent period (1995–2010 compared with 1979–94), now shows an area of significant warming in Libya when examining 2001–10 compared with 1991–2000.

When the differences between 1991–2000 and 1979–1990, and between 2001–10 and 1979–1990 are considered (Figs. 7a,b), a significant warming is observed in more
of the continent when the most recent period is compared with 1979–90. However, this significant warming is not observed in the 1991–2000 period. The mean temperature patterns for DJF for the period 2001–10 (Fig. 8) look similar to earlier periods shown in Figs. 5a and 5b.

Figures 9a–c show the analysis of the period 1979–94 compared with 1995–2010 like in Figs. 5a–c but now with El Niño and La Niña events removed so that only neutral ENSO years are considered. It can be seen when comparing Fig. 5 and Fig. 9 that similar but reduced results emerge, with a significant increase in temperatures for the region directly north of the equator in the more recent period. While there is a localized temperature reduction centered in Egypt, it is not found to be significant. Examining La Niña seasons only (Fig. 10) shows a significant warming pattern very similar to that found in Fig. 5. However, El Niño seasons only (Fig. 11) show widespread significant warming across Northern Hemisphere Africa. That this warming is not represented in the long-term plots suggests that ENSO does not account for the noted warming in Africa.

Figure 12c shows the mean temperature difference between the five strongest El Niño and La Niña events in the period 1979–2010. Warming is observed over the western Sahara and most of southern Africa in the strongest El Niño years compared with the strongest La Niña years, but the strongest areas of warming are not collocated with the significant long-term trend.

The interannual temperature variability in DJF (Figs. 13a–c), determined by the standard deviation, is largest over northern Africa with a secondary area of increased variability to the south. There is little temperature

Fig. 9. As in Fig. 5, but in each period ENSO ONI $\approx |0.5^\circ C|$ have been removed.
variability in the equatorial region, and for all areas the magnitude of temperature variability is consistent across all time periods.

d. June–August

The June–August temperature patterns in Africa are largely similar for the periods 1979–94 and 1995–2010 (Figs. 5d,e), with moderate expansion of the 284-K zone over the Sahara. However, an examination of the temperature differences between the two periods (Fig. 5f) shows that, unlike what was observed in DJF, significant warming occurs in both the Sahara and a band south of the equator. Equatorial regions see significant warming only in the coastal regions.

Again for the JJA season, recent decades are also analyzed in two parts—1991–2000 and 2001–2010—and the difference in temperatures between the two periods is noted in Fig. 6b. Little significant difference in warming is observed between the two decades. The area with significant warming increases over much more of the continent with greater temperature differences over the Sahara in the period 2001–10 more than in 1991–2000 when compared with the temperatures in the period 1979–90 (Figs. 7c,d).

Similar to the analysis of the DJF season, Figs. 9d–f show the analysis of the period 1979–94 compared with 1995–2010 as in Figs. 5d–f but now with significant ENSO events removed leaving just the neutral years. It can be seen when comparing Figs. 5 and 9 that again similar results emerge, that is, there is a significant increase in temperatures for the majority of Africa in the more recent period. Thus again supporting the

FIG. 10. As in Fig. 5, but in each period only La Niñas ≤ −0.5°C are included.
suggestion that ENSO does not account for the noted warming considering most of Africa. Similar results are found when considering the La Niña years (Figs. 10d–f) and El Niño years (Figs. 11d–f) separately.

Figure 12f shows the mean temperature difference between the five strongest El Niño and La Niña events during the period 1979–2010. Equatorial warming is observed over most of Africa in the strongest El Niño years compared with the strongest La Niña years with areas of cooling at the northern and southern extremes of the continent. However, areas with significance to the 5% level are minimal, not widespread, and not in regions previously identified as having significant long-term temperature trends. While this identifies the regions where El Niño and La Niña impacts most differ, it also further acts to confirm that ENSO is not a primary driver of long-term temperature variability in the region.

In the JJA season, little interannual variability is observed over much of the Sahara (Figs. 13d–f). Peak interannual variability is observed in South Africa in all periods and is strongest in the most recent decade.

e. March–May and September–November

The spatial patterns of March–May and September–November are shown in Figs. 14 and 15, respectively, for the periods 1979–94 and 1995–2010. Similar to what we observed for DJF and JJA, the temperatures in the MAM and SON seasons also changed when the most recent period was compared with the earlier period. For 1995–2010 compared with 1979–94, over much of the eastern and western coasts of Africa the temperatures significantly increased. Figure 15 also showed significant increases in temperature in the central Sahara for the SON period.
4. Summary and conclusions

This work shows how the near-surface mean air temperature in Africa varies in the multiple datasets between 1979 and 2010, with a focus on mean total lower-tropospheric temperature profiles. There are significant increasing temperature trends observed in both the RSS and UAH satellite datasets as well as in reanalysis comparison datasets (the NNR and ERA-40). Finding these trends in the satellite datasets provides us greater confidence in the results from the NNR and ERA-40. Considering mean annual temperatures from the RSS, warming was observed in the Northern Hemisphere and Southern Hemisphere, and tropical and subtropical regions, with greater warming in Northern Hemisphere regions. Considering the DJF season, significant warming was observed over northern tropical Africa comparing the period 1995–2010 with 1979–94. An examination of the more recent period shows more warming occurring in the most recent 10 years than the other periods examined. The difference between the time periods (1994–2010 and 1979–94) in the JJA season is different in that significant warming extends across both northern and southern regions of the continent, with larger temperature increases observed in the Sahara than anywhere else on the continent. During MAM and SON significant warming is also observed across central Africa but not to the levels seen in JJA. SON warming was significantly larger than the warming observed in MAM. This result is also consistent with Hulme et al. (2001) who examined the
period 1901–95 and notes that a slightly larger warming in Africa occurs in the months of JJA (and SON) than in the months of DJF (and MAM).

The analysis from the RSS also suggested while slightly greater warming is observed across Africa in El Niño events than La Niña events, the warming during the most recent period (1995–2010) compared with the earlier period (1979–94) is not a result of ENSO. When considering each of these phases, and the temperature difference between the two periods, again one can see in DJF a significant increase in temperatures for the majority of northern tropical Africa in the more recent period. Likewise in each of these three phases, in JJA one can observe warming throughout the whole continent. Because of these similarities between phases, this suggests that the temperature increases in Africa may not be due to ENSO but some other component of natural variability of the climate and/or may be a result of human activity.

The author would like to provide caution in the results. In particular, other natural forcing may be responsible for some of these results. In particular, when considering volcanic forcing, clearly the eruptions of volcanoes such as the April 1982 eruption of the Mexican volcano, El Chichón, and the subsequent June 1991 eruption of the Philippine volcano, Mount Pinatubo, both caused significant cooling in the tropical troposphere for a couple of years after the event (Kelly and Jones 1996) owing to a reduction in the total radiation received at the surface as a result of the volcanic aerosol
clouds. This cooling would have been reflected in the dataset of the earlier period, which certainly could affect the period differences and trends. However, Pachauri and Reisinger (2007) note that only models that include anthropogenic forcing can simulate the observed patterns of warming (Hegerl et al. 2007). Hegerl et al. (2007, p. 727) note that, “no model that used global natural forcing only has reproduced the observed global mean warming trend or the continental mean warming trends in individual continents (except Antarctica) over the second half of the twentieth century.” In fact when considering a more modest increase for the global scale, some authors (Wigley and Barnett 1992; Hulme and Jones 1994) state that natural processes alone cannot explain this increase, thus making the argument for anthropogenic warming for Africa stronger. Indeed, there has been more land use change and greater carbon dioxide release in the most recent period (Kalnay and Cai 2003). Only global and regional climate models with anthropogenic forcing can perhaps explain temperature warming due to human activities. It is possible that changes in the observational networks could influence the results; however, to verify this hypothesis it would be necessary to examine complete datasets from meteorological stations over a long period of time (which are hard to obtain for Africa).

![FIG. 14. Mean RSS total lower-tropospheric temperatures (K) in MAM during (a) 1979–94 and (b) 1995–2010, and (c) the difference of the mean temperature between these two periods. The shaded areas in (c) represent statistical significance at the 5% level.](image)

![FIG. 15. As in Fig. 14, but for SON.](image)
China and India are considered to be the major developing-country contributors to greenhouse gas-induced warming, while the contribution from countries in Africa has been relatively low. Each American produces nearly 16 metric tons of carbon dioxide annually, while each African produces just 1 metric ton year$^{-1}$ (Fields 2005). Despite this difference, the effects and potential effects of climate change in Africa have already been well noticed and documented. The Pew Center on Global Climate notes that Ethiopia is the country considered to be most vulnerable to the effects of global climate change. Ogodo (2006) warns that a third of Africa’s coastal settlements could be wiped out this century by rising sea levels and floods threaten as many as 70 million people. Increasing temperatures have caused fish populations in African lakes to decline, with Lake Tanganyika being a prime example (Verburg et al. 2003; O’Reilly et al. 2003). Thompson et al. (2009), who have mapped deglaciation of Mount Kilimanjaro, assert that if current climatological conditions are sustained, the ice fields atop Mount Kilimanjaro will likely disappear within several decades.

Rutherford et al. (1999) note that a number of species of flora are likely to become extinct on several different nature reserves if climate change continues on its estimated path of warming/drying in the majority of regions. The analysis maintains that, due to both changes in the number of optimum growth days and temperature, from 10.4% to 42.4% of species of flora are expected to become extinct in a range of natural parks in Africa. Downing et al. (1997) notes that whether the warming and drying trends in Africa persist and grow worse depend on how the nation handles mitigation and further development practices. The work shown here can help African countries see, on a continental scale, what will help them better plan for a changing climate. It should be noted, however, that the trends observed must be considered as a preliminary estimate because of the short analysis period involved.

Acknowledgments. The author would like to acknowledge the use of the satellite data from Remote Sensing Systems (RSS) and the University of Alabama at Huntsville (UAH) and reanalysis data from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) and the European Centre for Medium-Range Weather Forecasts (ECMWF). In addition the author would like to thank Ph.D. student David R. Roache for assistance with data analysis and scripting. The author would also like to thank the anonymous reviewers and editor for comments and suggestions on the manuscript.

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