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Climatology of Dust Sources in North Africa and the Arabian Peninsula, Based on *TOMS* Data

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Key Words
Dust sources • Aerosol index • *TOMS* • North Africa

Abstract
Aerosol Index (*AI*) values from the *TOMS* instrument were used to compute *AI* climatology in Africa north of the equator and in the Saudi Arabian desert (30°W–60°E, 0°–50°), for the period 1979–1992. Monthly and annual averages are presented for the whole area as well as for 9 other source areas.

The highest *AI* values were found in the summer months of May, June and July. The area around lake Chad has the highest value and, contrary to the other sources, is active throughout the year. The first 4 years of the research period has a significantly lower index value as compared with the later years. There is a sharp discontinuity between the years 1982 and 1983 in the western sources and a more moderate increase in the eastern sources. Two periods with very high *AI* values are identified, namely 1983–1984 and 1987–1988, while the year 1986 had a low index value. In 1991 and, to a lesser extent, in 1992, very high *AI* values were obtained in the eastern sources.

Introduction

The climatology of dust storms in the Middle East at a monthly time scale has been presented by Middleton [1] and more recently by Kutiel and Furman [2]. In both studies, averages were presented, but not the variability from year to year.

Starting in 1979, the Total Ozone Mapping Spectrometer (*TOMS* hereafter) provided daily dust measurements. Although originally it was intended to measure ozone, the spectral contrast between 340 nm and 380 nm wavelengths in the UV part of the spectra, may yield the Aerosol Index. The difference between measured contrast and calculated contrast for an *all-gaseous* atmosphere without Mie scattering is called the Aerosol Index (*AI* hereafter) and serves as an estimation of the amount of dust [3]. The greatest advantage of the *TOMS* is that, due to the very low and steady albedo of the UV above land, it is able to measure dust both above land and sea [4]. It is the only instrument measuring dust having these capabilities since 1979. However, near the ground, the *AI* measurements may be less reliable.

TOMS was mounted on the *NIMBUS-7* satellite and worked up to the end of the latter's active life in April 1993. Since 1996, another *TOMS* instrument has been mounted on the satellite *TERRA* and it is still active [5]. In this work we have used only the former *TOMS* data

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collected between 1979 and 1992 in order to maintain uniformity.

Recently, *TOMS* measurements were employed over Africa, central Asia, the Atlantic Ocean and South America, mainly by Middleton [1], Herman et al. [3], Prospero et al. [4], Hsu et al. [5], Herman and Celarier [6] and Moulin et al. [7]. In this work we have calculated some basic climatologies from the *TOMS* database between 1979–1992 for North Africa, north of the equator and the Saudi Arabian desert, which contains the largest and most active sources of dust on earth. Such statistics may serve as a starting point for further researches.

Table 1. Activity centres of dust sources in North Africa and Saudi Arabia (after [4])

Source area	Longitude	Latitude
Mauritania	15.5°W	18.0°N
Mali	6.0°W	18.7°N
Chad and Bodele Basin	16.5°E	16.5°N
Tunisia	7.5°E	33.5°N
Eastern Libya	18.7°E	24.5°N
Sudan	28.3°E	19.0°N
Ethiopia–Djibouti	40.6°E	14.3°N
Saudi Arabia	48.7°E	25.4°N
Oman	55.5°E	19.5°N

Methodology

The study area of the present work is delimited by the 30°W and 60°E meridians and by the 0° and 50°N parallels (Figure 1). Within this area, Prospero et al. [4] identified nine source areas as part of a review of dust sources around the globe. In every source area the highest *AI* value and its exact longitude and latitude were identified for every month during 1979–1992. Averaging the longitudes and the latitudes we deduced the approximate centre of activity of the sources presented in Table 1.

Monthly averages were calculated from the daily *AI* values. Using these 14 annual averages, we obtained the mean value for each month along the year, for the entire work period. Altogether, 434, 420 or 396 data points were used to obtain average values for each month, according to the length of each particular month.

$$AI_{ij} = \sum_{k=1}^{n} d_k / n \tag{1}$$

$$\overline{AI}_i = \sum_{j=1}^{14} A_{ij} / 14 \tag{2}$$

where AI_{ij} s the mean value of the month i, d is the daily value and k is the day in the month, $\overline{AI}_{ij}$ is the 14-year mean value for the month i and n is the number of the days in that month.

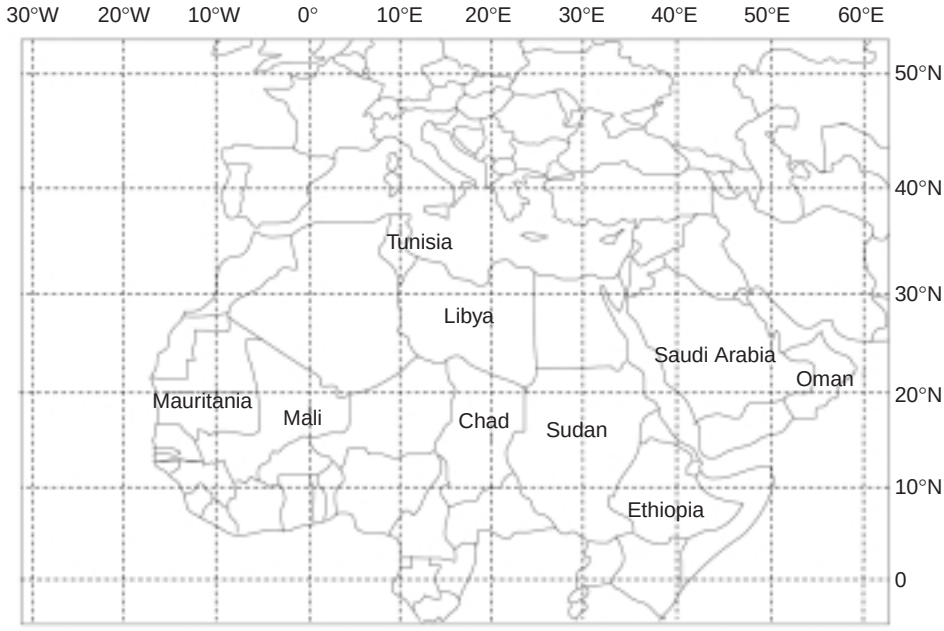


Fig. 1. Location map showing the main dust sources.

Annual averages were calculated from averaged monthly values of every year.

$$\overline{AI}_j = \sum_{i=1}^{12} A_{ij}/12 \quad (3)$$

where $\overline{AI}_j$ is the mean value of the year j.

Monthly means were standardised as follows:

$$z_{ij} = (AI_{ij} - \overline{AI}_i)/\sigma_i \quad (4)$$

where z_{ij} is the standardised value of AI in the month i, of year j, and σ_i is its standard deviation.

These calculations were performed for the entire research area and for each source area separately.

Results and Discussion

Figure 2 shows the distribution of the aerosol index by months and years for the entire research area. The maximum values are in the summer months of June and July from 1983 until the end of the research period. The values are particularly high in the years 1983–1985 and 1988–1992. The clearest months are October–December. The other winter and spring months are also quite clear, especially during the years 1979–1982.

Figure 3 represents the annual averages of the whole research area. The difference between the early years, 1979–1982, and the later period is very clear. The AI values in these later years were considerably higher. Figure 4 shows the monthly averages of the whole research area. The AI values increase from the winter towards the summer, with the maximum in June and the minimum in November.

Figure 5 shows the annual distribution of AI in the different source areas. The pattern identified for the entire research area is similar to the individual patterns found for the various source areas. One may observe lower values in the years 1979–1982, and higher in the following years, excluding 1986. The peak values are in 1984 and 1988, apart from the most western source of Mauritania where the peaks occurred a year earlier.

The absolute differences between the sources are very prominent. The values of the Chad source are by far the highest along the entire period. The source of Mali is the second highest since 1983. On the other hand, the Sudanian, Tunisian and especially the Ethiopian sources are quite low.

Figure 6 displays the mean monthly values in the

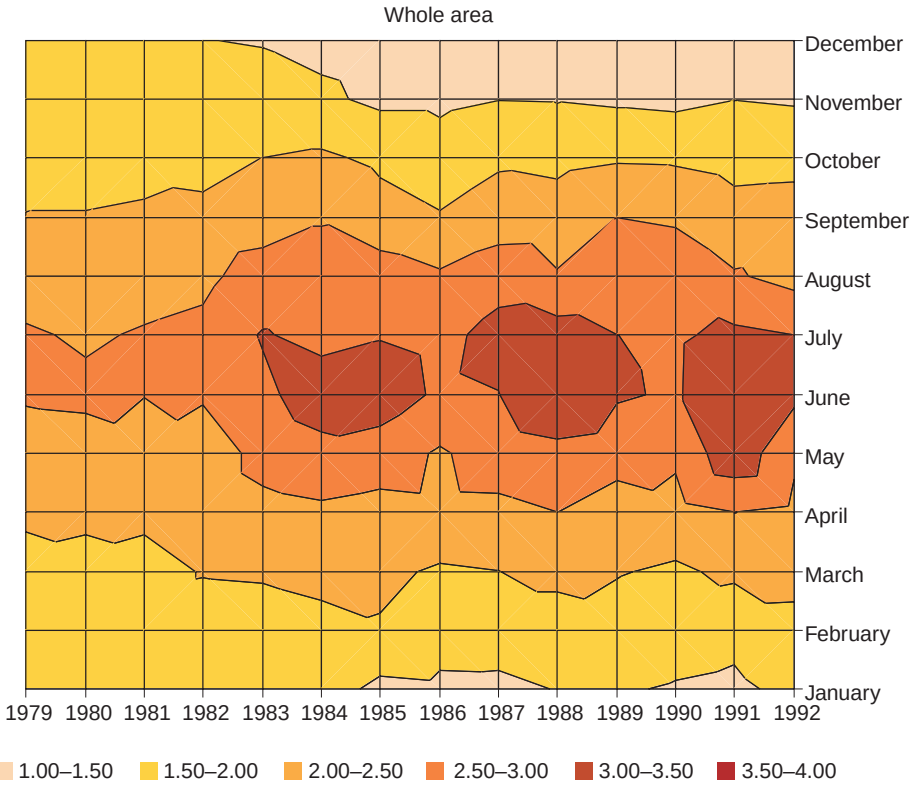


Fig. 2. Distribution of the mean AI by months and years, 1979–1992. All sources.

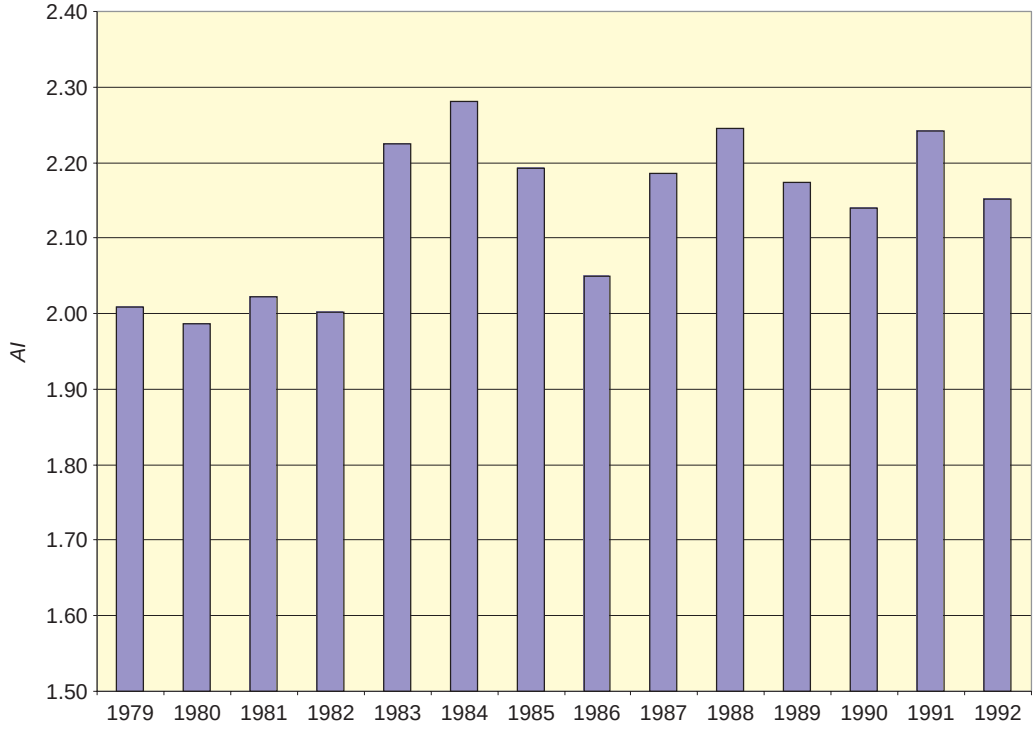


Fig. 3. Mean annual *AI* for the years 1979–1992. All sources.

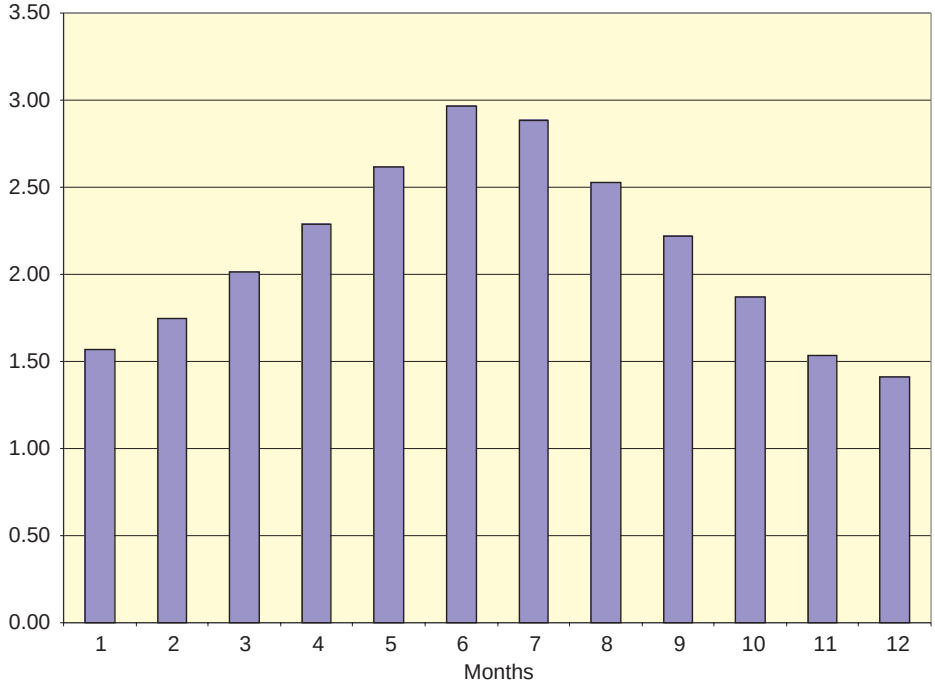
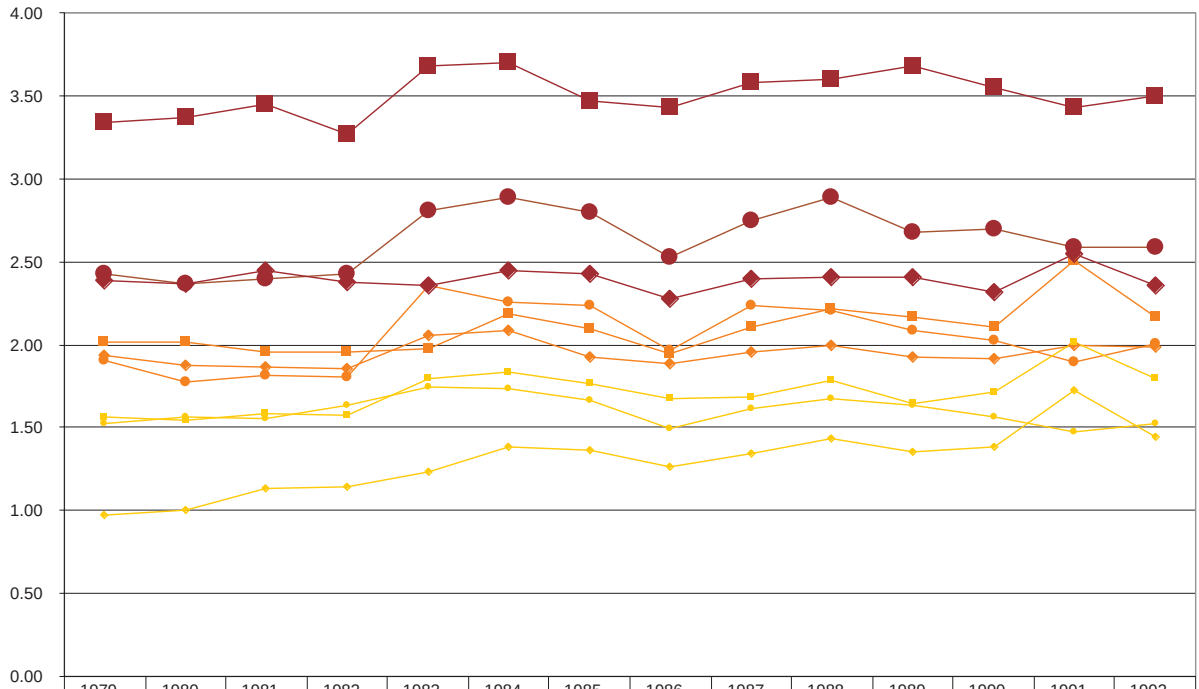


Fig. 4. Mean monthly *AI* for the years 1979–1992. All sources.



	1979	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
Mauritania	1.91	1.77	1.82	1.80	2.36	2.26	2.23	1.96	2.24	2.21	2.08	2.02	1.89	2.01
Mali	2.43	2.37	2.40	2.42	2.81	2.89	2.80	2.53	2.75	2.89	2.68	2.70	2.59	2.59
Tunisia	1.53	1.57	1.55	1.63	1.75	1.73	1.66	1.49	1.62	1.67	1.63	1.57	1.47	1.52
Chad	3.34	3.37	3.45	3.27	3.68	3.70	3.47	3.43	3.58	3.60	3.68	3.55	3.43	3.50
Libya	1.94	1.88	1.87	1.85	2.06	2.09	1.93	1.89	1.95	2.00	1.93	1.91	2.00	1.98
Sudan	1.56	1.55	1.59	1.57	1.79	1.84	1.76	1.67	1.69	1.79	1.64	1.71	2.02	1.80
Ethiopia	0.97	1.01	1.13	1.14	1.24	1.38	1.37	1.26	1.35	1.44	1.35	1.38	1.73	1.44
Saudi Arabia	2.01	2.01	1.96	1.96	1.98	2.19	2.10	1.94	2.11	2.21	2.17	2.10	2.50	2.17
Oman	2.39	2.36	2.45	2.37	2.36	2.45	2.42	2.28	2.40	2.40	2.41	2.31	2.55	2.35

Fig. 5. Annual *AI* at the source areas in the years 1979–1992.

different source areas. In most of the sources the peak values are in June or July with small differences between them. But in two sources, in Chad and in East Libya, the peak value is in May with a secondary peak in April and June.

The Chad source has by far the highest values in winter and during the transitional seasons. In summer, the difference between this and the other sources becomes much smaller and at the source of Mali the value becomes even higher in June, July and August. Contrary to the other sources, the Chad source is active all year around.

Figures 7–15 show the monthly and annual distributions of the *AI* for the various source areas. Two features are common for all source areas: high values during the summer months and the sharp increase of the values after 1982.

1. The Mauritanian Source (Figure 7)

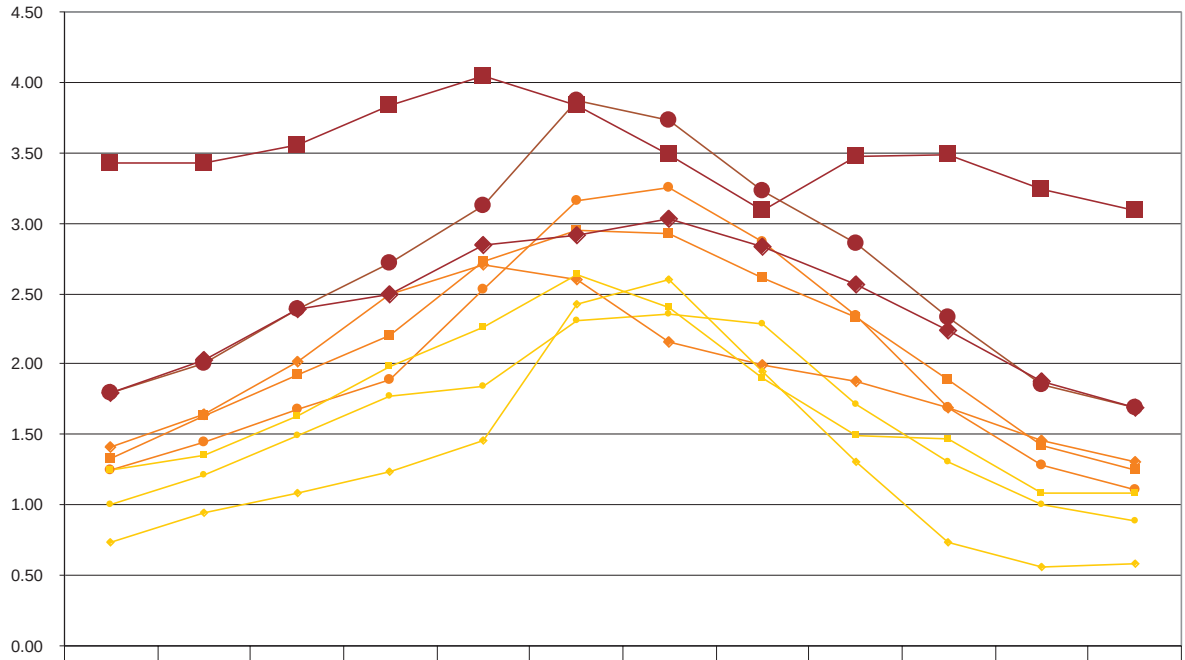
Outstandingly high values were observed in the years 1983–1989, especially in 1985 and 1988. The dustiest months were June and July and also May and August in certain years. In the middle of the dusty period the values of the years 1986 and 1987 were somewhat lower. The sharp increase in the value from 1982 to 1983 is very marked.

2. The Mali Source (Figure 8)

Like the Mauritanian source, a sharp increase in the index values was evident after 1982 and very high values were found between the years 1983–1992, excluding the year 1986. The dustiest months were June and July with high values also in May and August in some years. The absolute values in summer were very high.

3. The Tunisian Source (Figure 9)

Absolute values from this source were low. The dustiest period was relatively short, only from 1983 to 1988 with a peak in 1988. During the years 1986 and 1984 values were relatively low. The low values seen in 1984 are quite outstanding, because in most of the other sources it was a very dusty year. The difference between



	January	February	March	April	May	June	July	August	September	October	November	December
Mauritania	1.25	1.45	1.68	1.89	2.53	3.16	3.25	2.87	2.34	1.69	1.28	1.11
Mali	1.80	2.01	2.39	2.72	3.12	3.87	3.73	3.23	2.86	2.33	1.85	1.69
Tunisia	1.00	1.21	1.49	1.77	1.84	2.31	2.35	2.29	1.71	1.31	1.00	0.89
Chad	3.43	3.43	3.55	3.84	4.05	3.83	3.48	3.09	3.47	3.49	3.24	3.09
Libya	1.41	1.64	2.02	2.50	2.70	2.60	2.16	1.99	1.88	1.69	1.46	1.31
Sudan	1.25	1.35	1.63	1.98	2.26	2.64	2.40	1.90	1.49	1.47	1.09	1.09
Ethiopia	0.73	0.94	1.09	1.24	1.46	2.42	2.60	1.95	1.30	0.74	0.56	0.58
Saudi Arabia	1.33	1.63	1.92	2.20	2.73	2.95	2.93	2.61	2.33	1.89	1.42	1.25
Oman	1.80	2.03	2.39	2.50	2.85	2.91	3.03	2.83	2.57	2.24	1.88	1.69

Fig. 6. Same as Figure 5, but for monthly AI.

the former and the later years are not as prominent as for the other sources. August was dustier than in the other sources.

4. The Chad and Bodele Basin Source (Figure 10)

This source is quite different from the rest. The absolute value was very high not only in summer but in the other seasons as well. The dustiest months were more so during the spring than in summer with peak values in May and in April as a close second. However, there were high values in the autumn and winter months in some years as well. There was almost no differences in this source between the former and the later years of the research period.

5. The Eastern Libyan Source (Figure 11)

The highest *AI* values were in the years 1983–1989 with a peak in 1984 and a low in 1986. The dustiest month was May. The discontinuity seen between 1982 and 1983 is prominent. An interesting point is the high value found in May 1991 which was not evident in the more western sources and, as will be seen, was more prominent still in the more easterly ones.

6. The Sudanian Source (Figure 12)

The dustiest years were from 1983 to 1992 and the dustiest month was June. The peak years were 1988 and especially 1991. The 1986 value, on the other hand, was relatively low. The difference between the years 1979–1982 and the later years was not as sharp as that found in the more western sources.

7. The Ethiopian and Djibouti Source (Figure 13)

The dustiest months were June and July. There was a gradual increase of the values from the earlier years on, but not the sharp discontinuity, eminent in the more western sources. The peak years were 1987 to 1989, especially 1988.

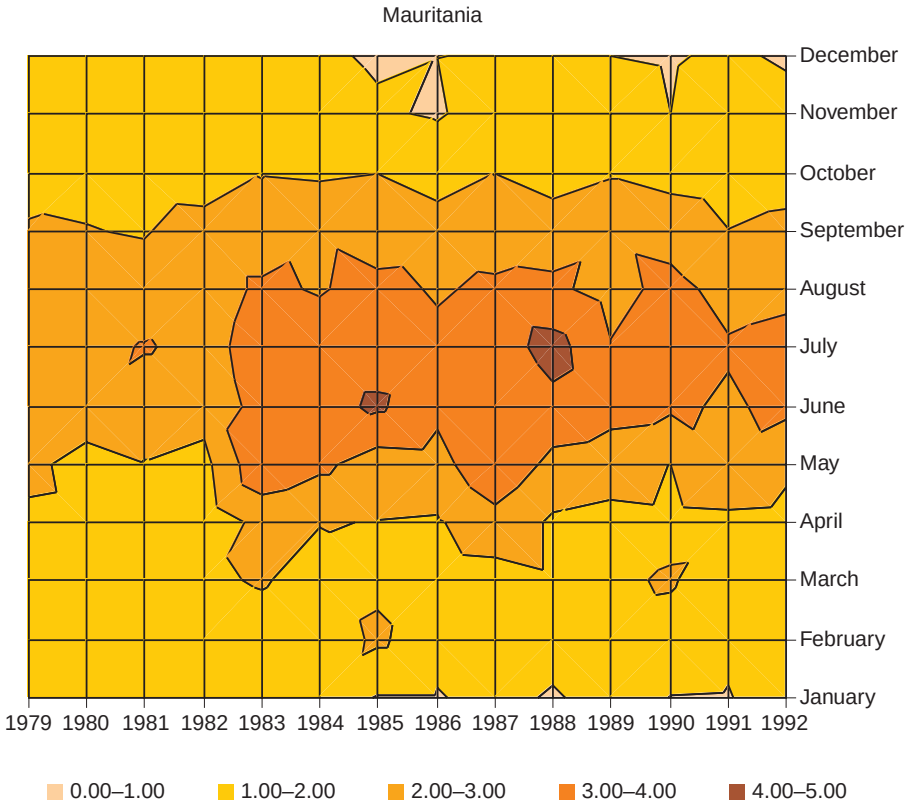


Fig. 7. Mean monthly distribution of AI (1979–1992) in Mauritania.

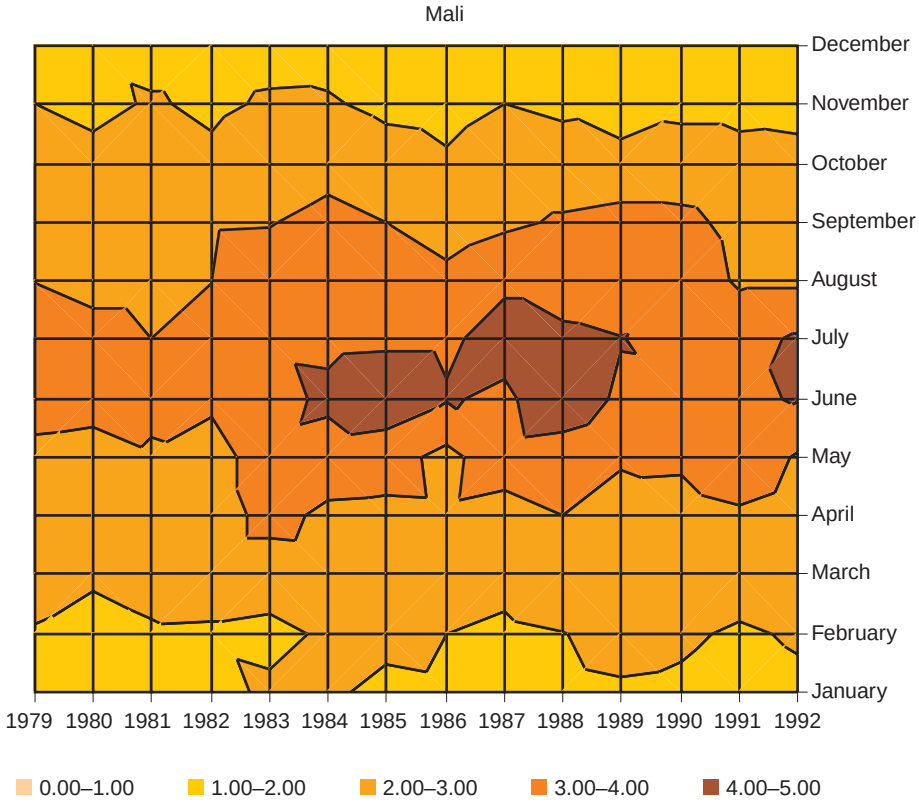


Fig. 8. Mean monthly distribution of AI (1979–1992) in Mali.

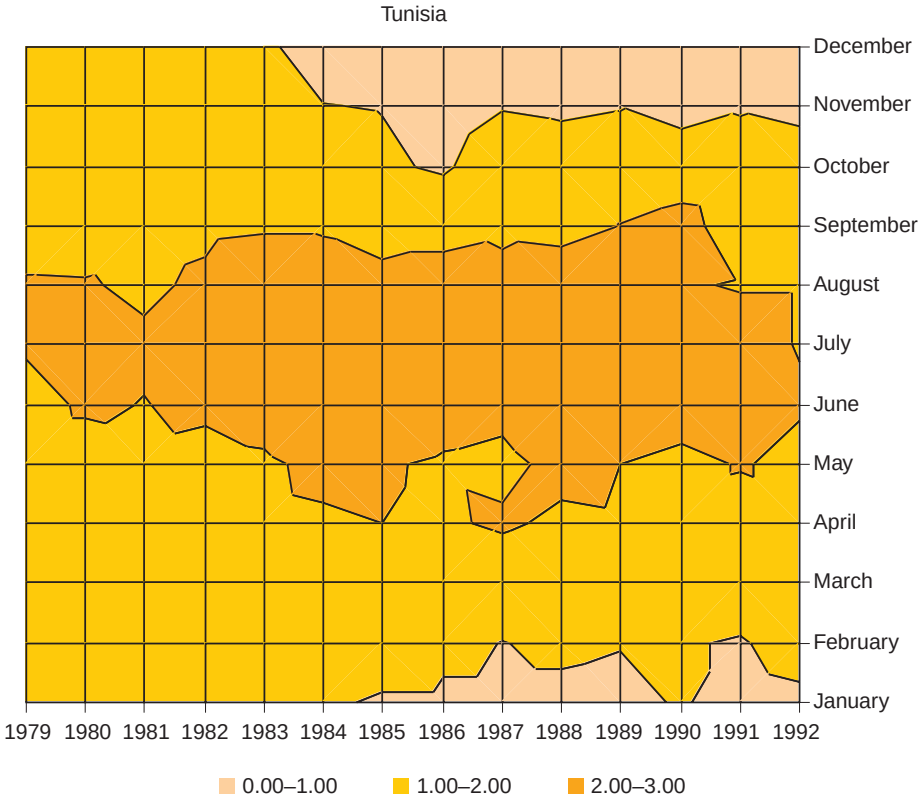


Fig. 9. Mean monthly distribution of AI (1979–1992) in Tunisia.

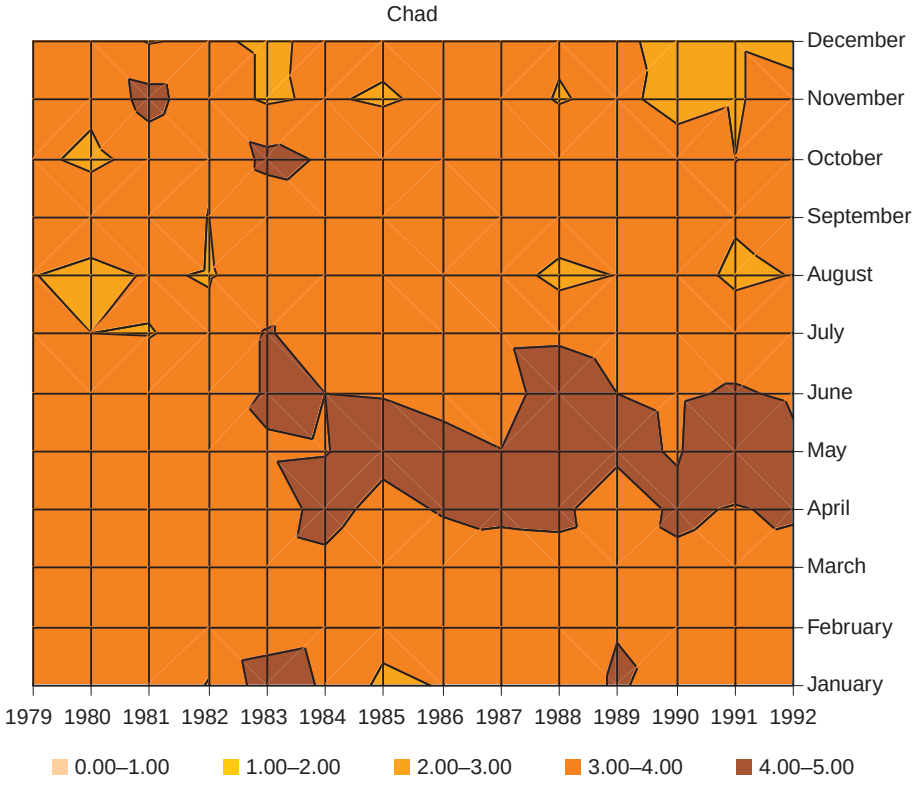


Fig. 10. Mean monthly distribution of AI (1979–1992) in Chad.

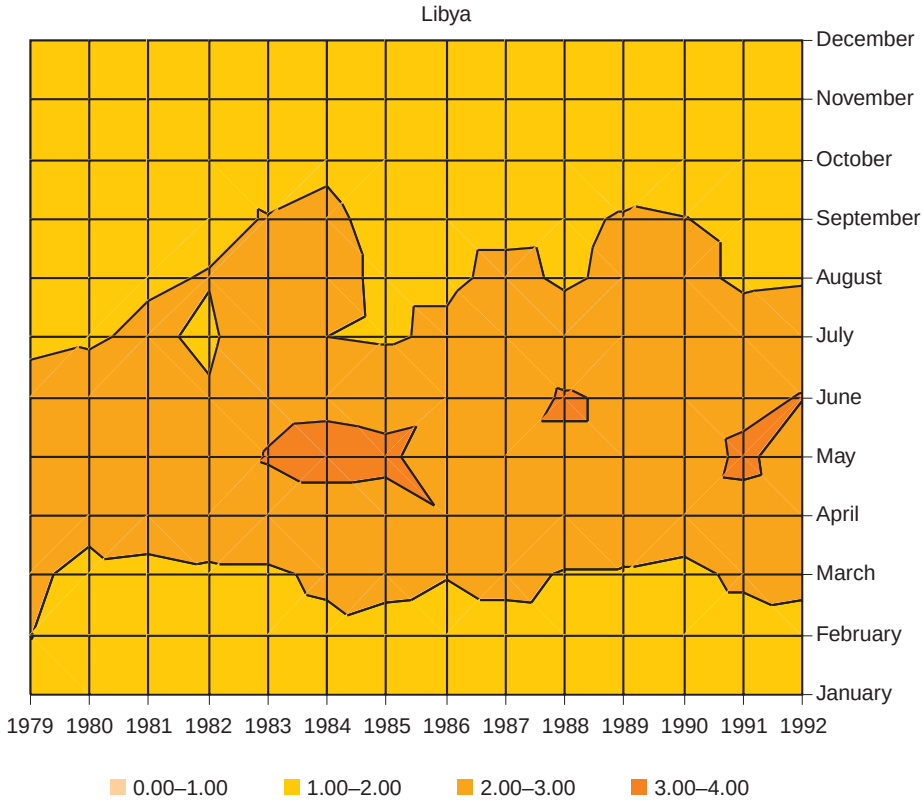


Fig. 11. Mean monthly distribution of AI (1979–1992) in Libya.

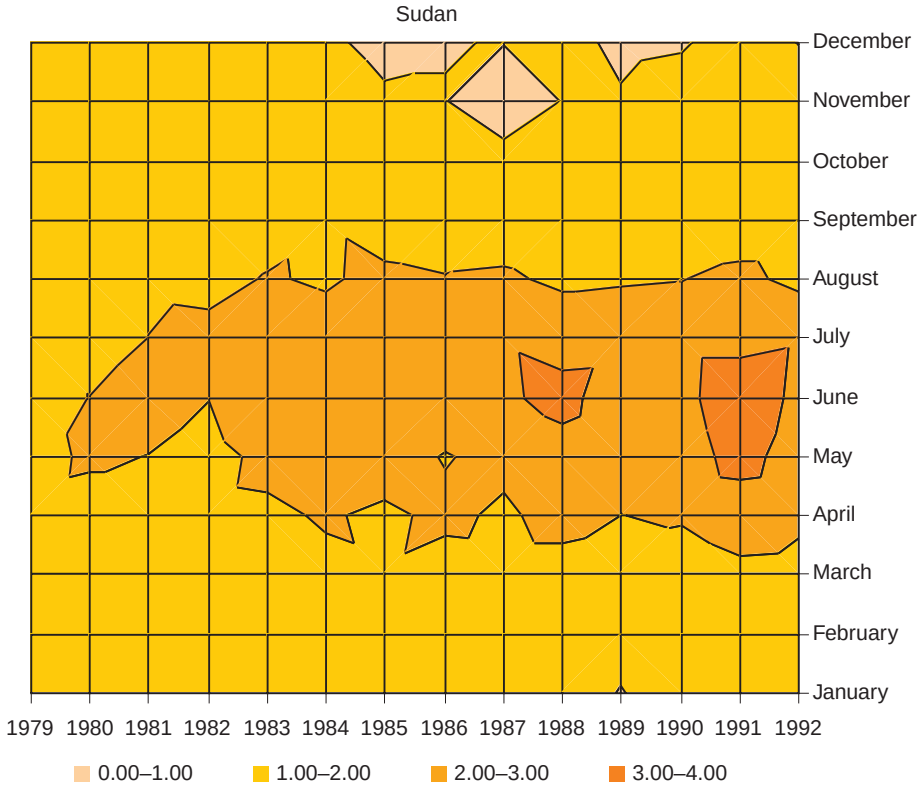


Fig. 12. Mean monthly distribution of AI (1979–1992) in Sudan.

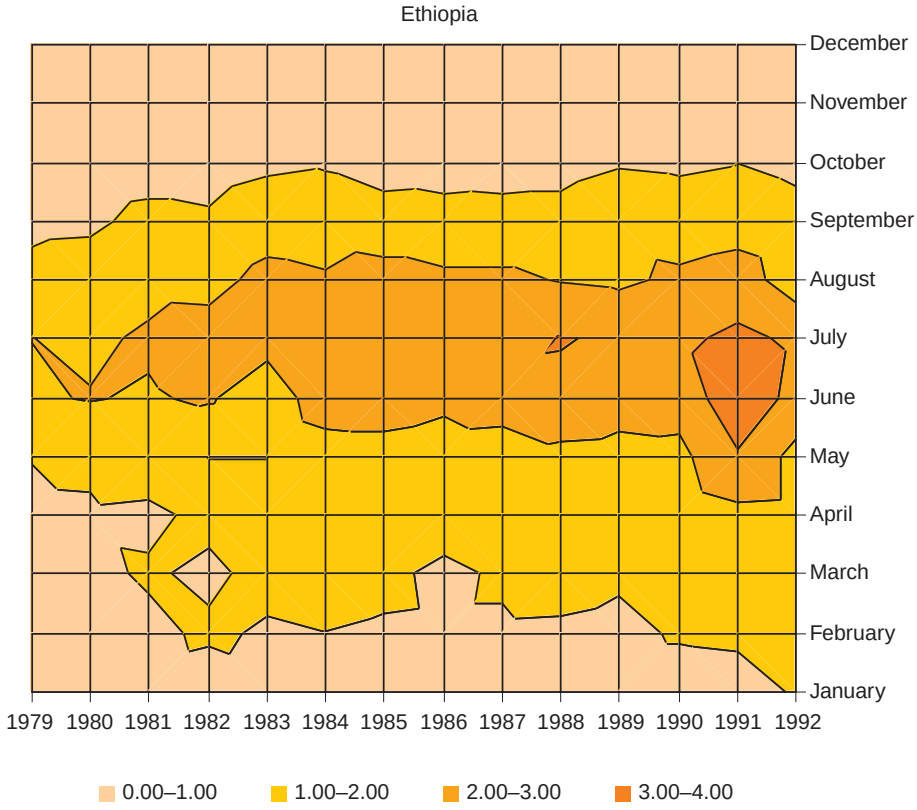


Fig. 13. Mean monthly distribution of AI (1979–1992) in Ethiopia.

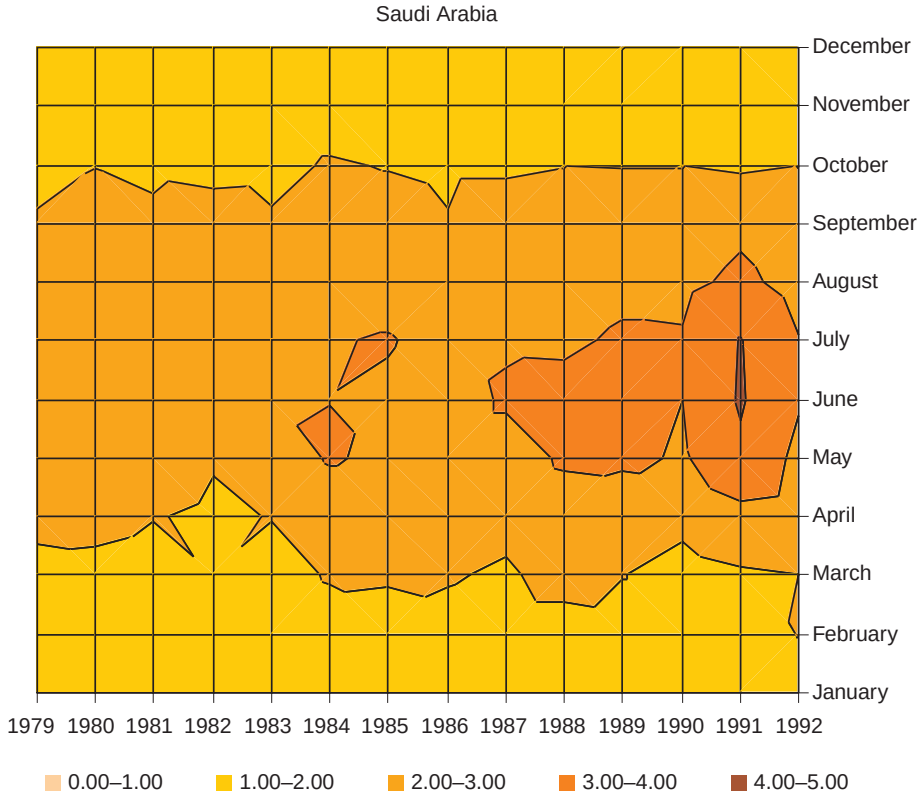


Fig. 14. Mean monthly distribution of AI (1979–1992) in Saudi Arabia.

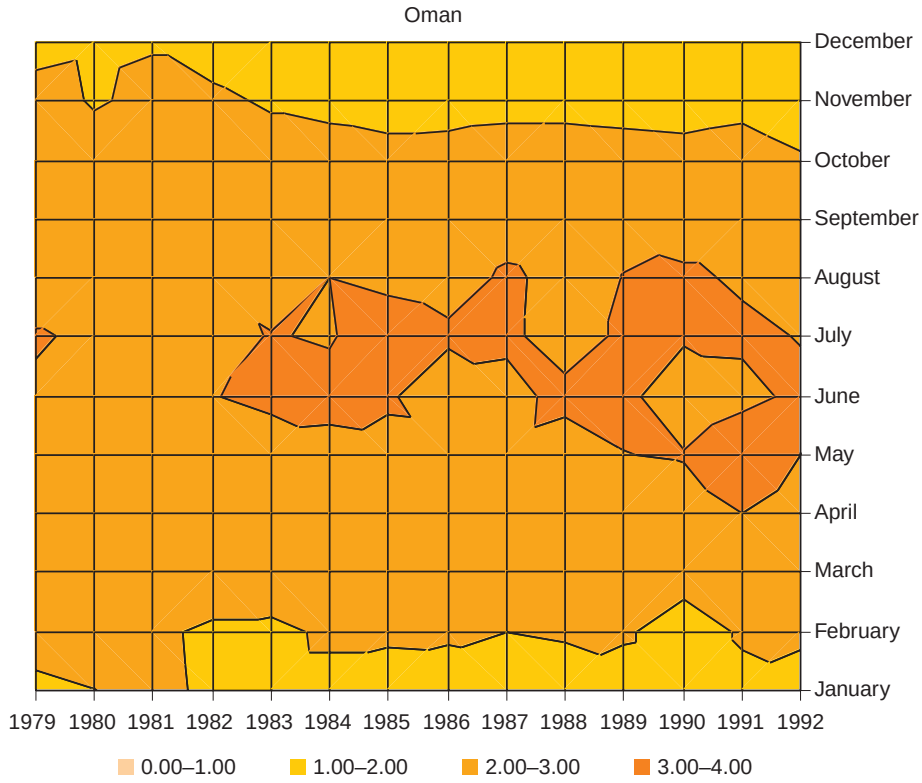


Fig. 15. Mean monthly distribution of AI (1979–1992) in Oman.

8. The Saudi Arabian Source (Figure 14)

At this source, the high *AI* values included May and August and also June and July. The two dustiest periods were 1983 and especially 1984 and 1988 to 1992. Between these two dusty periods the *AI* value of the year 1986 was relatively low. The values increased gradually from 1979, without a sharp divide between 1982 and 1983 unlike that found in the more western sources.

9. The Oman Source (Figure 15)

This source is a bit unusual compared with the others. The months May to August were almost equally dusty over the entire research period with a slight increase in the periods 1983–1985, July 1987 and in 1988–1992 alternately in May June or July. The year 1986 had a low value as did most of the other sources.

Figures 16 and 17 illustrate the temporal trend of the normalised *AI* values. Figure 16 shows the mean normalised *AI* by years. It is perhaps the most evident display of the characteristics of the various years and periods. The early years during the research period, 1979–1982, were below the multiyear average, while the period 1983–1988 was mostly above it, especially the years 1983 and 1984. The year 1986 is outstanding in this period, being clearly below the average.

Figure 17 shows the mean normalised *AI* by years for every source area. In the period 1979–1982 the index in all the sources, with only two exceptions, was below average. The *AI* in 1983, with two exceptions and all the sources in 1984 without any exception were above average. In 1985 some sources were above and others below average. In 1986 all the sources showed below average values. The *AI* values of 1987 and 1988 were all above average with only one exception. We have no explanation for the changes in values in the years 1989 and 1990. The behaviour of the index for the various sources in 1991 and 1992 is interesting. The index is below average in the western sources and definitely above in the eastern sources (excluding Oman in 1992), especially in 1991. This may lead to an assumption that it is due to a possible influence of the Gulf War. The Libyan source, which geographically has a transitional position between east and west, was slightly above the average at this time.

Conclusions

The highest *AI* values were in the summer months, especially in June and July. However, in two of the

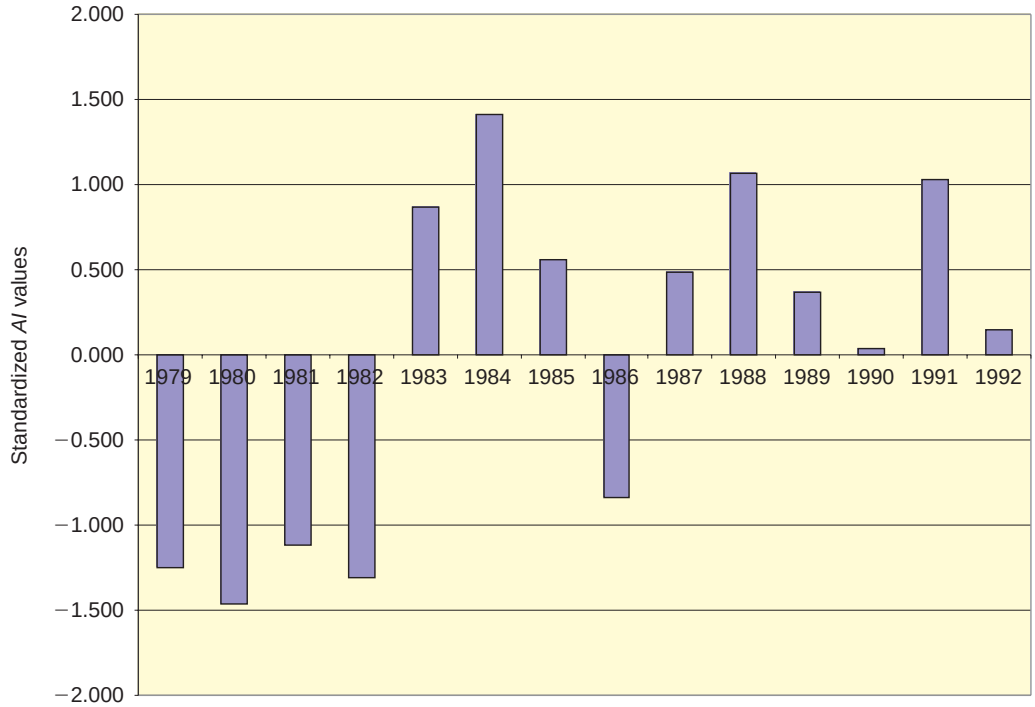


Fig. 16. Mean annual normalised *AI* for the years 1979–1992. Average of all sources.

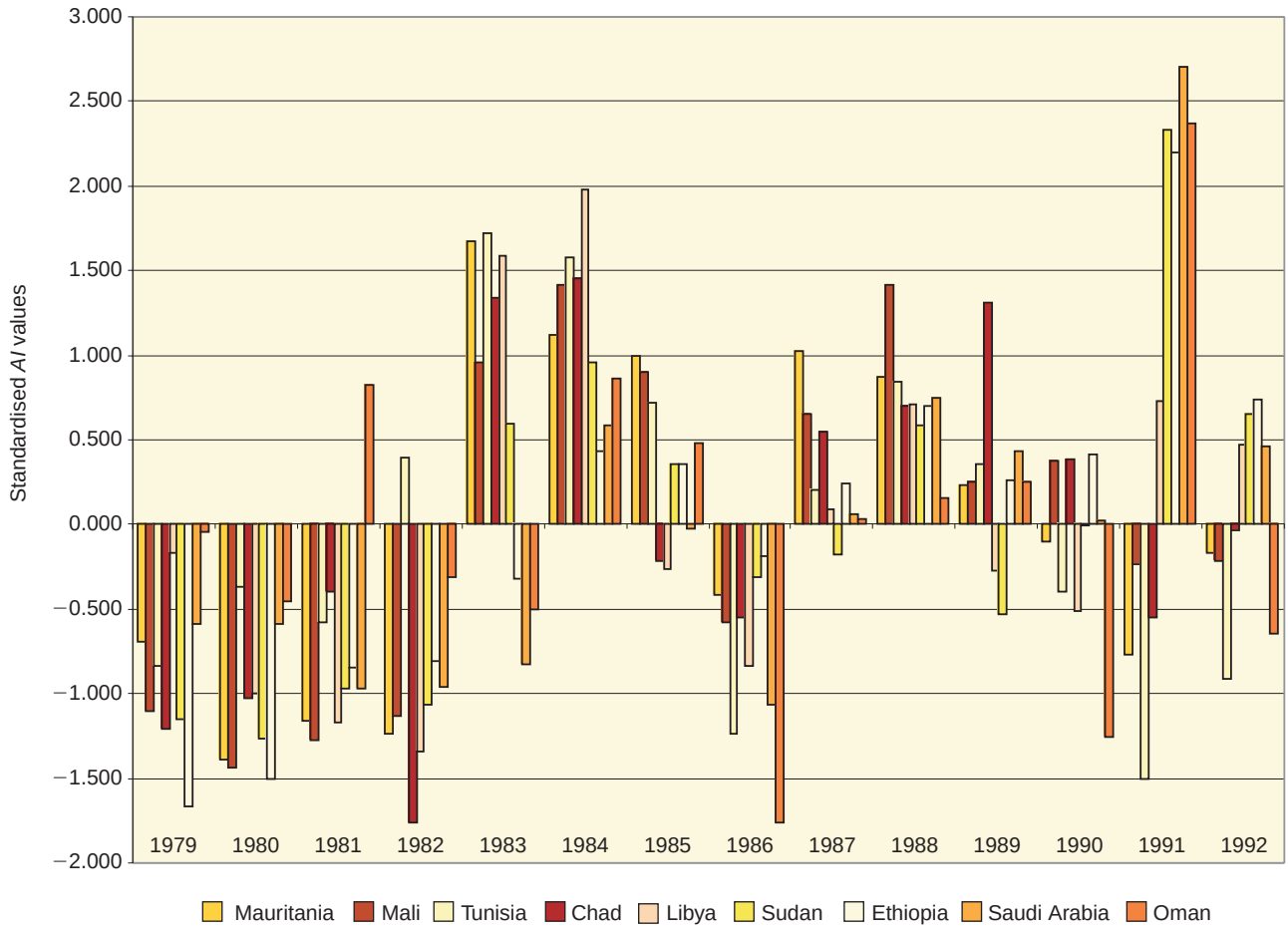


Fig. 17. Mean annual normalised *AI* for the years 1979–1992. All sources.

dustier and deserted sources, in Chad and in Mali, the peak was in May.

There was a very well defined discontinuity between the first four years of the research (1979–1982) and the period starting on 1983, in the western sources. In the eastern sources we noticed an increasing tendency of the index to change with time; however, the differences between the former and the later periods is not so prominent.

Two periods were particularly dusty: 1983–1984, mainly 1984, and 1987–1988, mainly 1988, in all the sources. The year 1986 on the other hand was outstandingly clear in all the sources.

The Chad and Bodele Basin source is distinctive, being active all the year around, contrary to the other sources.

There were very high *AI* values in the months May–July of the year 1991. The values increased going from west to east. They were very low at the Libyan source and very high at the Saudi Arabian source. In Oman, situated far to the south, no outstanding increase in the *AI* was measured.

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