Filters and Approximate Confidence Intervals for Interpreting Rainfall Anomaly Indices

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(Manuscript received 11 June 1990, in final form 8 March 1991)

ABSTRACT

The rainfall anomaly index (RAI) has been widely used to study variations over time in Sahelian rainfall. Its interpretation is often complicated by excessive missing data and changes in station network, both of which prevent a precise quantification of the significance of any given RAI estimate. Also, unless the time series are filtered, high interannual variability often obscures important rainfall fluctuations. Here we apply a simple method for calculating approximate confidence limits of areal rainfall estimates to annual data from two constant network configurations in Sudan and West Africa. These cover, respectively, the periods 1920–88 (13 stations) and 1922–85 (12 stations) and contain only 3 and 5 missing annual totals out of 897 and 768. The resulting annual RAI estimates, and 95% confidence limits, were subjected to a 9-point binomial filter, and a 30-point retrospective uniform filter (i.e., an annually updated WMO reference period), also called a running mean. By combining the RAI and confidence-level estimates with different filters we develop a technique that should be useful for interpreting RAIs and assessing the impact of climate on natural resources. This technique can be used to construct quantitative indicators of the terms *climate anomalies, climate fluctuations,* and *climatic change.* We illustrate this by applying tentative indicators to the two Sahel series, and also, by way of contrast, to an annual RAI for southern Sweden (15 stations covering the period 1861–1988 with 3 missing annual totals out of 1920). For example, recent individual anomalous years occurred in Sudan in 1978 and 1988 (wet) and 1984 (dry), and for both West Africa and Sudan a climatic change compared to century-mean rainfall had nearly occurred by the late 1980s. Southern Sweden has witnessed two recent climate fluctuations in the early 1970s (dry) and in the mid-1980s (wet). In conclusion, we hint at some refinements to the technique, but stress that for climate monitoring purposes the need for station networks of high quality and consistency over time will remain undiminished.

1. Introduction

Following the drought of 1968–73 in the African Sahel, a number of studies raised the question whether the drought was a manifestation of either a climatic change or a natural fluctuation within a basically stable climate. (Here we use the term Sahel when referring to tropical north Africa having an annual rainfall total of between 100 and 600 mm). Lamb (1979) reviewed much of the relevant literature and at that time found no consensus concerning the answer to this question. Some of the divergence in viewpoints could probably be attributed to the lack of any quantitative and sufficiently strict definition of the term "climatic change." After this initial debate in the 1970s numerous studies were devoted to monitoring Sahelian rainfall and to exploring possible physical causes of the subsequent variations in order to develop models with forecasting capabilities. These more recent works have been reviewed by Farmer and Wigley (1985), Druyan (1989), and Lamb and Peppler (1990).

The basic approach for describing temporal variations in Sahelian rainfall is similar in most studies: rainfall totals for individual stations are normalized before an area average is formed to reduce the influence of local effects. Normalized data are used in order to minimize problems caused either by averaging stations, which possess widely different mean rainfall or by a changing station network. In most studies one of the following two normalization procedures have been used: the percent departure from mean rainfall,

$$x'_{ij} = \frac{x_{ij} - \bar{x}_i}{\bar{x}_i} \tag{1}$$

or the standardized rainfall,

$$x'_{ij} = \frac{x_{ij} - \bar{x}_i}{s_i} \tag{2}$$

where

x'_{ij} is the normalized annual, seasonal, or monthly rainfall total for station i and year j,
x_{ij} is the corresponding rainfall total,

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$\bar{x}_i$ is the mean rainfall total for station i during a specified reference period, and

s_i is the standard deviation of the rainfall total during the same reference period.

Kraus (1977) compared both procedures. Noting that in dry climates the mean and standard deviation are correlated, he argued that (1) and (2) give essentially the same information and he advocated use of the latter. The former equation was common in earlier work, but following Kraus (2) has become increasingly popular. When averaged over several stations this yields what Katz and Glantz (1986) denoted the standardized anomaly index (SAI):

$$\bar{X}_j = \frac{1}{n} \sum_i x'_{ij} \qquad (3)$$

where

$\bar{X}_j$ is the SAI value for year j

n is the number of stations.

The term "standardized anomaly index" wrongly suggests, however, that the anomalies themselves have been standardized; in fact, it is the rainfall totals that are standardized. We will consequently use the general term rainfall anomaly index (RAI) when referring to this index. Kraus (1977) noted that in order to use an RAI, the within-year spatial variation has to be small compared with the temporal variation. To check this requirement he suggested an F-test based on analysis of variance. The statistical properties of the RAI were not dealt with in more detail, however, until the work of Katz and Glantz (1986). They noted that as the RAI involves the formation of a mean, its probability distribution will be closer to a Gaussian curve than the original data. They also pointed out the very important fact that,". . . it is not at all clear how to best adjust

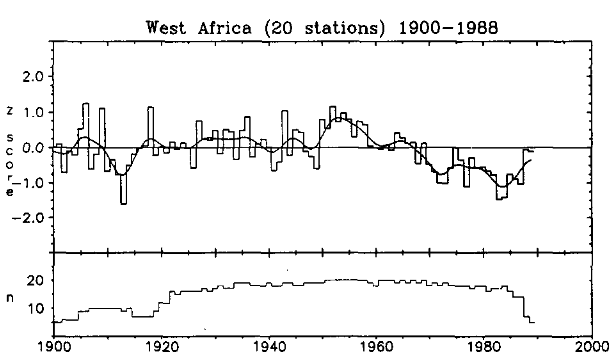

FIG. 1. The upper graph shows time-series plots of rainfall anomaly indices for Lamb's (1978) West African network. The thin staircase line shows the unfiltered time series, while the thick smooth line shows the 9-yr binomial filtered time series. The number of stations used to form the area average are shown in the lower graph. Note the decrease in number of available stations toward the ends of the time period.

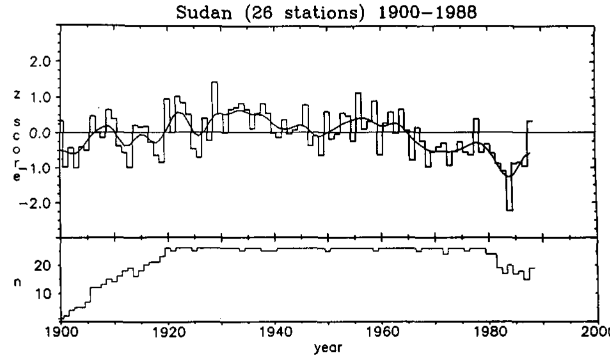

FIG. 2. Same as Fig. 1 but for Hulme's (1990) Sudanese network.

the index in the event that data were missing." This problem affects all of the published Sahelian rainfall time series because of the scarcity in the region of reliable station series containing long uninterrupted rainfall records. One way to overcome the problem is to preprocess the data by replacing all missing data with estimated values. This solution is only advisable if the missing observations are scarce and well scattered and is a suboptimal remedy for changing station networks.

For the purpose of monitoring Sahelian rainfall three key station networks have emerged, each of which maintain near-current data and for which regularly updated annual indices are published. These are the networks maintained by Nicholson (1979, 1983, 1985, and 1989) for the whole Sahelian region (118 stations), the West African network (20 stations) maintained by Lamb (1978, 1982, 1983, and 1985; cf. Fig. 1), and the Sudanese network (26 stations) maintained by Hulme (1987a, 1987b, and 1990; cf. Fig. 2). Time series from these networks give a very good general picture of Sahelian rainfall variations over the twentieth century. However, because of changing network configurations and gaps in the time series from individual stations, they cannot be used for a more precise quantitative comparison of the severity of anomalies for different years. In particular, this makes confidence intervals for the yearly RAI values difficult to determine. This becomes most apparent when attempting to compare recent dry years with those that occurred earlier this century.

A qualitative assessment of the significance of deviations from the mean has been attempted by some authors. Lamb (1983) used the percentage of individual stations having a departure larger, in an absolute sense, than a specified number of standard deviations, where the departure was in the same direction as the RAI departure. Katz and Glantz (1986) used a similar approach and used the percentage of stations above/below average rainfall. Finally, Hulme (1987b) used a nonparametric approach and used the median instead of the arithmetic mean when forming the area averages

TABLE 1. List of station names and their WMO station numbers for the three networks. Where station number begins with 99, no WMO code is known and the number refers to that used in the Climatic Research Unit precipitation dataset. Years where one or more monthly totals are missing are shown in parentheses.

West Africa (12 stations)	Sudan (13 stations)	Sweden (15 stations)
610240 Agadez (1942)	627210 Khartoum F/C	20760 Uppsala
610900 Zinder-Aero	627300 Kassala	24180 Karlstad
612230 Tombouctou	627500 Ed Dueim (1972)	24330 Falun (1982, 1983)
612260 Gao	627510 Wad Medani	24360 Örebro (1988)
612650 Mopti	627520 Gedaref	24460 Västerås
614970 Bamako-Senou	627600 El Fasher	24530 Gävle
614970 Nema	627620 Sennar	25211 Vänersborg
616000 Saint-Louis	627710 El Obeid	25330 Skara
616120 Podor (1926, 1927)	627720 Kosti	25760 Västervik
616410 Dakar-Yoff (1945, 1946)	627810 En Nahud	25900 Visby
650460 Kano	627900 Nyala	26040 Halmstad
655100 Bobo-Dioulasso	994112 Bara (1987)	26180 Lund
	994116 El Geteina (1981)	26400 Växjö
		26491 Karlshamn
		26720 Kalmar

and included upper and lower quartiles to determine an intraannual spatial variability.

In the present study we will use two almost complete datasets from stations selected from the networks of Lamb and Hulme to calculate annual time series of RAI for West Africa and Sudan, respectively. Each RAI value is a point estimate (in the statistical sense) of the corresponding true area average (in the hydrometeorological sense). For each RAI value we calculate an approximate confidence interval. The time series of RAI and its associated upper- and lower-confidence limits are subjected to various filters. Finally, we combine various filtered and unfiltered time series and outline how such combinations can be used as tools for interpreting RAI time series and for gaining useful information about climatic variability.

2. Data and methods

a. Data

Restricted station networks were selected from Lamb's West African network and Hulme's central Sudan network so as to minimize the proportion of missing data while retaining as wide a coverage as possible. In order to retain a useful network, a few missing annual totals had to be accepted (5 out of 768 for West Africa and 3 out of 897 for Sudan). Generally, missing data are more common toward the earlier and later parts of the available datasets. Consequently, selection of a restricted network is a balance between the number of possible stations, the amount of missing data, and the period of analysis. The very few remaining missing totals in the two resulting datasets were accounted for by omitting missing data and adjusting the value for n in the equations. This is, in effect, the equivalent of replacing the missing data with the mean of the other totals.

To enable comparisons with an annual RAI from a temperate climate a third network was selected from southern Sweden. This dataset contains three missing annual totals out of 1920. The stations included in each dataset are listed in Table 1, and maps of the station distribution are given in Fig. 3. All data are

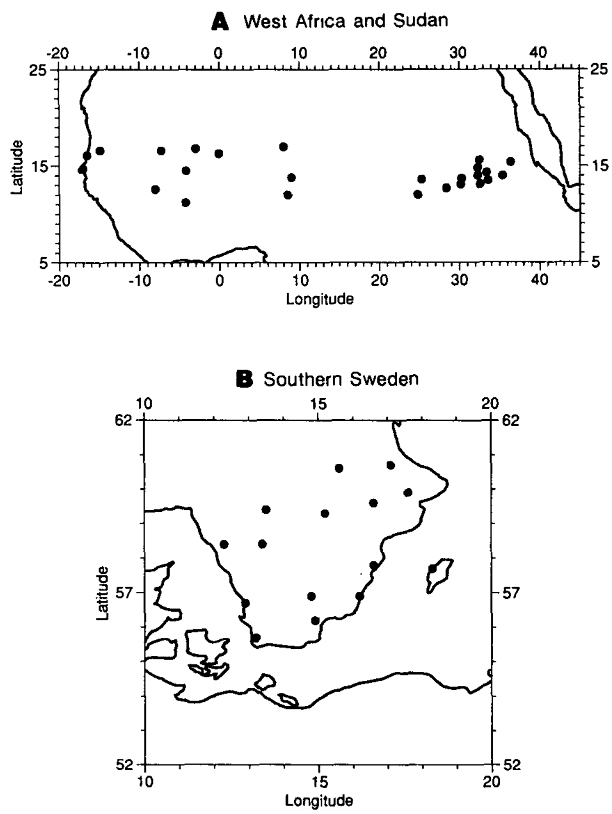

FIG. 3. Maps showing the spatial distribution of stations for the three networks used in this study. (a) West Africa (12 stations) and Sudan (13 stations) (b) Southern Sweden (15 stations).

taken from the global precipitation dataset maintained by the Climatic Research Unit. In this study annual totals are used for all networks, in line with the work of Nicholson and of Hulme. Lamb uses inclusive seasonal totals for April to October, which in Sahelian West Africa virtually corresponds to the full duration of the rainy season.

The raw rainfall data were normalized using (2) and averaged to yield one time series of annual RAI values for each dataset. In order to make the three different series directly comparable, the reference period 1925–84 was selected for the normalization despite the fact that this period is not the same as used by the original authors. Lamb used the reference period 1941–74, and later 1941–82, and Hulme used 1921–80. With the assumption of constant variance over time, the different reference periods will result only in a change of level.

b. Calculation of confidence intervals

The calculation of confidence intervals is based on the procedure of Wigley et al. (1984). They use the following model:

$$W_{ij} = \mu_j + e_{ij} \tag{4}$$

where

W_{ij} is the quantity of station i and year j,
μ_j is the systematic effect of year j, and
e_{ij} is the local and random effect of station i and year j.

The model is assumed to be homoscedastic, i.e., the variance of e_{ij} is assumed constant over time. If we take W_{ij} to be the unnormalized rainfall total, a more appropriate model would be

$$W_{ij} = \theta_i + \mu_j + e_{ij} \tag{5}$$

where θ_i is the systematic effect of station i.

However, by using rainfall totals normalized by (2), the term θ_i is superfluous, and (5) reduces to (4). The RAI provides a point estimate (in the statistical sense) of the parameter μ, which is the true area average. Jones (1989) extends the work of Wigley et al. (1984) and arrives at the following approximation for the standard error (SE) of W, which in the present situation is the RAI, based on n stations [cf. his Eq. (12)]:

$$\mathrm{SE}_n = \left[\frac{\bar{s}_i^2}{n} \cdot (1 - \bar{r})\right]^{1/2} \tag{6}$$

where

$\bar{s}_i^2$ is the mean over all stations of the temporal variance of rainfall,
n is number of stations,
$\bar{r}$ is the mean interstation correlation, excluding the elements where there is perfect correlation (i.e., the diagonal in the correlation matrix).

This procedure assumes that the stations are evenly distributed over the area of interest. In (6) all summations are performed over the whole data period. The confidence limits were calculated using the standard formula for a Gaussian distribution: thus,

$$\bar{X} \pm z_\alpha \cdot \mathrm{SE}_n \tag{7}$$

where SE_n is calculated using (6) and z_α is the standard normal deviate.

The assumption of a Gaussian distribution was checked using a test essentially equivalent to the Shapiro–Wilks W test, the exact details being given in Ryan and Joiner (1976). For all three datasets the null hypothesis of a Gaussian distribution was accepted at the 5% level, which is in agreement with the conclusions of Nicholson and Entekhabi (1986) and Katz and Glantz (1986).

The procedure for calculating a confidence interval for the RAI yields only an approximate result. This is so because the calculation of standard errors (6) requires the stations to be evenly distributed throughout the study area, a requirement not adequately met in either network. Furthermore, the covariance structure of the rainfall field is not known with any precision. Nevertheless, these approximate confidence intervals can be used to compare different years within the same time series.

c. Filtering procedures

The time series of the annual RAI and its upper and lower confidence limits (henceforth, denoted RAW) were subjected to different filters for exploring various aspects of rainfall variations at different time scales. Following Mitchell (1966), we use a binomial-weighted filter for removing short-term fluctuations. A filter window of 9 years (henceforth 9BI) effectively removes fluctuations shorter than about one decade. In order not to lose data at the ends of the time series they were padded by "mirroring" data points from inside the series. For the 9BI the mirroring required is four terms at either end. Such a padded filter has previously been used by Farmer and Wigley (1985) and Hulme (1987a). Also, we use a 30-yr retrospective running mean with uniform weights (henceforth 30RU). This noncentered filter can be regarded as producing an annually updated WMO 30-yr reference period average, i.e., an average is formed using equal weights from the 30 most recent years. The WMO standard normals are defined for consecutive 30-yr periods (1901–30, 1931–60, etc.) and are complemented by an additional definition of provisional normals if at least 10 years worth of data are available (WMO 1989).

These two filters (9BI and 30RU) are not strictly comparable. The 9BI is centered and, consequently, uses "earlier" as well as "future" observations, whereas 30RU is totally retrospective and uses only earlier observations. These two particular filters were chosen because centered binomial filters having a window size of 5 to 11 terms are commonly used in the literature, and the 30RU filter is of particular interest since it produces a time series of annually updated 30-yr means. We stress that these two filters are only examples, and that there are numerous possibilities for selecting combinations of window size, lag, and weighting schemes to meet the requirement of any particular application. Todorov (1985), for example, criticizes the often mechanical and uncritical acceptance of WMO standard normals as descriptors of current rainfall conditions in the Sahel region and notes that they are often of limited use for many practical applications. He suggests instead that the most recent data available should be used, either based on a fixed period length or only using data since the decline in rainfall commenced. Although he did not discuss the matter in terms of filters, the suggestion to base a climatic mean using only the most recent years is in effect the same as our 30RU filter.

The predictive capabilities of retrospective filters of various lengths have been investigated by several authors. For example, Lamb and Changnon (1981) applied the method to precipitation and temperature data from Illinois and conclude that 5-yr normals often provide the best predictions while 20-yr to 30-yr normals performed consistently worse. Subsequently, Dixon and Shulman (1984) pointed out some limitations in the method of Lamb and Changnon for assessing forecast skill and concluded that by using a more conservative method of assessing skill 15-yr to 30-yr filters performed better than short-term filters. A further study was carried out by Sabin and Shulman (1985). Quinlan (1986), in a critical comment on Todorov's (1985) paper, cautions against the use of only updated 30-yr (or shorter period) averages for any use other than a best guess of next year's performance. Instead, he advocates the use of all available data. More recently, Karl (1988) used ARMA models in a study of variations in United States seasonal and annual rainfall. He points out that significant decadal fluctuations are often embedded in the 30-yr averages and concludes that the normals should be complemented by other statistical methods more appropriate for modeling variations. It is not our intention, however, to use the filters as a method for forecasting future rainfall in the Sahelian region. On the contrary, we will use them only to reveal more precisely what has already happened.

It is worth pointing out that when the time series of confidence limits are filtered they lose their property of being confidence limits. Instead, we suggest the following interpretation as being useful. As we are assuming a Gaussian distribution, the unfiltered RAI time series (RAW) represent the 50th percentile (median) and the lower and upper confidence levels represent, respectively, the 2.5th and 97.5th percentiles. By adopting this interpretation of the confidence levels, filtering the confidence levels can be justified on exactly the same grounds as filtering the RAI time series. For simplicity we will continue to use the term "confidence levels" when referring to time series of the filtered percentile values.

3. Results

The time series resulting from the aforementioned calculations are shown in Figs. 4 to 6. These figures include equivalent selections of graphs, but for the three different networks. The time series of the spatial standard deviations are plotted in the top diagram to provide background information. The mean spatial standard deviation over the whole data period is indicated by the horizontal line. This value is surprisingly similar over the three networks; 0.75 in West Africa, 0.8 in Sudan, and 0.7 in Sweden. The different spatial extent of the three networks may mask differences between the spatial variability of rainfall between the tropical and temperate regimes. The maximum interstation distance for the West African and Sudanese datasets, respectively, are 2855 km and 1307 km, compared to 600 km for the Swedish network.

In the following paragraphs we will restrict our attention to the two African networks and defer a comparison with the Swedish network until the discussion. The graphs of the RAW RAI values and their confidence limits (second from top) show which years deviate significantly, in a statistical sense, from the reference period average. The transitions toward generally drier conditions in the mid-1960s suggested by numerous studies and recently found statistically significant by Snijders (1986), Hubert and Carbonnel (1987), and Demarée and Nicolis (1990) are clearly visible in both regions. In Sudan, 1984 stands out as extremely dry with a z-score of -2.21 compared with a z-score of about -1.0 for other recent dry years (Fig. 5b). In West Africa the driest year was 1983 ($z = -1.65$) with 1984 only slightly wetter ($z = -1.36$). In West Africa the 1950s are significantly wetter than the reference period average (Fig. 4b). In Sudan, this decade is not so wet, although there are three scattered wet years. For the period 1925–40 the situation is reversed; Sudan is comparatively wet throughout while West Africa has only four scattered wet years.

Despite these initial conclusions, interpretation of the graphs of RAW time series is hampered by the high frequency variability of both mean and confidence levels. It would be useful to use mildly smoothed time series of confidence levels when interpreting the rainfall performance of single years and short periods. To illustrate this we have graphed the RAW RAI time series together with the 9BI-filtered confidence limits in the third diagram from the top. This graph now shows the features of the RAW graph in a clearer manner and enables a more precise interpretation of the significance of the departures of single years and decades. For example, the 1950s in Sudan are not significantly wetter

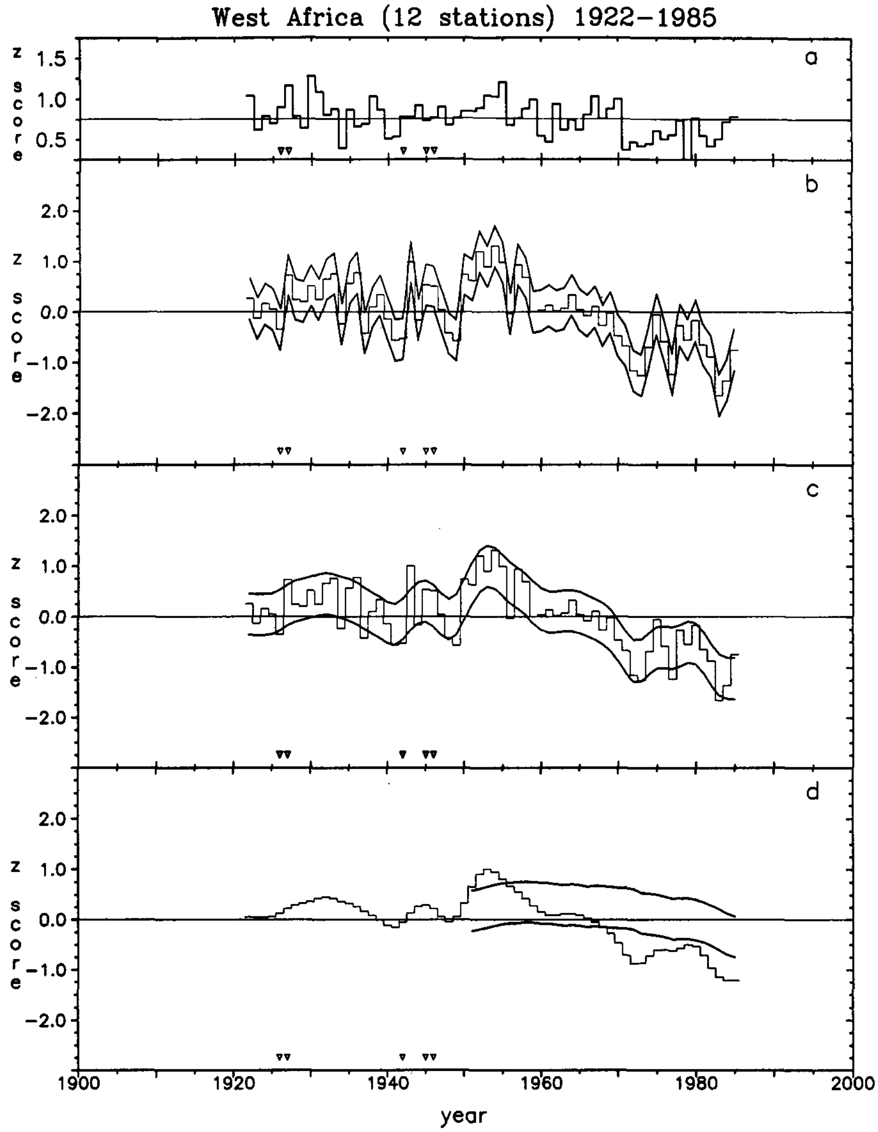

FIG. 4. Time-series graphs of the spatial standard deviation (a) and some combinations of unfiltered and filtered rainfall anomaly indices and corresponding confidence limits for the West African network: (b) staircase line: unfiltered RAI; heavy lines: unfiltered 95% confidence levels. (c) Staircase line: unfiltered RAI; heavy lines: 9BI-filtered 95% confidence levels. (d) Staircase line: 9BI-filtered RAI; heavy lines: 30RU-filtered 95% confidence levels. See text for definitions of filters. In the top graph (a) the horizontal line indicates the mean over the whole data period, while in the other graphs the lines indicate the mean for the reference period only. The inverted triangles indicate years where data were missing for one or more months.

at the 2.5% level than the reference period average (Fig. 5c). This kind of smoothing is exactly what is desired. When interpreting rainfall variations on a decadal or shorter time scale one does not want a judgment based on a few scattered significant deviations. A further advantage with this kind of graph is that it is possible to compare the rainfall during individual years with prevailing decade-scale rainfall conditions. Since a centered filter is used, it will not be possible, however, to use this method to assess the rainfall for the current or immediately preceding years because there will always be a lag of half the filter length between obtaining a yearly index value and the appropriate smoothed confidence interval. In an operational application of such indicators it would be more useful to replace the 9BI filter with some kind of retrospective filter.

Finally, the bottom graphs extend the possible interpretation still further. Here, we have combined the 9BI-filtered time series of RAI with 30RU-filtered series of confidence limits. In these graphs the decline in

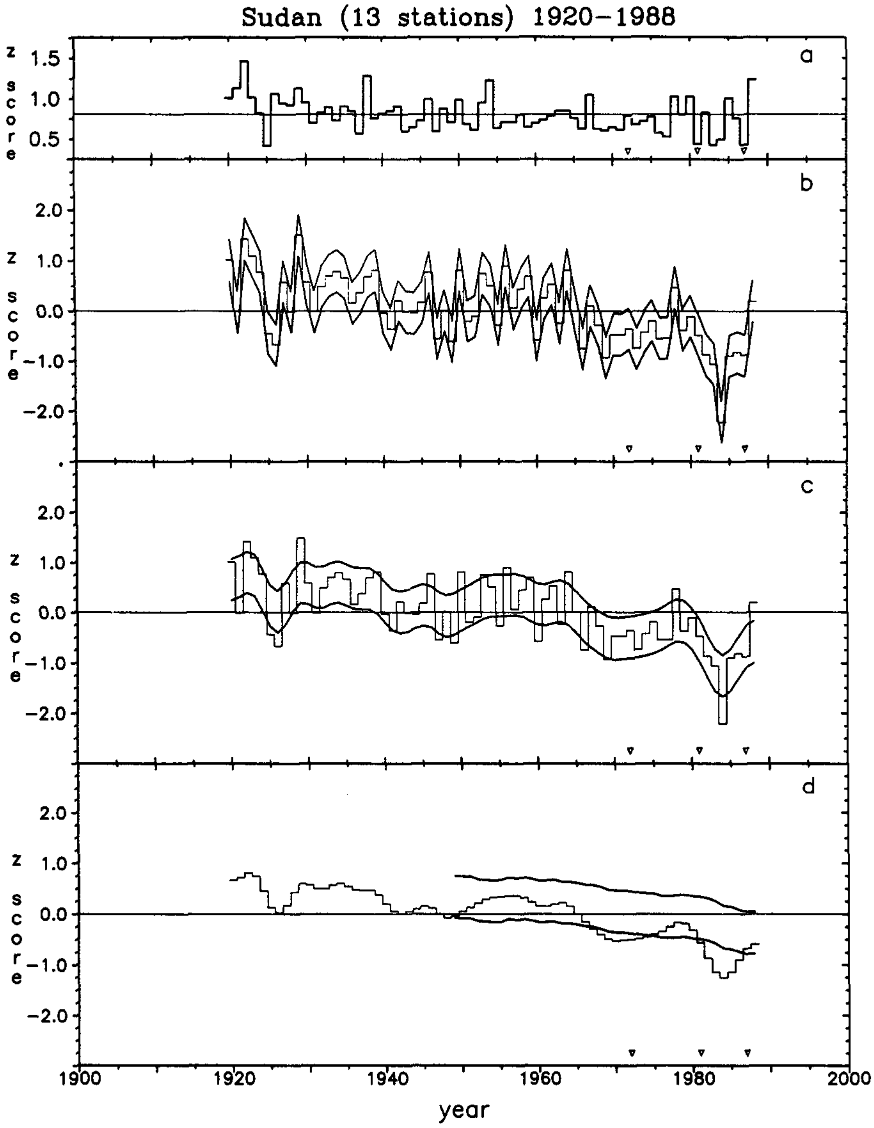

FIG. 5. Same as Fig. 4, but for the Sudanese network.

rainfall is more evident than in either of the previous two graphs. The 9BI-filtered RAI series for Sudan shows a number of fluctuations, but an overall trend toward drier climate throughout the whole period (Fig. 5d). The curves of the corresponding 30RU-filtered confidence limits, which start in 1948, accentuates this picture. In 1948 the lower confidence limit was close to the reference period average, but by 1988 this had changed so that the upper confidence limit now lies close to the reference period average. If this downward trend continues, the upper level will drop below the reference period average within a few years. If this were to happen, then the most recent 30-yr average will be significantly different from the reference period average. On the other hand, if wetter conditions return to central Sudan it will take several years to restore the updated 30-yr mean to the level of reference period average. It is also interesting to study the relationship between the 9BI-filtered RAI and its 30RU-filtered confidence limits. The RAI curve stays within the confidence limits until the mid-1960s, when it drops below until the mid-1970s. It then returns to within the confidence limits and stays there until about 1980. The marked drop between 1980 and 1986 is, of course, largely caused by the extremely dry 1984, although for the whole of that period the 9BI-filtered RAI was below the 30-yr confidence limit.

The picture is broadly the same for West Africa. The 9BI-filtered RAI curve shows a marked peak during the 1950s and a general trend downward since then with only a slight recovery in the late 1970s. The 30RU-filtered confidence limits start in 1950 with a positive

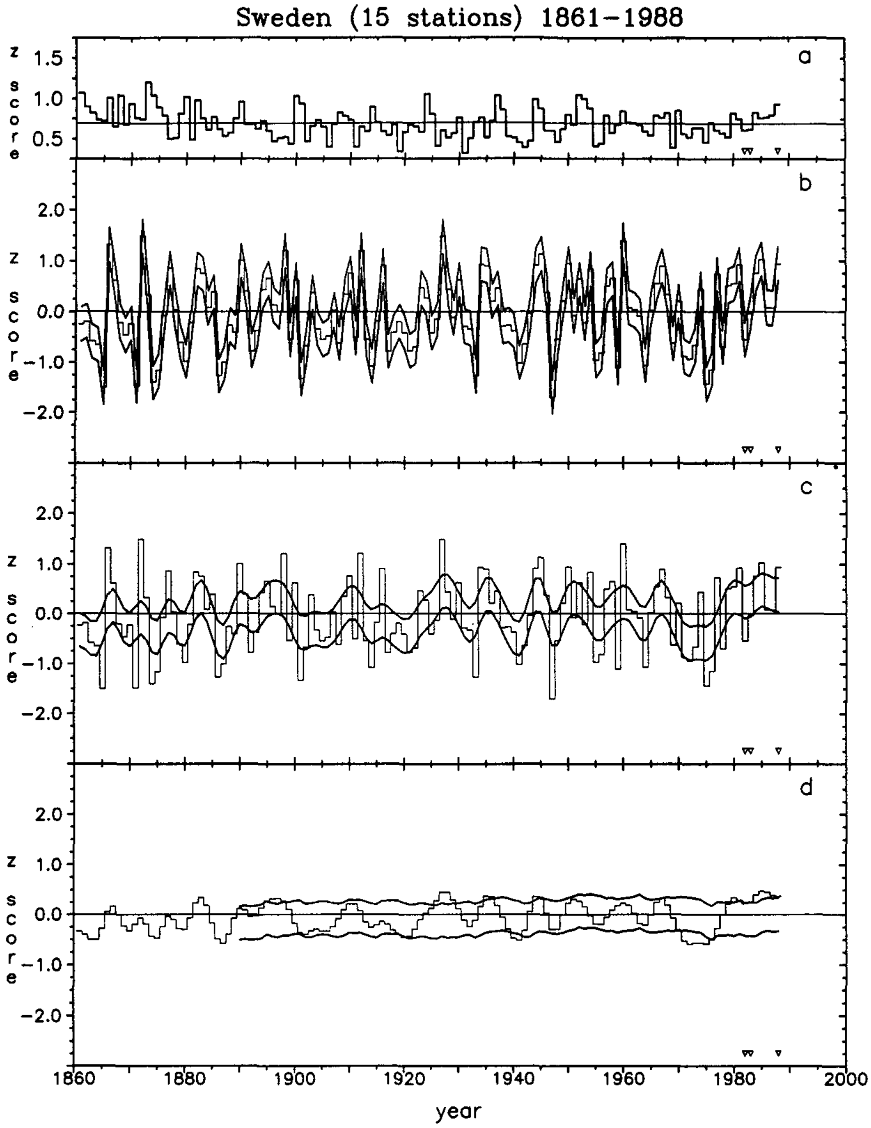

FIG. 6. Same as Fig. 4, but for the Swedish network.

trend which smoothly changes to a downward trend by the late 1950s. At the highest point the lower confidence limit is close to the reference period average, but as in Sudan the situation in 1988 is that the upper-confidence limit lies close to the reference period average. The peak in the RAI curve during the 1950s is well above the confidence limits, but in the mid-1960s the RAI curve drops well below the lower 30-year confidence limit. Since then it has stayed below the limit, failing to match the late 1970s recovery that occurred in Sudan.

4. Discussion

The method outlined previously for constructing and presenting time series of RAIs and associated approximate confidence intervals possesses several advantages over the more common approach of calculating and using RAIs for assessing regional rainfall variations.

First, by selecting only stations having an almost complete data record, we obtained a network and a resulting RAI time series that were consistent over time. The advantage of this is that RAI values for different years can be compared quantitatively with better precision. The drawback is that the requirement of no missing data restricts the number of stations and the time period available for analysis. In practice, as in this study, one often has to accept a few scattered missing data. As long as only a very small portion of the data are missing, and they are not clustered either in time or space, their influence will be virtually eliminated from an annual RAI such as the ones used here. In the context of monitoring climatic variations, the importance of reliable and constant station networks cannot be overemphasized. There is a recent trend among some national meteorological services, not only in Africa, to reduce the number of stations and to replace human observers with automatic equipment in order to achieve greater cost efficiency. These changes have often been planned and evaluated with the needs of operational meteorology rather than climate monitoring in mind. The result is that it is increasingly difficult for climatologists to find still operational regional station networks that have remained consistent over time.

Second, a network consistent over time makes it possible to calculate approximate confidence intervals using the method developed by Wigley et al. (1984) and Jones (1989). The inclusion of confidence intervals stresses that the RAI value is a point estimate (in the statistical sense) of an area average (in the hydrometeorological sense). As with all estimates, it has a certain sampling error which in this particular case is approximated by (6). From a practical point of view this means that there always is a nonzero probability that the estimate is above (below) the long-term mean while the true value is below (above) the mean. As long as the 95% confidence interval contains the long-term mean this probability is less than 5%. This provides the tool for quantitatively distinguishing between significant (at the selected significance level) and nonsignificant deviations from the long-term mean.

Third, by using various filters we have showed how high frequency rainfall variations can be suppressed to reveal longer term variations more clearly. Although this technique is commonly used when presenting RAI time series, by including a confidence interval and using different combinations of filters we have created the means for a novel interpretation of RAI time series.

In our interpretation of Figs. 4 and 5, we have deliberately avoided the terms "climatic variation," "climatic fluctuation," and "climatic change." As mentioned in the Introduction, there are divergent viewpoints about the precise definition of these terms particularly in the context of Sahelian rainfall. The following definitions have been laid down by WMO (1979, p. 752):

- *Climate* is the synthesis of weather over the whole of a period essentially long enough to *establish* its statistical ensemble properties (mean values, variances, probabilities of extreme events, etc.) and is largely independent of any instantaneous state.
- *Climate change* defines the difference between long-term mean values of a climatic parameter or statistic, where the mean is taken over a specified interval of time, usually a number of decades.
- *Climatic variability* includes the extremes and differences of monthly, seasonal, and annual values from the climatically expected value (temporal mean). The differences are usually termed anomalies.

Several features of these definitions should be noted. The commonly used terms "climatic fluctuations" and "climate variations" are not explicitly included among the definitions, instead being encompassed by the general heading of "climatic variability." Second, the length of the time period used for forming mean values is deliberately left unspecified. Finally, as Todorov (1985) points out, a strict use of consecutive long-term mean values would prevent a continuous monitoring of a continuously varying climate. Furthermore, Parkinson (1989) has shown that variations in a time series of consecutive mean values does not necessarily follow the variations in the original time series.

Bearing these three points in mind, we believe that the procedure outlined in this paper points toward possible ways to furnish the details necessary to develop quantitative indicators related to these WMO definitions. To illustrate this idea we return to the interpretation of Figs. 4 and 5. Our basic assumption is that variations at any particular time scale should be judged against the prevailing conditions at a somewhat longer time scale and not against an overall mean. This is in line with Todorov's (1986) reply to Quinlan's (1986) criticism and, also, the climate monitoring procedure advocated by Craddock (1981). For example, the anomaly of individual years should be judged against the prevailing climate on a decadal time scale. The following tentative indicators were developed:

- *Anomalous years* are years when the RAW RAI value extends outside the 9BI-filtered confidence interval.
- *A climatic fluctuation* occurs when the 9BI-filtered RAI value extends outside the 30RU-filtered confidence interval.
- *A climatic change* occurs when the 30RU-filtered confidence interval does not contain the long-term mean value.

We immediately point out that these tentative indicators are not internally consistent. For example, the 9BI filter is a centered filter while the 30RU filter is totally retrospective, and climatic change is indicated when a filtered confidence interval does not contain a long-term mean while the other two indicators are designed the other way around, namely, when a (filtered) mean value extends outside a long-term filtered confidence interval. However, it is not our current intention to develop definitive and consistent indicators, but merely to suggest different ways of developing such indicators.

Despite these shortcomings it is interesting to apply the preceding indicators to Figs. 4 and 5. In doing so we find that in West Africa (cf. Fig. 4) there have been some anomalous years; 1927, 1936, 1943, and 1975 stand out as wet years while 1926, 1934, 1937, 1949, 1956, 1977, and 1983 were dry years. The wetness of the 1950s should be regarded as a climatic fluctuation, and as yet the transition toward drier conditions since the mid-1960s is one continuous climatic fluctuation, which commenced in 1968. Through 1985 there had not been any climatic change, but if the dry fluctuation continues for only a few more years this would occur.

The graph of the unfiltered time series (Fig. 4b) shows that during the last few years there has, however, been a recovery toward somewhat wetter conditions. The interpretation of the Sudanese data (cf. Fig. 5) is slightly different. There are more anomalous years; 1922, 1929, 1946, 1950, 1956, 1964, 1978, and 1988 were wet years, while 1921, 1924, 1925, 1931, 1947, 1949, 1955, 1960, 1966, and, in particular, 1984 stand out as dry. The transition toward drier conditions during the last few decades shows up as two climatic fluctuations; one 1967 to 1974 and the other 1981 to 1986. As in the case of West Africa, no climatic change can be detected thus far (to 1988), although only one or two more dry years would alter this conclusion. Of the last two years in Sudan (not shown), 1989 was slightly below the 1925–84 average and 1990 was an anomalously dry year. The use of indicators based on our methodology seem to corroborate well-established knowledge based on more subjective interpretations of Sahelian rainfall, but provide an unambiguous and consistent basis for such knowledge.

In order to be useful, the proposed indicators must not be relevant only to one specific climatic regime, but be applicable to various climates and regions. We therefore applied the same methodology to data from the southern Swedish network, cf. Fig. 6. A conspicuous feature of the RAW time series is the pronounced high frequency variations. This is an effect of Sweden being situated under the polar front where the cyclone tracks display high interannual variability. This results in an abundance of anomalous years, that makes the anomalous years indicator somewhat unsuitable for this region; a negative autocorrelation over a lag of one or a few years is not accounted for. A number of climatic fluctuations were also singled out; for example, the latter part of the 1890s were wet, as was the latter part of the 1920s, while a few years around 1940 were dry. However, the most pronounced climatic fluctuation occurred during the 1970s, which are well known to be dry (S. Bergström, SMHI, personal communication 1990), while the mid-1980s have seen a wet fluctuation. Finally, there are no signs of a climatic change in our Swedish dataset. On the contrary, the 30RU-filtered confidence interval is well centered around the long-term mean. Although our suggested indicators pick out some relevant features, they are not ideally suited to the southern Swedish rainfall series.

5. Conclusions

We have drawn attention to a problem intrinsic to the time series commonly used for assessing temporal variations in Sahelian rainfall; namely, those used by Lamb (1985), Nicholson (1989), and Hulme (1990), cf. Figs. 1 and 2. The problem is caused by scattered missing data and stations being opened or closed during the study period. This makes the station network inconsistent, which means that the deviations from the mean for different years are not directly comparable. To circumvent this problem and obtain almost complete datasets we selected slightly shortened study periods and subsets of stations. This enabled us not only to make more quantitative comparisons of anomalies (RAI values) for different years, but by using a technique developed by Wigley et al. (1984) and Jones (1989) we were also able to compute time series of approximate confidence intervals for the RAI values, cf. Figs. 4b and 5b.

To remove high frequency fluctuations and concentrate on the decadal and longer time scales we applied a 9-yr binomial-weighted filter to the time series of RAI values and lower and upper 95% confidence limits. Furthermore, to study the effect of using an annually updated WMO reference period (i.e., an average calculated over the preceding 30 years) we applied the less common 30-yr retrospective filter with uniform weights to the three time series. The result of these two filtering operations are shown in Figs. 4c, 4d, 5c, and 5d. By comparing the RAI time series filtered by one method with the confidence interval filtered by another method we were able to identify quantitatively several pertinent features of recent variations in the Sahelian rainfall climate. Individual anomalous years were readily detected in Figs. 4c and 5c. The wetness of the 1950s in the West Africa Sahelian region stands out clearly in Fig. 4d and, in the same way, the two recent droughts in Sudan are easily detected in Fig. 5d. Based on these results we suggested a framework for how quantitative indicators for the terms anomalous year, climatic fluctuation, and climatic change could be developed. Also, in order to study the performance of the technique in a different climate, we carried out a similar analysis of a comparable annual RAI for southern Sweden. The anomalous year indicator did not perform well, although we were able to identify several fluctuations and to support the notion of a basically constant annual rainfall climate in southern Sweden over the last 100 years (Alexandersson and Eriksson 1989).

Our final conclusions are as follows.

- The technique in its present form can be very useful for interpreting RAI time series in Sahelian Africa and for assessing the impact of climate on water and other resources.
- Further developments of this technique need to address the basic problems of how best to calculate area-average rainfall, possible where some data are missing, and how best to estimate the standard errors. This could include spatial interpolation methods such as kriging (Lebel et al. 1987), or methods based on pooling information from different time series that are based on networks partially overlapping in space or time.
- In order to be useful as indicators of anomalous years, climatic fluctuations, and climatic changes the technique needs to be refined and developed further. This could include further scaling or standardization of the rainfall anomalies.

• Despite these possibilities of more refined climate monitoring techniques which cope better with missing data and network inconsistencies, the requirement of station continuity and network consistency for climate monitoring must be given a much higher priority when pruning and optimizing meteorological networks.

Acknowledgments. The Climatic Research Unit (CRU) dataset has been compiled with support from the U.S. Department of Energy and the U.K. Department of the Environment. The African data are based on data available from NCAR and originally collected by S. E. Nicholson, extensively updated and extended by the CRU with more recent data. We thank a number of national meteorological services and individuals for providing much additional data. In particular, we thank P. J. Lamb for supplying recent data for West Africa. Also, we thank P. D. Jones for very useful discussions, and P. J. Lamb and two anonymous reviewers for suggesting very useful improvements to the text. MH's work was supported by the U.K. Department of Environment. LB's work was made possible by a postdoctoral fellowship from the Swedish Natural Sciences Research Council, and the generosity of the Climatic Research Unit in hosting his 1-yr secondment.

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