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COMMENT

THE RECENT SAHEL DROUGHT IS REAL

AIGUO DAI,[a,*] PETER J. LAMB,[b] KEVIN E. TRENBERTH,[a] MIKE HULME,[c] PHILIP D. JONES,[d] and PINGPING XIE[e]
[a] *National Center for Atmospheric Research, PO Box 3000, Boulder, CO 80307, USA*
[b] *Cooperative Institute for Mesoscale Meteorological Studies and School of Meteorology, The University of Oklahoma, Norman, OK 73019, USA*
[c] *Tyndall Centre for Climate Change, School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK*
[d] *Climatic Research Unit, School of Environmental Sciences, University of East Anglia, Norwich NR4 7TJ, UK*
[e] *Climate Prediction Center, National Centers for Environmental Prediction, National Weather Service, National Oceanic and Atmospheric Administration, Camp Springs, MD 20746, USA*

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ABSTRACT

Using station rainfall data extracted from two comprehensive data sets, we show that large decreasing rainfall trends were widespread in the Sahel (10–20 °N and 18 °W–20 °E) from the late 1950s to the late 1980s. Thereafter, Sahel rainfall has recovered somewhat through 2003, although the drought conditions have not ended in the region. These results confirm the findings of many previous studies. We also found that large multi-year oscillations appear to be more frequent and extreme after the late 1980s than previously. Analyses of Sahel regional rainfall time series derived from a fixed subset of stations and from all available stations show that the decreasing trend in Sahel rainfall is not an artifact of changing station networks. The rainfall model used by Chappell and Agnew (2004 *International Journal of Climatology* **24**: 547–554) is incorrect and their modelled rainfall time series is totally unrepresentative of Sahel average rainfall. Their conclusion about the Sahel rainfall trends being an artifact of changing station locations is emphatically wrong and their speculative statements about the implications of their results for other studies and other regions of the world are completely unfounded. Copyright © 2004 Royal Meteorological Society.

KEY WORDS: Sahel; drought; rainfall; precipitation

1. INTRODUCTION

The drought conditions in the Sahel of West Africa since the early 1970s have been well documented by analyses of rainfall (e.g. Hulme, 1992; Lamb and Peppler, 1992; Nicholson *et al*., 2000; L'Hôte *et al*., 2002), vegetation cover (Tucker *et al*., 1991), dust transport (Prospero and Lamb, 2003), and other agricultural and societal data (e.g. Nicholson *et al*. 1998; Tarhule and Lamb 2003; and numerous reports in news media). Several possible causes or mechanisms, including local land–atmosphere interactions (e.g. Charney, 1975; Nicholson, 2000), tropical Atlantic and global sea-surface temperature influences (e.g. Folland *et al*., 1986; Lamb and Peppler, 1992; Ward, 1998; Giannini *et al*., 2003), and atmospheric wave disturbances (Druyan and Hall, 1996), have been identified and investigated. It is safe to say that the decreasing rainfall and devastating droughts in the Sahel region during the last three decades of the 20th century are among the most undisputed and largest recent climate changes recognized by the climate research community. Indeed, substantial field-based research has been conducted into the impacts and coping strategies deployed by Sahelian pastoralist

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[*] Correspondence to: Aiguo Dai, National Center for Atmospheric Research, PO Box 3000, Boulder, CO 80307, USA; e-mail: adai@ucar.edu

communities in response to their deteriorating natural resource base (e.g. Mortimore and Adams, 2001; Tarhule and Lamb, 2003).

We were, therefore, very surprised to read the paper by Chappell and Agnew (2004) published in a recent issue of the *International Journal of Climatology*, in which they 'suggested that the perceived drying trend in the Sahel was an artifact of the crude statistical aggregation of the data and historical changes in the climate station networks'. Based on this finding, they 'question(ed) the validity of the hypotheses and speculations for the causes of the drying trend (in the region) and its effects on global climate change'. Furthermore, they concluded that their results 'also increased the likelihood that changes over time in other regional and global climate station networks have influenced the performance and interpretation of global climate models'. They suggested that all prior climate data analyses and 'Research decisions and model optimizations/validations should be re-evaluated in light of these corrected data'.

These are very serious claims that would have very profound and comprehensive implications for climate research, if they were correct. However, as we show below, there is absolutely no basis for these claims: the Chappell and Agnew (2004) study is seriously flawed in its methodology and interpretations. The methods that Chappell and Agnew (2004) assume that researchers widely use to estimate regional rainfall when station numbers and distribution vary have not been used in most published literature on climate change and variability; therefore, their conclusions are simply wrong.

2. FLAWS IN CHAPPELL AND AGNEW (2004)

We begin with a brief summary of exactly what Chappell and Agnew (2004) did and how they came to their conclusions. In essence, they modelled proxy June–September rainfall in the Sahel (defined as the land region 10–20 °N and 20 °W–20 °E in their paper) as a function of the number of stations in the western and eastern sectors of the region. By choosing the longitude boundary between the two sub-regions at 6 °W, they were able to simulate a downward trend in this station-number-predicted rainfall that accounted for 87% of the variation in their station rainfall data. They considered this trend as artificial, arising entirely due to trends in the station numbers within the western and eastern Sahel regions, and therefore removed it from the station data. The implicit assumption is that the changes in the station network had the same effect on the observed regional rainfall as on their modelled rainfall. Their 'corrected' rainfall data did not show any statistically significant trends for the period (1931–90) examined, although a decreasing trend is still evident from the mid-1950s to the mid-1980s. Based on these data, they made the conclusions mentioned above.

Prudent researchers would review carefully previously published studies and perform additional analyses of the data before making such wide-reaching conclusions, especially when they are in direct conflict with a large body of earlier studies, including those analyses of rainfall trends at fixed stations (e.g. Lamb and Peppler, 1992; Nicholson *et al*., 2000; L'Hôte *et al*., 2002). For example, Lamb's index (Tarhule and Lamb, 2003; also see Figure 3(b)) has used the same 20 Sahelian stations since it was first developed in the mid-1970s; exactly half of those stations are west/east of the 6 °W boundary used by Chappell and Agnew (2004), and only 13 station-years out of 1220 during 1941–2001 had missing data. However, Chappell and Agnew (2004) ignored most prior studies of Sahel rainfall data and came to their conclusions without any additional analyses of the station data. As we show below, some simple tests of their modelling results would have revealed many serious flaws in Chappell and Agnew (2004) that eventually led them to make those unsupportable conclusions and speculations.

For example, in section 2 and other parts of their paper, Chappell and Agnew (2004) assumed that Sahel regional rainfall values have traditionally been calculated using the simple arithmetic mean of all available station data within the region, whereas in fact they have generally been derived as normalized station rainfall time series (e.g. by standard deviation (SD)) using area-weighted averaging (e.g. Lamb and Peppler, 1992; Rowell *et al*., 1995; Nicholson *et al*., 2000). The normalization, combined with the area-weighted averaging, minimizes the impact of varying station networks on the regional time series in a region with a large precipitation gradient, like the Sahel (Jones and Hulme, 1996). Averaging anomalies across spatial data gaps is preferred because of higher spatial correlation of anomalies compared with absolute rainfall values, which include stationary spatial variations associated with topography and location (Dai *et al.*, 1997). For almost normally distributed variables with spatially comparable SD, such as monthly temperature, spatially averaging deviations from a climatological mean is adequate. However, for variables with large spatial variations in SD, such as monthly rainfall in the Sahel, normalizing the deviations (e.g. by SD) before averaging is necessary in order to reduce regional biases towards areas with large SD. In fact, Katz and Glantz (1986) found that the claim that the Sahel had recently experienced a long run of relatively dry years did not appear to be sensitive to the exact form of index used. Area weighting is also necessary for reducing the regional biases arising from uneven distributions of the stations (e.g. Dai *et al.*, 1997). This originates from the generic definition of the mean $\overline{V}$ of a given variable V over an area A, which is the areal integral of the variable over the domain divided by the area of the domain:

$$\overline{V} = \frac{1}{A}\int_A V \, \mathrm{d}A$$

To our knowledge, all published regional, hemispheric, and global time series of temperature (e.g. Hansen and Lebedeff, 1987; Folland *et al.*, 2001; Jones and Moberg, 2003) and precipitation (e.g. Dai *et al.*, 1997; New *et al.*, 2001) are based on area-weighted averages.

Based on the above false perception, Chappell and Agnew (2004) devised a proxy of Sahel regional mean rainfall $\overline{w}(t)$ for year t based on time series of station numbers in the western $(n_a(t))$ and eastern $(n_b(t))$ part of the Sahel as follows:

$$\overline{w}(t) = \frac{\overline{a}\, n_a(t) + \overline{b}\, n_b(t)}{n_a(t) + n_b(t)}$$

where $\overline{a}$ and $\overline{b}$ were considered, respectively, as the regional mean rainfall for the western (a) and eastern (b) Sahel. A fundamental error in this model is that the weighting factors $n_a(t)$ and $n_b(t)$ should be the areas of the two sub-Sahel regions, not the station numbers. The problem with the station-number weighting is illustrated in the following example. Suppose region a has only one station whose mean rainfall happens to be the same as region a's mean, and region b has 99 stations, but their areas are the same, then this model gives $\overline{w} = 0.01\,\overline{a} + 0.99\,\overline{b}$ instead of the correct formula of $\overline{w} = 0.5(\overline{a} + \overline{b})$. The incorrect estimate for region $(a + b)$ is severely biased towards region b. In contrast, the area weighting would work correctly.

Another serious error in Chappell and Agnew's (2004) rainfall model $(\overline{w}(t))$ is that they used constant mean rainfall ($\overline{a}$ and $\overline{b}$) for the two sub-regions to estimate Sahel rainfall for individual years. This does not make sense, as the mean rainfall amounts for regions a and b vary from year to year. In a correct model, temporal variations in Sahel rainfall should come from temporal variations in the regional mean rainfall for the two sub-regions, not from their number of stations.

Starting with an ill-formulated rainfall model, the Chappell and Agnew (2004) made another serious mistake by estimating constants $\overline{a}$ and $\overline{b}$ through fitting $\overline{w}(t)$ to observed Sahel rainfall time series using nonlinear least squares, which in general do not ensure that $\overline{a}$ and $\overline{b}$ represent mean rainfall for the two sub-regions. Indeed, their estimates of these two constants ($\overline{a} = 973$ mm, $\overline{b} = 142$ mm) are nowhere near the actual mean rainfall (565 mm and 382 mm; see below). By using values that are too large for $\overline{a}$ and too small for $\overline{b}$, their model overestimated the effect of the decreasing station numbers in the western Sahel and underestimated the effect of the increasing station numbers in the eastern Sahel, resulting in a generally downward trend, even from 1931 to 1968, when station rainfall data showed little such downward trend.

Any one of these severe errors makes Chappell and Agnew's (2004) rainfall model irrelevant to Sahel rainfall, let alone Chappell and Agnew's (2004) combination of them all. The fact that their model produced a good match to Sahel rainfall data is a direct result of the least-squares fitting, but nothing else. There are many combinations of various functions that can produce good matches to the Sahel rainfall time series. For example, if we replace $n_a(t)$ and $n_b(t)$ by functions of time, namely $n_a(t) = n_b(t) = 1$ for $t < 1968$, and $n_a(t) = 1 + t'$ and $n_b(t) = 1 - t'$ for $t \geq 1968$, where $t' = t - 1968$, then the model becomes $\overline{w}(t) = (\overline{a} + \overline{b})/2$ for $t < 1968$, and $\overline{w}(t) = [(\overline{a} + \overline{b})/2] + [t'(\overline{a} - \overline{b})/2]$ for $t \geq 1968$. If we set $(\overline{a} + \overline{b})/2$ equal to the mean Sahel precipitation of 1931–67 and $(\overline{a} - \overline{b})/2$ equal to the slope of 1968–90 Sahel rainfall time series (see Figure 1(b)), then these functions produce a much better fit than Chappell and Agnew's (2004) model to the Sahel rainfall data. Does this suggest that the decreasing Sahel rainfall since the late 1960s is an artifact arising from changes in the calendar year? Obviously not!

Consequently, their 'corrected' rainfall data are irrelevant to real Sahel rainfall. Real downward trends exist in Sahel rainfall and they have been discussed in many previous studies. All of the conclusions and speculations of Chappell and Agnew (2004) are both completely wrong and unfounded. We emphasize that, even if the modelled rainfall of Chappell and Agnew (2004) were a reasonable proxy of Sahel rainfall, their results would still have few implications for previously published analyses of Sahel rainfall because the effects of changing station networks were excluded from or minimized in earlier studies.

3. ANALYSIS OF SAHEL RAINFALL DATA

3.1. Effects of changing station networks

The potential effects of changes in station networks and other nonclimatic inhomogeneities in historical records of temperature and precipitation have long been recognized and investigated (e.g. Mitchell *et al.*, 1966; Hansen and Lebedeff, 1987; Groisman *et al.*, 1991; Jones and Hulme, 1996; Folland *et al.*, 2001). For example, Dai *et al.* (1997) showed that nonclimatic changes in station records of precipitation are unlikely to be significant for the majority of global stations, and that sampling the data using station networks that existed in 1900 and 1930 resulted in global and hemispheric precipitation time series fairly similar to those derived using all available stations. A similar analysis (termed 'frozen' grids) was conducted for hemispheric and global temperature averages by Jones *et al.* (1986) with the same conclusion: namely that the network available in 1900 results in temperature time series similar to the full sample, particularly with respect to long-term trends. Folland *et al.* (2001) go one step further and give estimates of the total uncertainty in global temperature and its trends, including the effects of time-varying data coverage and other causes of uncertainty.

For the Sahel, the total number of rain-gauge stations has been decreasing since the early 1970s (Hulme, 1992), and this may well be one of the devastating impacts of the persistent drought itself in the region. However, one can easily verify whether the decreasing trend in the number of stations is a cause of the trend in the Sahel regional rainfall time series by, for example, looking at trends at fixed stations (e.g. Nicholson *et al.*, 2000; L'Hôte *et al.* 2002), or analysing a subset of fixed stations with nearly continuous rainfall data, as we do here.

We extracted Sahel rainfall monthly data from the updated Global Historical Climatology Network version-2 (GHCN2; Peterson and Vose, 1997) and the Climate Anomaly Monitoring System (CAMS; Chen *et al.*, 2002) data sets. Of the 195 stations in these data sets within the Sahel region 10–20 °N and 20 °W–20 °E, 89 stations have continuous or nearly continuous (i.e. total data gaps less than a few years) monthly rainfall totals for June–September months from 1931 to 1986. Figure 1(a) shows the linear trends of June–September rainfall during 1931–86 calculated at these 89 stations after the trends were averaged within each 1° × 1° grid box to facilitate display. Decreasing rainfall trends are widespread in the Sahel, with larger magnitudes in the west, where the mean June–September rainfall is also higher. We also gridded the station data onto a 2.5° × 2.5° grid (results similar on a 1° × 1° grid) using the inverse distance-weighted scheme of Dai *et al.* (1997), and then derived area-weighted regional averages of June–September rainfall for the Sahel (Figure 1(b)). The Sahel rainfall time series derived using the 89 stations versus all stations does not differ substantially, and both show large decreases after the late 1950s (Figure 1(b)). Using the gridded rainfall from all 195 stations, the area-weighted long-term (1931–90) mean June–September rainfall is 565 mm for the west (west of 6 °W) and 382 mm for the east Sahel region. These results are consistent with earlier studies (e.g. Nicholson *et al.* 2000; Tarhule and Lamb, 2003) and show that the decreasing trends in Sahel regional rainfall are not an artifact of changing station networks; using all existing stations (as in most previous analyses) does *not* result in artificial trends associated with changes in station numbers or locations.

3.2. Updated Sahel rainfall time series: 1920–2003

Here, we also provide updated time series of Sahelian rainfall based on the GHCN2 and CAMS data sets. Most of the annual rainfall occurs from April to October in the Sahel, thus we consider the April–October

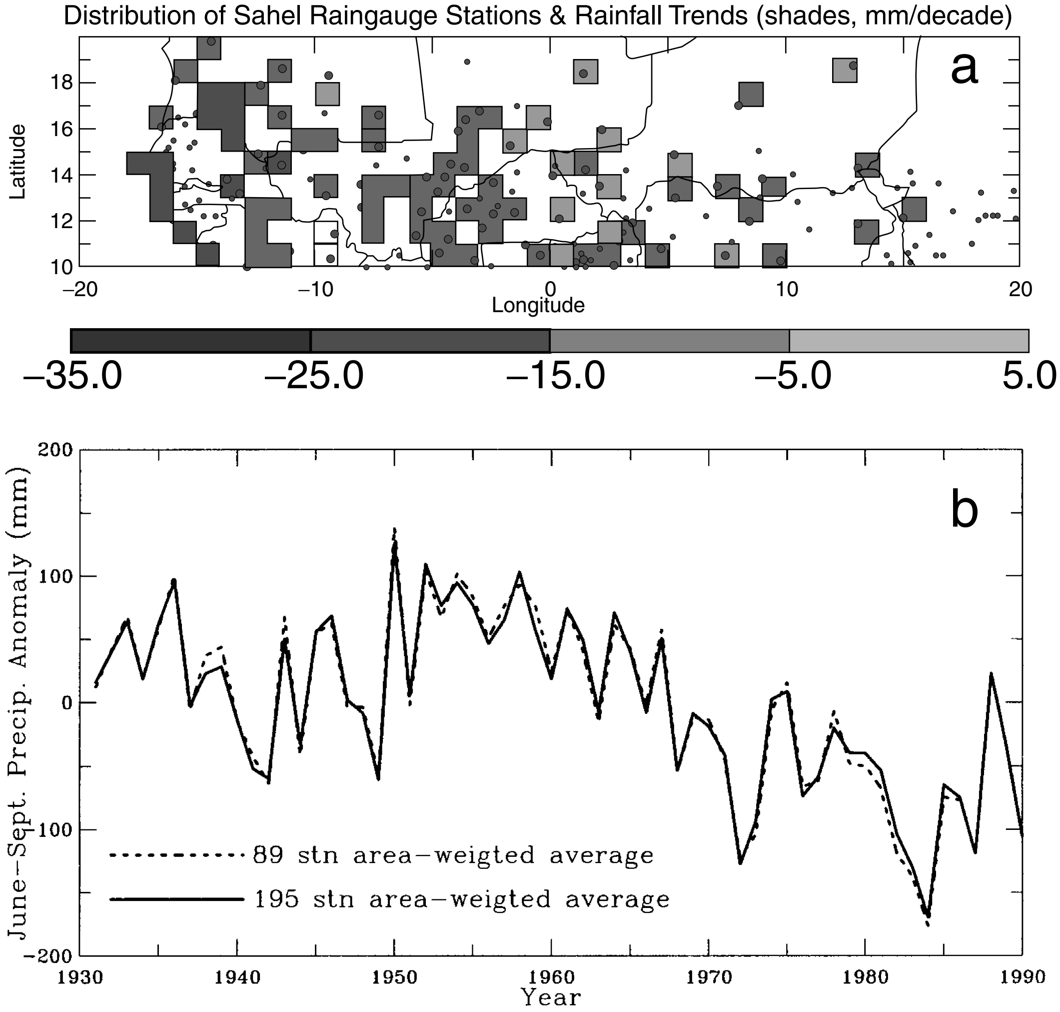

Figure 1. (a) Distribution of the 89 rain-gauge stations (big dots) with continuous or nearly continuous data from 1931 to 1986, and the other stations (small dots) of the 195 stations included in the GHCN2 and CAMS datasets. The shades of grey indicate the linear trend (mm/decade) of June–September rainfall during 1931–86 calculated using the data from the 89 stations. (b) Area-weighted regional mean June–September rainfall for the Sahel region shown in (a) derived based on the 89 stations (dashed line) and all the available stations (solid line)

rainfall totals, as in the Lamb index (Tarhule and Lamb, 2003). In these data sets, there were only 5–24 stations for years within 1900–19; thereafter, the spatial sampling is fairly good (Figure 2), with the total number of stations ranging from 27 (in 2001) to 190 (in 1970) (Figure 3(a)). We gridded both the un-normalized station anomaly (in millimetres) and normalized anomaly (in SD units) and then averaged them using area-weighting to derive Sahel regional rainfall time series. Figure 3(b) shows that the time series derived from the two anomalies co-vary closely ($r = 0.99$). Also shown in Figure 3(b) is the Lamb Sahel rainfall index (Tarhule and Lamb, 2003) derived by averaging the normalized time series from 20 fixed stations fairly evenly distributed west of 10 °E. The Lamb index does not differ substantially from our estimates based on more stations ($r = 0.95$). The negative anomalies around 1972–73 and 1983–84 are lower for the un-normalized time series than the normalized indices; otherwise, these Sahelian rainfall estimates match each other closely. This again confirms that the recent drought conditions in the Sahel since ∼1970 are real.

Figure 3(b) shows that Sahel rainfall reached a minimum of ∼170 mm below the long-term (1920–2003) mean of ∼506 mm in 1983–84 following the major El Niño–southern oscillation (ENSO) event in 1982–83.

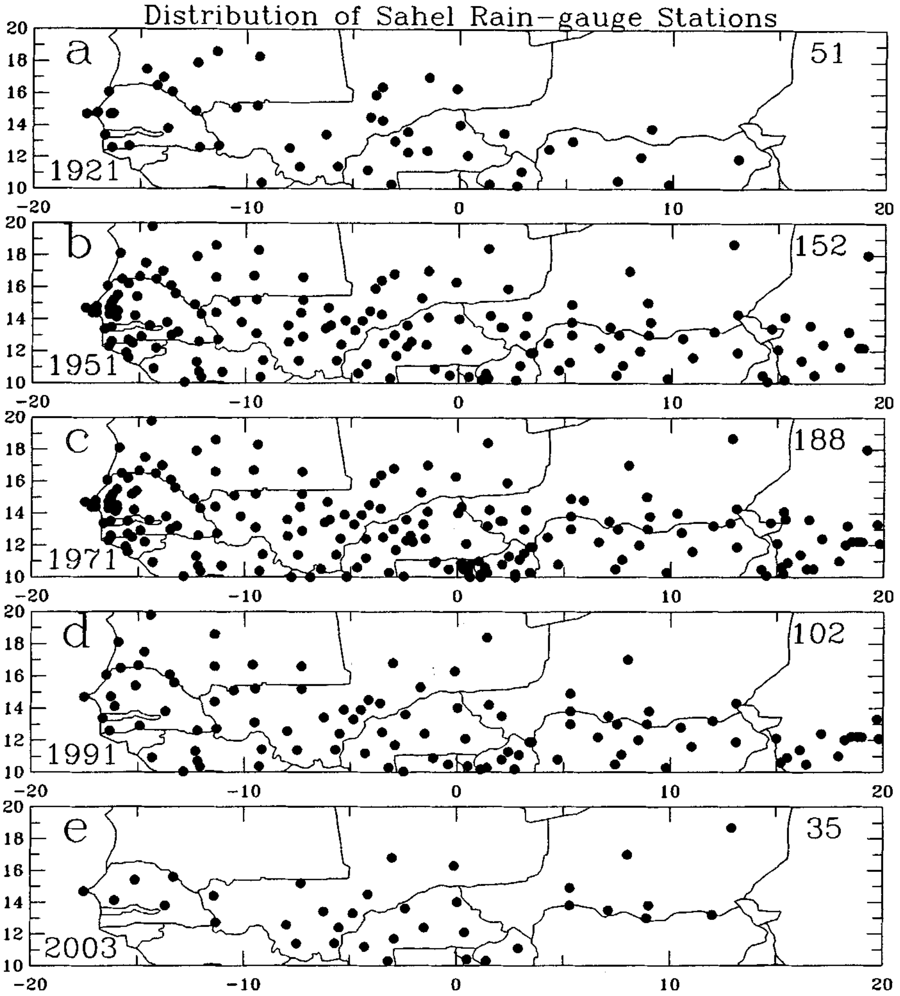

Figure 2. Distributions of Sahelian rain-gauge stations with April–October rainfall data for (a) 1921, (b) 1951, (c) 1971, (d) 1991, and (e) 2003. The number on the upper-right corner is the total number of stations shown in the panel

Since then it has recovered somewhat, but the mean of the last decade is still below the pre-1970 level (~540 mm), although it reached the pre-1970 mean in 1994, 1999 and 2003. The Palmer drought severity index, which accounts for the memory of soil moisture, shows that the Sahel is still experiencing drought conditions (Dai *et al.*, in press). Another feature is that large multi-year oscillations appear to be more frequent and extreme after the late 1980s than previously. This might suggest that the region's climate has become more unstable and prone to droughts after the prolonged severe droughts from the early 1970s to late 1980s due to, for example, reduced water-holding capacity by soils and vegetation that would normally provide some smoothing or stabilizing effects (e.g. Charney, 1975; Trenberth and Guillemot, 1996).

As shown previously (e.g. Folland *et al.*, 1986; Dai *et al.*, 1997; Ward, 1998; Dai and Wigley, 2000), Sahel rainfall is significantly affected by ENSO. This is evident by the large negative anomalies during or following many strong El Niño years (e.g. 1925–26, 1940–41, 1972–73, 1982–83, 1986–87, 1991–92, and 1997–98), except for 1949 when it was a normal ENSO year. The association with the cold phase of ENSO is weak, however.

It is difficult to assess time-evolving uncertainties in the time series of Sahel rainfall formally, although small differences among the three different estimates in Figure 3(b) suggest that the uncertainties are relatively small. Although analyses derived from all available gauge observations yield smaller random errors than those

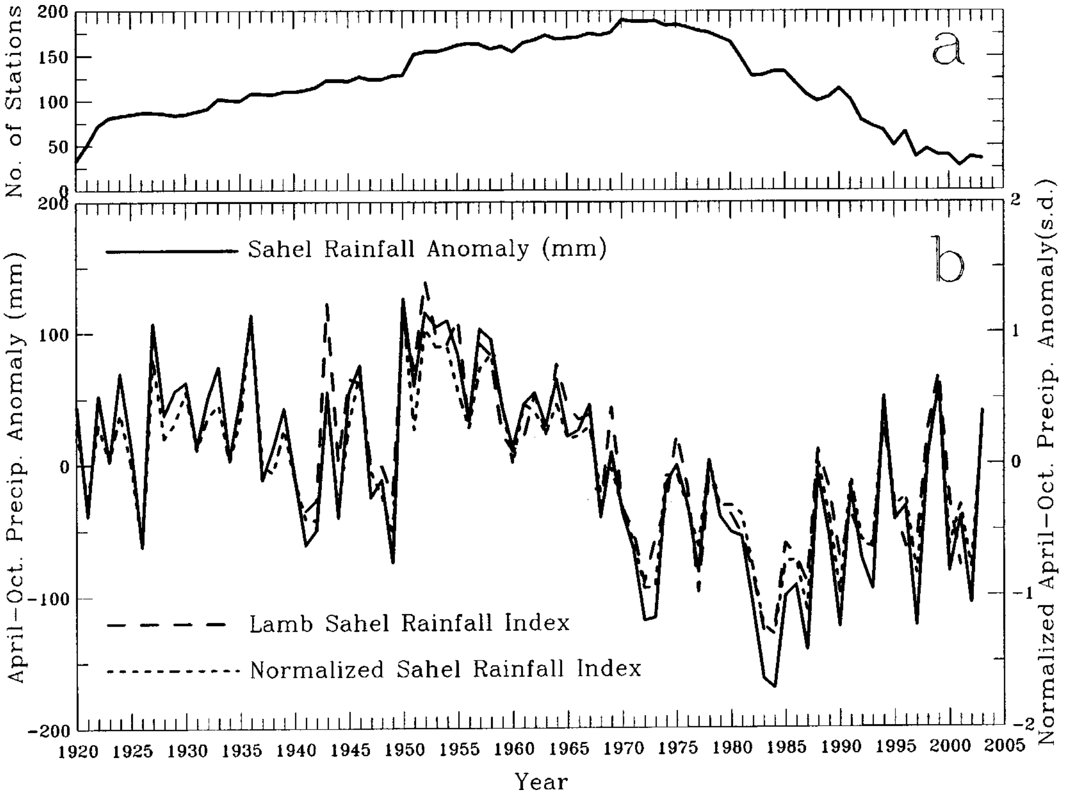

Figure 3. (a) Time series of total number of Sahelian rain-gauge stations with data for months April–October. (b) Time series of Sahel regional rainfall for April–October from 1920 to 2003 derived from by gridding station anomalies (solid line) and normalized station anomalies (short-dashed line) and then averaging them using area weighting. Also shown (long-dashed line) is the Lamb Sahel rainfall index for 1941–2001 derived from 20 fixed stations (Tarhule and Lamb, 2003)

based on a fixed station network, uncertainties arise when systematic differences in precipitation exist between stations with full temporal coverage and those with partial records. Utilization of an optimum-interpolation-based technique (e.g. Chen *et al.*, 2002), which considers the statistical structure of the target field, is able to produce an analysis of precipitation with reduced uncertainty. An investigation is under way at NOAA/CPC to examine quantitatively the bias caused by gauge network changes and its influence on long-term trend assessments (Xie and Chen, 2004, personal communications).

4. CONCLUDING REMARKS

Using station rainfall data extracted from the GHCN2 and CAMS, we show that large decreasing rainfall trends were widespread in the Sahel from the late 1950s to the late 1980s; thereafter, Sahel rainfall has recovered somewhat through 2003, even though the drought conditions have not ended in the region. These results are consistent with many previous studies. We also found that large multi-year oscillations appear to be more frequent and extreme after the late 1980s than previously. Our comparisons of Sahel regional rainfall time series derived from a fixed subset of stations and from all available stations show that the decreasing trend in Sahel rainfall is not an artifact of changing station networks. The rainfall model used by Chappell and Agnew (2004) was ill-formulated, incorrectly applied, and its results were poorly interpreted, making their simulated rainfall time series irrelevant to Sahel regional rainfall. Consequently, the results of Chappell and Agnew (2004) are wrong and their conclusions and speculative implications are completely unfounded.

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