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The
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Editorial

Dear readers,

I do not intend to make it part of my duties to bore you with editorial comment very often, but I will avail myself of the opportunity from time to time.

I write this time about the contents and our circulation. We would like to increase our circulation by about 15% over the next year — this would help to keep the price down and increase the number of pages. To do this we need to know more about our readers and what they want; a questionnaire will be included soon. Meanwhile, we are trying to make the magazine both useful, and more readable, by having occasional review articles to accompany major papers or to introduce topics that are to be covered in future issues.

Most of the papers submitted to us are major works that occupy nearly half an issue. These are very welcome and we hope they will continue to come in from all over the world at the rate they have been recently. However, difficulty arises because there is often room for only two topics in one issue — and neither may be of interest to you. I would like you all to consider whether you might be able to write, or encourage colleagues to write, some shorter items of perhaps 2000 words, but please glance at the inside back cover. An issue with one main article and six short ones is more likely to be interesting than one with two main articles. Why not write a letter to me? We do not publish 'letters to the editor' because we do not have any to print!

I will close on the rather vexed question of style and language. A recent article in *New Scientist*, 9 May 1992 tells of the growing incomprehensibility of specialist scientific journals. On a scale where 'comics' score −26, newspapers 0 and more difficult works above zero, two prestige journals scored 0 in the 1930s (i.e. were easily read and understood) but by 1990 their scores were about +30 (too hard for many specialists). Those of you who have English as your mother tongue, please consider your foreign readers and use simple English and, if it is at all possible, the present tense and first person (write 'I saw' NOT 'it was observed that'). If English is not your first language, you should still write in simple English because it is easier for you and your first readers — the editor and his helpers. It is most unlikely that we will reject work because the language is too simple. We do reject what WE cannot understand!

Rodney Blackall

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Indian summer monsoon rainfall indices: 1871–1990

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Summary

The Indian summer monsoon rainfall, because of its importance to the country's economy and in the global atmospheric circulation, has motivated many studies pertaining to its behaviour, characteristics, teleconnections with global/regional features and long-range prediction. These studies have used various types of rainfall series, most of them based on a variable network of rain-gauges, with the consequent inhomogeneities in the data series. The present paper describes some homogenous representations of the Indian summer monsoon rainfall for the period 1871–1990, prepared on the basis of a fixed and well-distributed network of 306 rain-gauges. An Indian Summer Monsoon Rainfall (ISMR) Index, indicating the net excess or deficient rainfall conditions over the country, is proposed. This index, and some others are listed in the papers, for ready use in the studies of monsoon, its teleconnections and other related aspects.

Statistical analysis of the above series identifies 18 large-scale dry years and 15 large-scale wet years during the last 120 years. The decadal means of ISMR index were continuously negative for three decades 1901–30, positive 1931–60 and again became negative during the current period 1961–90.

1. Introduction

The importance of the Indian monsoon rainfall to the country's economy and also as a major global circulation parameter has motivated many studies during the last century, pertaining to its characteristics, variability, teleconnections with regional/global circulation features and long-range prediction. A systematic study of the variability in annual rainfall and droughts over British India (including present-day Pakistan, Sri Lanka, Bangladesh and Burma (now Myanmar)) was first made by Blanford (1886), using areal mean rainfall (annual) during 1867–85, based on a varying network of about 500 rain-gauges. Later, Walker (1910) estimated the monsoon (June–September) rainfall of India (subsequently updated (Annual Reports of IMD) for the period 1841–1935), using a variable rain-gauge network as follows: 20–71 stations prior to 1865; 500–1500 stations for the period 1866–90 and 1500–2000 stations from 1891 to 1935. The monsoon rainfall series for the Post-independence India (as one unit) has been prepared by Parthasarathy and Dhar (1976), Parthasarathy and Mooley (1978), Thapliyal (1990) and Thapliyal and Kulshrestha (1991) with the number of rain-gauges varying from 300 to 3000 spread all over India for the different lengths of period starting from 1865 onwards. Subdivisional monsoon rainfall of India has also been estimated and studied by Rao and Jagannathan (1963), Parthasarathy and Dhar (1974), Banarjee and Raman (1976), Shukla (1987), Chowdhury *et al.* (1989) and Chowdhury and Mhasawade (1991) for the period starting from 1875 onwards using a variable rain-gauge network. However, due to the obvious inhomogeneities introduced by the variable rain-gauge network, these data sets are not suitable for advanced statistical analysis.

Monsoons also play an important role as major energy sources in the global-scale circulation. There are many recent studies notably Drosdowsky (1990), Joseph *et al.* (1991), Yasunari (1990, 1991) and Kiladis and Sinha (1991) have brought out that the Indian summer monsoon rainfall is used as an input parameter in forecasting or estimating the other regional parameters. In view of this, there is a great demand by scientists all over the world for a homogeneous data series representing the monsoon rainfall of India for their further investigations.

In this context, a long, homogeneous rainfall time-series having adequate spatial and temporal representativeness would be a very useful tool, as the amount of latent heat energy released to the atmosphere through condensation of water vapour can be obtained completely from relevant precipitation amounts (Fleer 1981). Mooley and Parthasarathy (1984) and Parthasarathy *et al.* (1987) put in considerable efforts to prepare a homogeneous rainfall series for whole India as well as different meteorological subdivisions, on the basis of a fixed network of 306 rain-gauges for the period 1871 onwards. These series have been well recognized and extensively used by many scientists (Gregory 1986, 1988, 1989; Mooley and Shukla 1987; Hastenrath 1991, etc.).

For a country as vast as India, with spatial variability of monsoon rainfall, there would almost always be some areas of deficient rain even in the best of monsoons (or some areas of floods even in the worst of monsoons). It is very difficult to incorporate all such complex spatial and temporal variabilities in a single series. Therefore, it becomes necessary to express the Indian monsoon rainfall in a variety of ways depending on the application. The present paper addresses itself to this problem.

2. Details of rainfall data

The total number of rain-gauges in India varied from 50 in 1850 to 5000 in 1990. After an initial screening of all the available data series, a fixed number of 306 well-distributed rain-gauge stations, one from each of the districts (a small administrative area) in the plain regions of India, have been selected for the present study. Care has been taken to exclude non-homogeneous records and only reliable or corrected station data have been used in the calculation of area averages. The Symon's pattern rain-gauge with a 127 mm (5 inches) diameter funnel, one foot above the surface, was used in the data period, and there had been no changes in instruments. The earliest year for which reliable data is available for these stations is 1871. The relevant rainfall data at these 306 stations have been obtained for the period 1871 to present from the records of the India Meteorological Department, Pune (for further details of data see the publications of Mooley *et al.* 1981; Mooley and Parthasarathy 1984 and Parthasarathy *et al.* 1987). The hilly regions consisting of four subdivisions in the Himalayas (hatched areas in Fig. 1) have not been

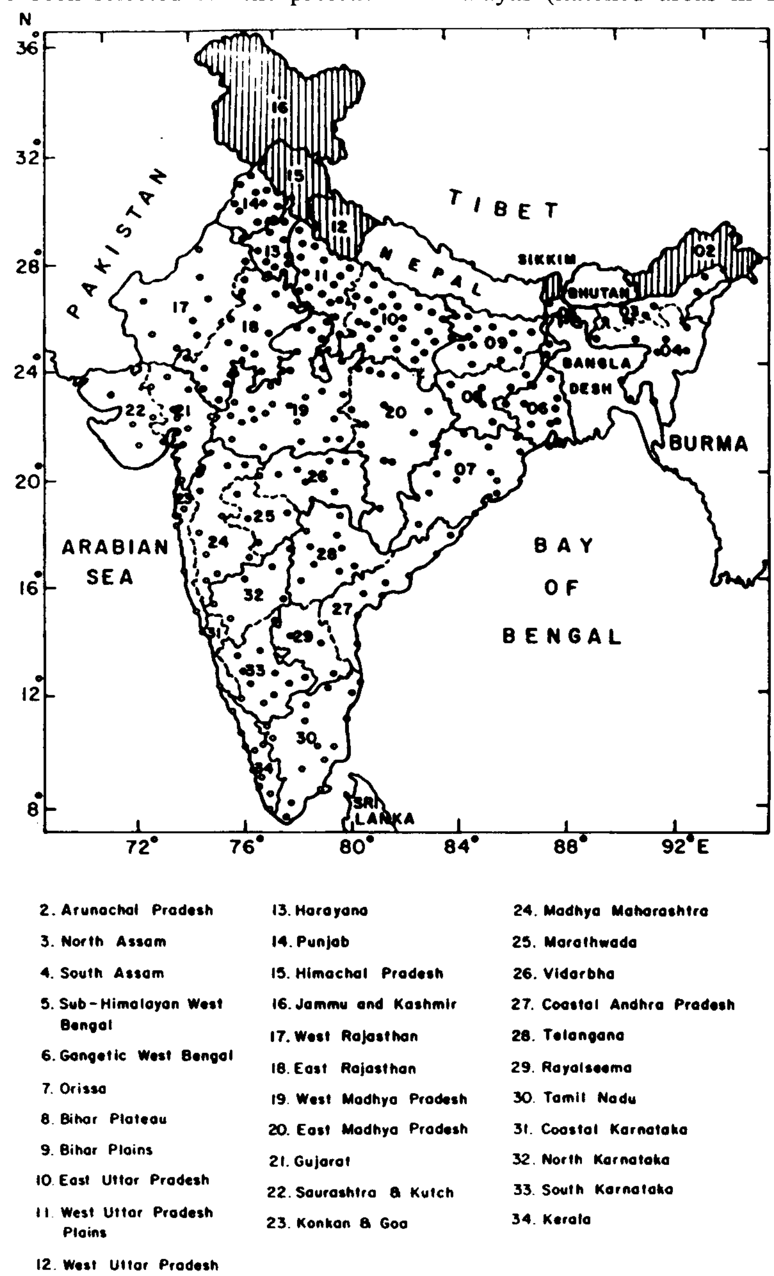

Figure 1. Latest Meteorological subdivisions of India with network and locations of rain-gauges considered. Hatched hilly subdivisions are not considered.

considered in view of the inadequate rain-gauge network, their limited representativeness and non-monsoonal nature of rainfall there. The islands in the Bay of Bengal (subdivision number 1) and the Arabian Sea (subdivision number 35), not shown in Fig. 1, have also not been considered for the present study to maintain contiguity. The contiguous area considered measures 2.88×10^6 km^2, which consitutes about 90% of the country's total area. The spatial pattern of mean summer monsoon rainfall based on data for 306 stations over the period 1871–1978 (Parthasarathy 1984a) is in good agreement with the climatological (normal) map prepared by the India Meteorological Department (IMD) on the basis of about 3000 rain-gauge stations for the period 1901–50; (IMD 1981, Rao 1976). This shows that the rainfall stations selected here are adequately representative. Also, the rainfall data of all the individual stations used in this analysis have been found to be homogeneous, Gaussian-distributed and free from persistence for the period 1871–1978 (Parthasarathy 1984a).

Fig. 1 shows the latest meteorological subdivisions into which the country has been divided and the area considered along with the location of rain-gauges used in this study. Area-weighted mean summer monsoon rainfall (June through September) for each of the 29 meteorological subdivisions have been prepared by assigning the district area as the weight for each representative rain-gauge station for the period 1871–1984 (Parthasarathy *et al.* 1987). Similarly, the All-India (India taken as one unit) mean monsoon rainfall is computed by taking the weighted average of the subdivisional monsoon rainfall, with the subdivisional areas as the weights. For the recent period after 1985, the rainfall data for some of the 306 stations are not readily available in published form; however, to make the study up-to-date, the following procedure has been followed. The Hydrology Unit of IMD, Pune compiles the monthly and seasonal rainfall data based on all reported observatory stations (about 350) soon after every season for different meteorological subdivisions of India, and these are published in the subsequent issues of official IMD Journal *Mausam*. From these and from other IMD publications, we obtained the seasonal rainfall data (R_{ij} for the ith subdivision and jth year) for the period 1985–1991 for each of the 29 subdivisions used in this study; however, the number of reporting stations varied from year-to-year. The IMD seasonal normal rainfall ($\bar{R}_{ij}$ period 1901–1970) of each of the subdivisions prepared on the basis of reporting stations are also available for each year. From these data, the estimates of subdivisional monsoon rainfall R^*_{ij} for the period 1985–1991 are obtained from the expression

$$R^*_{ij} = R_{ij}\,(R^*_i/\bar{R}_{ij})$$

where R^*_i is the subdivisional normal based on the stations used by Parthasarathy *et al.* (1987) for the period 1871–1978. As such, these data may be considered to be approximate and realistic for immediate use.

The 29 subdivisional and All-India monsoon rainfall series are found to be homogeneous, random and normally distributed (Mooley and Parthasarathy 1984; Parthasarathy *et al.* 1987) for the period 1871–1978. The values for the period 1981–91 are presented in Table I, i.e. updating the values of the Table II of the paper by Parthasarathy *et al.* (1987).

3. All-India monsoon rainfall series

The yearly All-India monsoon rainfall data, along with the percentage departure from the long term (1871–1984) average, are listed in Table II for the period 1871–1990. The mean (R), standard deviation (S) and coefficient of variation (CV) of the All-India monsoon rainfall respectively are 852 mm, 83 mm and 9.8% for the period 1871–1984. The highest rainfall was 1017 mm in the year 1961 and lowest 604 mm in 1877. The range of All-India rainfall during a period of 120 years is 413 mm which is 48% of the average. The monsoon rainfall of an individual year is classified as large-scale deficient (dry year) when it is less than $\bar{R}-S$ and excess (wet year) when it is more than $\bar{R}+S$. With this criterion, there are 21 dry and 18 wet years during the period 1871–1990 (Fig. 2). It is also observed that there are many negative departures during the periods 1899–1920 and 1962–87 and positive departures during 1874–94 and 1942–61. A general increase in the rainfall from 1899 to 1961 can also be seen. To delineate the slow variations, the rainfall series has been subjected to a binomial low-pass filter (Mitchell *et al.* 1966, Tyson *et al.* 1975) and the filtered rainfall curve along with the percentage departure of All-India rianfall series are shown in Fig. 2. It is observed that the low-pass filter curve is generally below the normal rainfall during the periods 1899–1920 and 1962–87 and positive departure during 1874–94 and 1942–61.

This All-India data set gives a generalized picture but does not satisfactorily quantify the spatial extents of anomalous situations. Therefore, an attempt has been made to prepare data sets indicating the spatial extent of excessive and deficient rainfall conditions, by adopting suitable criteria.

4. Methodology

Various definitions have been used to define drought/flood over a region, depending on the context. In a tropical country like India, rainfall invariably becomes the dominant parameter in almost all the definitions of droughts and floods. The India Meteorological Department (1971) (see also Raman (1975) Government of India (1976)) consider drought to have occurred in a year over a subdivision when the seasonal rainfall is less than 75% of the normal. However, this criterion does not take into account the variability of the rainfall over the different

Table I. Summer monsoon (June–Sept.) rainfall values (mm) for 29 subdivisions of India for the period 1981–91 with long-term means for comparison

Subdivision number and name	Area of India (%)	1871–1984 mean	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991
03 North Assam	1.96	1451	1314	1363	1503	1502	1598	1339	1698	1676	1595	1552	1235
04 South Assam	4.28	1451	1113	1258	1308	1312	1304	1082	1350	1449	1497	1353	1294
05 Sub-Himalayan West Bengal	0.75	1991	1838	1636	2051	2316	2080	1775	2718	2439	2146	1832	2462
06 Gangetic West Bengal	2.30	1143	1158	905	981	1519	1305	1317	1460	1561	1421	1429	1602
07 Orissa	5.41	1168	1094	1074	1009	1288	1373	1258	781	1132	1263	1237	1283
08 Bihar Plateau	2.27	1100	936	889	987	1220	952	1005	1186	1125	1180	1427	1230
09 Bihar Plains	3.27	1032	1113	721	895	1502	1096	1002	1682	1075	1013	860	920
10 East Uttar Pradesh	5.09	912	1085	989	958	1032	1037	796	541	893	921	1051	807
11 West Uttar Pradesh	3.36	771	639	681	1059	814	883	595	425	994	686	726	663
13 Haryana	1.59	458	435	315	622	497	537	331	167	843	326	548	352
14 Punjab	1.75	492	283	338	413	549	570	544	160	1086	456	829	481
17 West Rajasthan	6.77	256	215	197	383	208	180	176	102	280	237	445	133
18 East Rajasthan	5.11	641	602	467	691	580	488	551	322	695	506	679	458
19 West Madhya Pradesh	8.07	923	817	912	1061	865	807	893	712	855	707	1066	742
20 East Madhya Pradesh	7.79	1205	964	987	1167	1098	1185	1041	954	1081	1061	1384	1114
21 Gujarat	2.99	873	974	580	1110	1032	395	426	354	1148	786	1001	601
22 Saurashtra and Kutch	3.82	437	490	232	607	388	195	261	84	721	454	329	220
23 Konkan and Goa	1.18	2382	2598	2383	3556	2389	2510	1632	2420	2695	2370	2660	2427
24 Madhya Maharashtra	4.00	581	725	415	732	500	393	460	410	933	627	654	703
25 Marathwada	2.24	690	757	616	1054	367	479	556	571	1324	1055	940	613
26 Vidarbha	3.39	900	1136	726	1038	613	654	870	569	1076	793	1140	715
27 Coastal Andhra Pradesh	3.23	505	599	425	758	381	458	468	313	722	749	420	639
28 Telangana	3.98	718	916	728	1083	576	513	697	580	1103	988	740	667
29 Rayalseema	2.40	421	471	396	690	291	295	344	373	636	546	397	485
30 Tamilnadu	4.52	308	398	185	402	322	451	259	275	441	343	294	333
31 Coastal Karnataka	0.64	2852	3271	3376	3654	2491	2474	2476	2274	3358	3010	2744	3277
32 North Karnataka	2.77	603	764	590	819	551	467	490	491	765	692	500	685
33 South Karnataka	3.24	503	568	376	599	499	339	564	529	751	611	356	689
34 Kerala	1.35	1940	2526	1749	2054	1622	1656	1531	1469	2114	1826	1435	2405

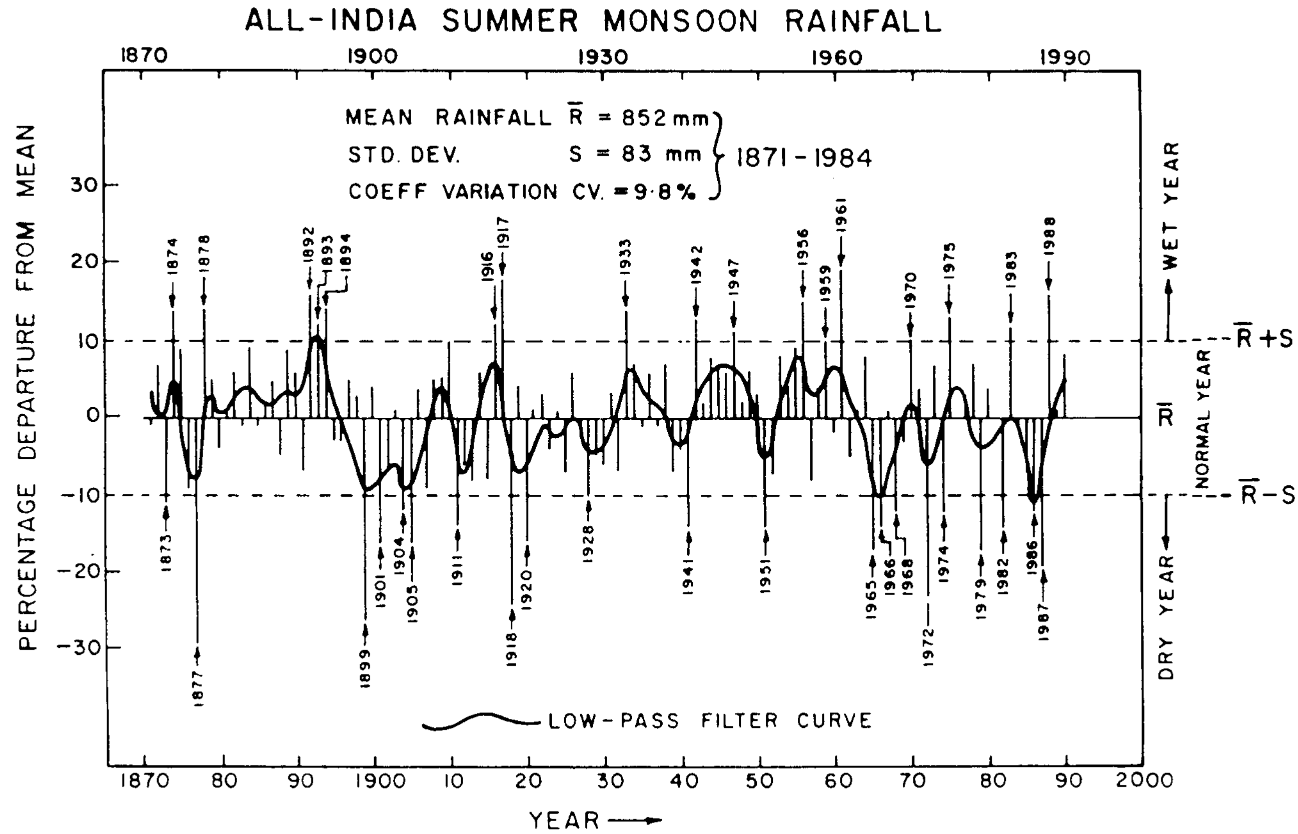

Figure 2. Year-to-year percentage departure (from mean) of All-India summer monsoon rainfall from 1871 onwards. Excess/deficient years are marked against the bars.

subdivisions of the country which varies from 12% in Assam to 44% in Gujarat. In any region, human activities are adapted to the prevailing climatic pattern of the region and also to the average rainfall variability. Therefore, it may be presumed that only rainfall deficits/excesses exceeding the average variability of the season are felt by the people of the respective region as being significantly detrimental. In general terms it can be regarded as the condition where there is lack of sufficient water to meet the requirements of plants, animals and human population of the region. It appears reasonable to define normal rainfall over a region in terms of the standard deviate, $(R_i - \bar{R})/S$, since CV over different parts of India varies between 15% and 45%. Parthasarathy *et al.* (1988, 1992) classified the All-India monsoon rainfall of an individual year as deficient when it is less than $\bar{R}-S$ and excessive when it is more than $\bar{R}+S$, and showed the impact of these extreme rainfall years on the total as well as rainy-season food-grain production of the country. Similar reasoning can be extended to the subdivisional scale also. Thus, the seasonal rainfall (R_i) for a meteorological subdivision in the ith year is classified as being deficient when it is less than $\bar{R}-S$ and excess rainfall when R_i is more than $\bar{R}+S$. If R_i is within $\bar{R}\pm S$, the rainfall is treated as normal.

5. Area under deficient/excess rainfall conditions

On the basis of the criterion described in the earlier section, the seasonal rainfall values over each of the 29 meteorological subdivisions are classified into deficient, excess and normal categories in each year of the period from 1871 to 1990. In each year, the total area of the country falling under the deficient/excess rainfall conditions has been computed and expressed as percentage of the total area of the country and is presented in Table II. The year-to-year variation in the area under deficient monsoon rainfall can be seen in Fig. 3. The number of subdivisions reporting deficient/excess monsoon rainfall conditions are also shown in Fig. 3. The mean, standard deviation and CV are 15.1 (D), 16.3 (S_D) and 108% respectively for Deficient area (DA) series and 15.3 (E), 12.0 (S_E) and 78% for Excess area (EA) series, respectively, for the period 1871–1984. It can be noted that the mean for DA and EA series is almost same, but the variability is relatively more for DA series.

A large-scale deficient (Dry) and Excess (Wet) rainfall year can be defined as that when the area under deficient and excess rainfall exceeds the corresponding long-term (1871–1984) mean area by one standard deviation (i.e. Dry year, $d \geqslant D+S_D$ and Wet year, $w \geqslant E+S_E$). Based on this criterion, there are 21 large-scale excess (Wet)

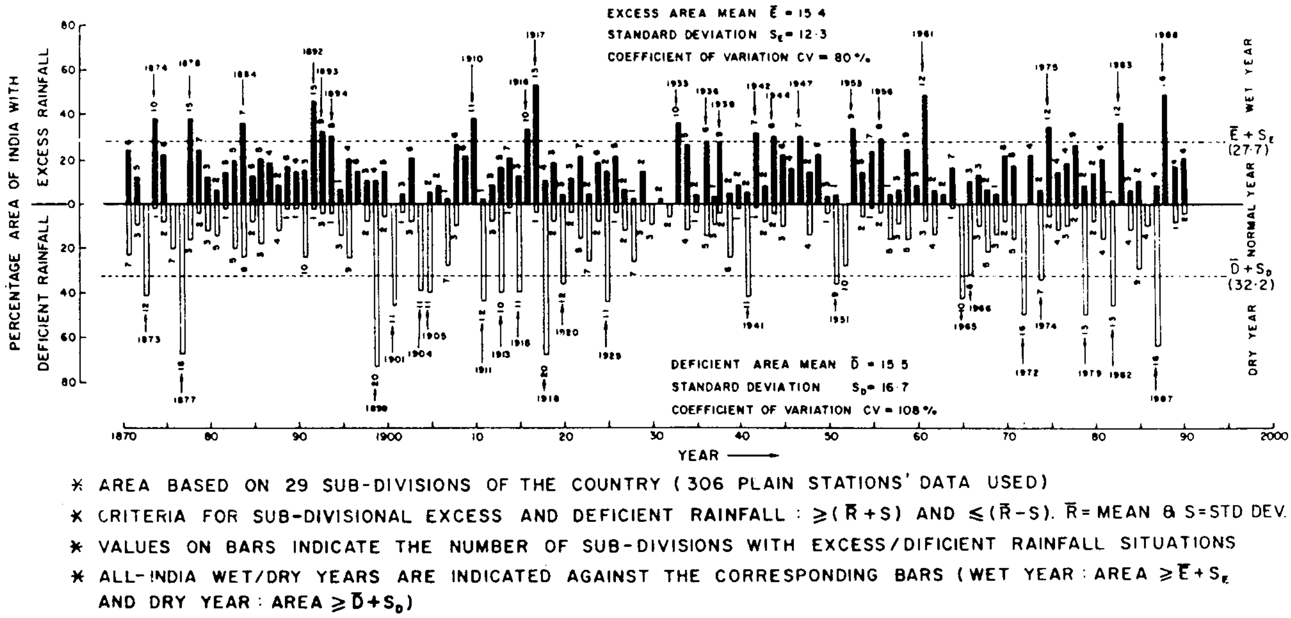

Figure 3. Year-to-year variations in the percentage area of India with excess and deficient monsoon rainfall conditions for the years from 1871 onwards.

years and 20 large-scale deficient (Dry) years (see Tables III and IV) during the period 1871–1990 (Fig. 3). It may be mentioned here that the DA and EA series are skewed and the use of standard deviation to define the thresholds may be of doubtful effectiveness. To examine this aspect, Gamma distribution has been fitted to the series and the extreme years have been identified by following the extreme 15% criterion on either side. It has been observed that these years are closely tallying with those identified by means of standard deviation (Tables III and IV). Therefore, the authors have proceeded with the use of standard deviation. It can be seen that the wet and dry years are clustering alternatively in two groups:

(a) during 1874–1894, six wet years,
(b) during 1899–1925, ten dry years,
(c) 1933–61, nine wet years, and
(d) 1965–87, seven dry years.

The country suffered the six worst dry years 1877, 1899, 1918, 1972, 1979 and 1987 when the deficient area (DA) was more than D+2S_D and the five wettest years 1878, 1892, 1917, 1961 and 1988 when the excess area (EA) was more than E+2S_E. The highest value of DA is 66.8 for the year 1877 and that of EA is 52.8 for the year 1917.

To examine the long-term variability in the DA and EA series, their decadal means are presented in Fig. 4. It can be seen that most of the decadal means of EA are close to the overall mean, while those of DA show several decades of large departures from mean. There is a gradual increase from the decades 1881–90 to the highest value in 1911–20, and then a decrease to the lowest in 1931–40. Subsequently, the DA shows a monotonic increase up to the recent decade, 1981–90. Seven decadal means of DA are more than the long-period mean D, of which three are in the recent period. In two decades, 1931–40 and 1951–60, the decadal means of both EA and DA are lower than their overall means.

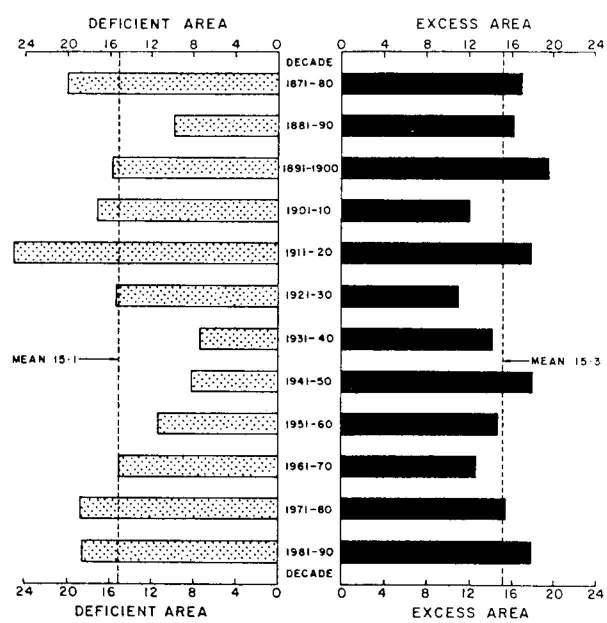

Figure 4. Decadal percentage area of India with deficient/excess monsoon rainfall conditions.

6. Indian summer monsoon rainfall (ISMR) index

It may also be of interest to know the net performance of the monsoon over the country as a whole. Subtracting DA from EA yields our Indian Summer Monsoon Rainfall (ISMR) Index (=EA−DA). The ISMR index values for the period 1871–1990 are shown in Fig. 5 and listed in Table II. The ISMR index gives the net total

Table II. Different Indian summer monsoon (June–Sept.) rainfall indices for the period 1871–1991 of contiguous India

Year	All-India rainfall (mm)	Departure from mean (%)	Deficient rainfall: Area of DA (%)	Deficient rainfall: Number of subdivisions	Excess rainfall: Area of EA (%)	Excess rainfall: Number of subdivisions	ISMR index (EA−DA) (%)
1871	846.1	−0.7	23.0	7	23.4	6	0.4
1872	910.1	6.8	9.0	3	11.8	5	2.8
1873	754.5	−11.4	40.9	12	0.0	0	−40.9
1874	971.2	14.0	2.3	1	38.5	10	36.2
1875	928.5	9.0	7.2	2	21.9	6	14.7
1876	776.4	−8.9	19.8	7	0.0	0	−19.8
1877	604.0	−29.1	66.8	18	0.0	0	−66.8
1878	973.8	14.3	16.0	3	39.0	15	23.0
1879	893.6	4.9	3.6	2	23.8	7	20.2
1880	817.1	−4.1	11.7	3	12.0	3	0.3
1881	860.2	1.0	13.2	5	5.7	2	−7.5
1882	900.7	5.7	2.0	1	13.6	5	11.6
1883	848.9	−0.4	19.8	5	19.0	5	−0.8
1884	929.4	9.1	23.2	8	36.2	7	13.0
1885	842.4	−1.1	7.2	2	11.4	5	4.2
1886	870.2	2.1	17.2	3	19.3	5	2.1
1887	896.8	5.3	0.0	0	18.1	4	18.1
1888	810.0	−4.9	12.2	4	8.4	2	−3.8
1889	926.9	8.8	2.3	1	16.0	6	13.7
1890	903.6	6.1	1.3	1	14.5	4	13.2
1891	789.2	−7.4	24.5	10	14.8	3	−9.7
1892	989.8	16.2	2.3	1	46.7	15	44.4
1893	953.5	11.9	3.9	3	32.2	9	28.3
1894	969.3	13.8	3.2	1	29.8	8	26.6
1895	825.2	−3.1	13.1	3	5.4	1	−7.7
1896	824.3	−3.3	24.4	9	19.2	4	−5.2
1897	890.2	4.5	0.0	0	13.3	6	13.3
1898	880.3	3.3	7.0	2	10.7	3	3.7
1899	628.5	−26.2	73.0	20	10.3	4	−62.7
1900	885.4	3.9	6.2	2	13.9	5	7.7
1901	718.9	−15.6	45.4	11	0.0	0	−45.4
1902	791.4	−7.1	3.4	1	3.3	3	−0.1
1903	858.1	0.7	8.3	3	20.1	6	11.8
1904	749.5	−12.0	38.9	11	0.0	0	−38.9
1905	715.2	−16.1	40.1	11	5.0	2	−35.1
1906	882.8	3.6	0.0	0	7.5	2	7.5
1907	776.4	−8.9	27.8	7	1.3	1	−26.5
1908	894.7	5.0	9.1	3	25.3	6	16.2
1909	888.8	4.3	0.0	0	20.8	6	20.8
1910	934.8	9.7	0.0	0	37.3	11	37.3
1911	733.1	−14.0	43.5	12	2.8	1	−40.7
1912	804.4	−5.6	7.3	3	8.4	3	1.1
1913	782.0	−8.2	40.3	10	15.1	5	−25.2
1914	899.0	5.5	2.8	1	20.2	7	17.4
1915	780.1	−8.4	39.7	11	11.6	3	−28.1
1916	949.7	11.5	0.0	0	33.0	10	33.0
1917	1003.2	17.7	4.3	1	52.8	13	48.5
1918	648.3	−23.9	68.2	20	10.3	4	−57.9
1919	884.8	3.8	8.3	2	18.6	3	10.3
1920	717.6	−15.8	36.5	12	4.9	3	−31.6
1921	863.4	1.3	4.5	2	10.8	3	6.3
1922	867.4	1.8	15.6	5	20.9	7	5.3
1923	818.7	−3.9	25.6	7	4.1	2	−21.5
1924	861.8	1.1	8.8	2	18.2	6	9.4
1925	802.9	−5.8	43.1	11	13.2	2	−29.9
1926	901.4	5.8	4.0	1	21.0	5	17.0
1927	849.4	−0.3	11.3	2	6.2	2	−5.1
1928	766.4	−10.0	25.4	7	2.3	1	−23.1
1929	819.5	−3.8	7.2	3	13.2	2	6.0

Table II. (Continued)

1930	800.4	−6.1	8.5	3	0.0	0	−8.5
1931	876.8	2.9	0.0	0	2.5	2	2.5
1932	800.6	−6.0	5.6	2	0.0	0	−5.6
1933	972.8	14.2	0.0	0	35.5	10	35.5
1934	913.4	7.2	12.4	4	26.4	5	14.0
1935	843.5	−1.0	3.2	1	4.4	2	1.2
1936	904.1	6.1	14.4	5	27.7	6	13.3
1937	843.3	−1.0	9.2	3	3.0	1	−6.2
1938	908.1	6.6	4.4	2	28.4	9	24.0
1939	788.8	−7.4	23.0	6	5.1	2	−17.9
1940	850.4	−0.2	1.6	1	8.8	2	7.2
1941	729.3	−14.4	41.8	11	5.1	2	−36.7
1942	958.4	12.5	0.8	1	32.1	7	31.3
1943	866.3	1.7	7.9	2	8.2	2	0.3
1944	921.5	8.2	4.7	2	29.5	6	24.8
1945	907.6	6.5	10.1	3	21.9	6	11.8
1946	901.4	5.8	0.0	0	15.2	4	15.2
1947	942.5	10.6	0.0	0	29.8	7	29.8
1948	872.6	2.4	13.7	4	13.2	2	−0.5
1949	901.8	5.8	0.0	0	22.2	8	22.2
1950	875.1	2.7	3.4	1	3.1	3	−0.3
1951	737.1	−13.5	36.3	9	4.3	1	−32.0
1952	792.0	−7.0	27.9	10	0.0	0	−27.9
1953	919.9	8.0	0.0	0	33.9	9	33.9
1954	885.4	3.9	5.1	2	13.6	5	8.5
1955	930.0	9.2	2.8	1	22.8	7	20.0
1956	979.6	15.0	3.3	2	28.8	8	25.5
1957	784.5	−7.9	15.5	5	3.2	1	−12.3
1958	886.5	4.0	8.5	3	6.1	3	−2.4
1959	938.4	10.1	15.3	5	24.4	9	9.1
1960	839.6	−1.5	0.0	0	8.3	3	8.3
1961	1017.2	19.4	7.0	3	48.9	12	41.9
1962	807.2	−5.3	14.8	4	5.0	2	−9.8
1963	855.5	0.4	0.0	0	3.4	2	3.4
1964	920.2	8.0	2.3	1	15.7	7	13.4
1965	706.9	−17.0	43.0	10	0.0	0	−43.0
1966	735.4	−13.7	31.3	8	10.8	3	−20.5
1967	858.9	0.8	9.5	3	11.2	3	1.7
1968	753.7	−11.5	22.0	5	5.6	2	−16.4
1969	829.3	−2.7	14.5	3	4.0	1	−10.5
1970	939.6	10.3	8.6	2	20.6	8	12.0
1971	886.1	4.0	16.3	5	17.0	5	0.7
1972	653.4	−23.3	49.5	16	0.0	0	−49.5
1973	911.7	7.0	0.0	0	21.7	4	21.7
1974	747.1	−12.3	34.1	7	6.2	2	−27.9
1975	960.2	12.7	6.2	2	33.4	12	27.2
1976	854.9	0.3	12.3	4	13.1	4	0.8
1977	880.6	3.4	9.8	3	17.2	4	7.4
1978	908.1	6.6	2.7	2	25.4	9	22.7
1979	707.7	−16.9	49.2	13	7.1	2	−42.1
1980	882.7	3.6	8.8	2	12.9	2	4.1
1981	852.7	0.1	16.6	4	20.0	6	3.4
1982	735.3	−13.7	46.4	13	0.6	1	−45.8
1983	955.6	12.2	0.0	0	36.7	12	36.7
1984	835.7	−1.9	11.3	4	6.3	3	−5.0
1985	786.8	−7.7	28.8	9	9.9	2	−18.9
1986	746.5	−12.4	9.8	4	0.0	0	−9.8
1987	687.9	−19.3	64.3	16	8.3	4	−56.0
1988	990.6	16.3	0.0	0	48.9	18	48.9
1989	862.3	1.2	8.1	1	17.4	6	9.3
1990	917.1	7.6	4.6	2	19.2	6	14.6
1991	814.5	−4.3	29.1	6	14.9	6	−14.2

Table III. Large-scale deficient (dry) years of India, identified on the basis of different analysis of All-India/29 meteorological subdivisional monsoon rainfall data for the period 1871–1990

Serial number	Year	All-India monsoon rainfall Amount (mm)	Departure from normal (%)	Area of India with deficient rainfall conditions (%)	ISMR Index (%)	Rank based on ISMR Index
1	1873	755	−11.4	40.9	−40.9	10
2	1877	604	−29.1	66.8	−66.8	1
3	1899	629	−26.2	73.0	−62.7	2
4	1901	719	−15.6	45.4	−45.4	7
5	1904	750	−12.0	38.9	−38.9	12
6	1905	715	−16.1	40.1	−35.1	14
7	1907+	776	−8.9	27.8	−26.5	21
8	1911	733	−14.0	43.5	−40.7	11
9	1913*	782	−8.2	40.3	−25.2	22
10	1915*	780	−8.4	39.7	−28.1	18
11	1918	648	−23.9	68.2	−57.9	3
12	1920	718	−15.8	36.5	−31.6	16
13	1925*	803	−5.8	43.1	−29.9	17
14	1928+	766	−10.0	25.4	−23.1	23
15	1941	729	−14.4	41.8	−36.7	13
16	1951	737	−13.5	36.3	−32.0	15
17	1952+	792	−7.0	27.9	−27.9	19
18	1965	707	−17.0	43.0	−43.0	8
19	1966	735	−13.7	31.3	−20.5	24
20	1968*	754	−11.5	22.0	−16.4	25
21	1972	653	−23.3	49.5	−49.5	5
22	1974	747	−12.3	34.1	−27.9	20
23	1979	708	−16.9	49.2	−42.1	9
24	1982	735	−13.7	46.4	−45.8	6
25	1986+	747	−12.4	9.8	−9.8	26
26	1987	688	−19.3	64.3	−56.0	4

+ Identified by one index
* Identified by two indices

area over the country under rainfall deficiency (negative area) or excess (positive area). It is shown by Parthasarathy *et al.* (1991a) that the *Kharif* food-grain production (rice, wheat, sorghum, pearl millet, maize, chick-pea, pulses, etc.) of the country and ISMR index for the period 1966–88 had a high correlation of 0.865 (however, with All-India rainfall series the CC is 0.878) indicating that this index also adequately represents the net monsoon performance over the country. This index could be very useful to the governmental agencies for resource assessment and planning purposes. The mean (A) and standard deviation (S) of ISMR index are 0.2 and 24.1 respectively for the period 1871–1984. The lowest index value was −66.8 in the year 1877 and the highest 48.9 in the year 1988.

For identifying the extreme rainfall years based on ISMR index, the similar procedure as adopted in the earlier section is used, i.e. the index in any year if it is less than $A-S$ denoting a dry year and more than $A+S$ denoting wet year. It is observed that there were 17 wet years and 21 dry years during the data period (Fig. 5). There is a conspicuous clustering of dry and wet years in two periods:

(a) 1899–1925 containing eleven dry monsoon years, and

(b) 1933–1961 containing seven wet monsoon years.

The frequent occurrence of dry years during the period 1899–1925 caused severe hardship as the crop production was critically dependent on the rainfall in this period, with agricultural technology not as developed as at present. The Census reports of Mitra (1978) indicate that the population growth rate decreased from +5.8 per thousand during 1901–11 to −0.3 per thousand during 1911–21. This population decrease is mainly noticed over West Bengal, Bihar, Madhya Pradesh Orissa, Rajasthan, Maharashtra and Karnataka states, where many deficient rainfall years are also noticed during the decade 1911–20, clearly showing the disastrous impact of the monsoon failure.

Fig. 6 shows the decadal means of ISMR index during the period 1871–1990. It is interesting to note

Table IV. Large-scale excess (wet) years of India, identified on the basis of different analysis of All-India/29 meteorological subdivisional monsoon rainfall data for the period 1871–1990

Serial number	Year	All-India monsoon rainfall Amount (mm)	All-India monsoon rainfall Departure from normal (%)	Area of India with excess rainfall conditions (%)	ISMR Index (%)	Rank based on ISMR Index
1	1874	971	+14.0	38.5	36.2	7
2	1878*	974	+14.3	39.0	23.0	19
3	1884+	929	+9.1	36.2	13.0	21
4	1892	990	+16.2	46.7	44.4	3
5	1893	954	+11.9	32.2	28.3	12
6	1894	969	+13.8	29.8	26.6	15
7	1910	935	+9.7	37.3	37.3	5
8	1916	950	+11.5	33.0	33.0	10
9	1917	1003	+17.7	52.8	48.5	2
10	1933	973	+14.2	35.5	35.5	8
11	1936+	904	+6.1	27.7	13.3	20
12	1938+	908	+6.6	28.4	24.0	18
13	1942	958	+12.5	32.1	31.3	11
14	1944*	922	+8.2	29.5	24.8	17
15	1947	943	+10.6	29.8	29.8	12
16	1953*	920	+8.0	33.9	33.9	9
17	1956	980	+15.0	28.8	25.5	16
18	1959+	938	+10.1	24.4	9.1	23
19	1961	1017	+19.4	48.9	41.9	4
20	1970+	940	+10.3	20.6	12.0	22
21	1975	960	+12.7	33.4	27.2	14
22	1983	956	+12.2	36.7	36.7	6
23	1988	991	+16.3	48.9	48.9	1

+ identified by one index
* Identified by two indices

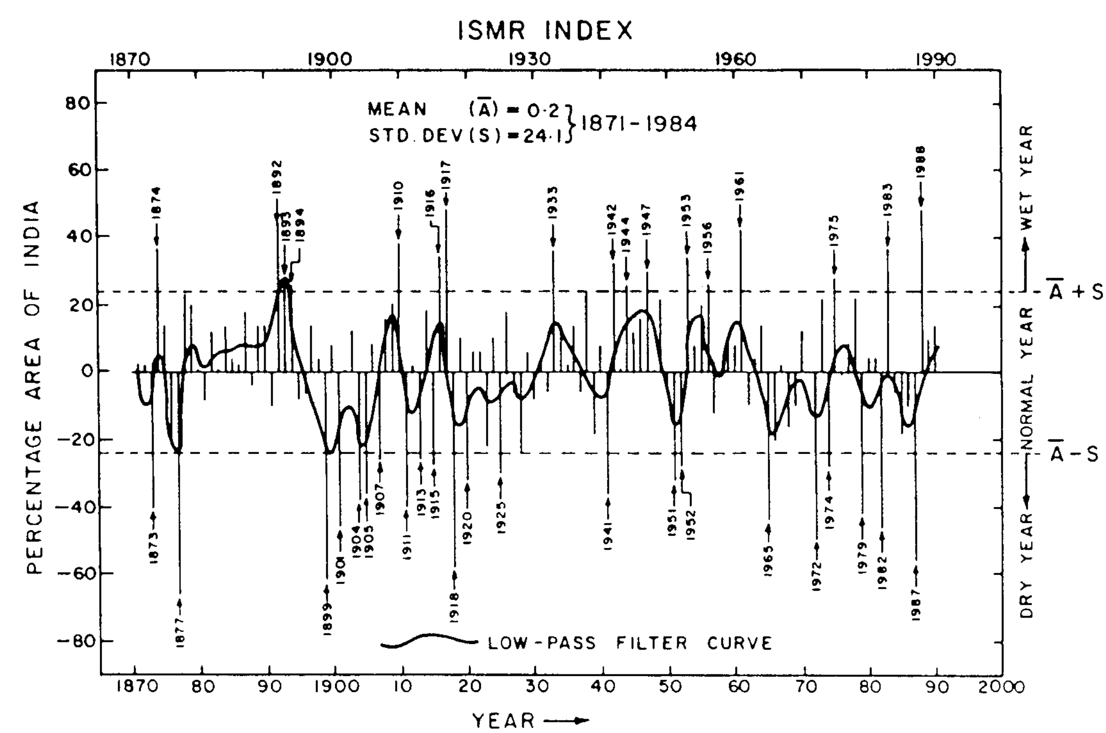

Figure 5. Year-to-year variation of Indian summer monsoon rainfall (ISMR) index for the years from 1871 onwards, wet/dry years are indicated against bars.

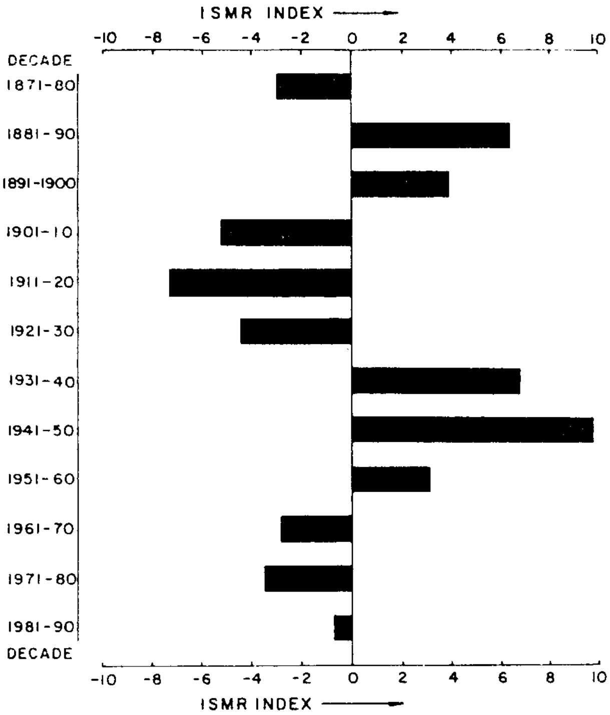

Figure 6. Decadal mean of ISMR index, for the period 1871–1990.

from Fig. 6 that three continuous decades (1901–30) reported negative index followed by three decades (1931–60) of positive index and, later again, three decades (1961–90) of negative index. It is well known that the release of latent heat energy over the Indian subcontinent is responsible for some of the low/middle latitudinal circulations over the globe (Fleer 1981). It can clearly be seen how this energy source has varied from long-term normal during the decades 1871–1990 (Fig. 6), further suggesting that some major circulation changes over India or other parts of the tropical regions might have taken place during these decades in response to the latent heat changes over India. Parthasarathy *et al.* (1991b), Fu and Fletcher (1988) and Elliott and Angell (1987, 1988) have shown that some evidence of large signals of decadal-scale climatic variations over the tropical regions of the globe. The present study provides some supporting evidence to their work.

To identify the significantly prolonged occurrence of extremes in the series, the 10-year moving *t*-test (called Cramer's test) as suggested by Lawson *et al.* (1981) has been applied on all the four series for the period 1871–1990. The calculated Cramer's *t*-values exceeding the table value of ±1.96 (significant at 5% level) have been found for:

(a) five decades in All-India rainfall series (1896–1905; 1897–1906; 1898–1907; 1899–1908 and 1965–74),

(b) three decades in DA series (1898–1907; 1899–1908 and 1911–20),

(c) four decades in EA series (1897–1906; 1898–1907; 1908–17 and 1923–32), and

(d) three decades in ISMR indices (1896–1905; 1898–1907 and 1899–1908).

The decade 1898–1907 (deficient rainfall period) was common in all the series. Thus, it can be seen that there were definite clusters of positive and negative extremes in the rainfall roughly in the periods separated by the turning point mentioned above. These are not gradual changes but are in the form of epochs.

The above four series have also been subjected to power spectrum analysis following the Blackman–Tukey algorithm (Mitchell *et al.*, 1966) to find significant periodicities if any. The only significant cycle at 5% level corresponding to Quasi-Biennial Oscillation (2–3 years) in the series. However, this cycle accounts for only about 10% or less of the total variance and therefore is of limited practical application.

The intercorrelations among the four indices are presented in Table V. All the Correlation Coefficients (CCs) are high and statistically significant at 0.1% level. The CC between DA and EA, though negative as expected, is relatively low, indicating that they do not necessarily exclude each other. The ISMR index is highly sensitive to both DA and EA as well as the All-India monsoon rainfall.

7. Discussion

In this study, the monsoon rainfall performance over India has been quantified in four different ways, which may be useful for different purposes. Identification of large-scale deficient (dry) or excess (wet) years of the country are of primary concern to the planners, as the economy is dependent upon these vagaries.

Out of the 26 dry years based on different indices (Table III), 18 years are common to all types of the indices. Three years (1913, 1915 and 1925) are identified as dry years by only two indices while five years (1907, 1928, 1952, 1968 and 1986) are identified as dry years by only one index. Therefore, it can be inferred that the country has suffered from large-scale deficient conditions in 18 years during 1871–1990 and the other years might have had marginal rainfall deficiency. Out of the 23 wet years based on different indices (Table IV), 15 years are common to all types of the indices. Three wet years 1878, 1944 and 1953 indicated by only two indices while five wet years 1884, 1936, 1938, 1959 and 1970 are indicated by only one index.

8. Conclusions

Suitable indices are presented to represent the Indian summer monsoon rainfall during the data period 1871–1990 based on area-weighted mean rainfall series of 29 subdivisions, in turn computed from the rainfall data at 306 well-distributed rain-gauges over the country. The following are the main conclusions of the study:

(a) The mean All-India monsoon rainfall for the period 1871–1984 is 852 mm, with a standard deviation (S) of 83 mm and CV of 9.8%.

(b) The rainfall was below average in many years during 1899–1920 and 1962–87, and above average during 1874–94 and 1942–61.

Table V. Interrelationships (CCs) between the indices for the period 1871–1984

Indices	SMRF	DA	EA	ISMR
All-India summer monsoon rainfall (SMRF)	1.0			
Deficient area (DA)	−0.84	1.0		
Excess area (EA)	+0.78	−0.45	1.0	
ISMR index	+0.95	−0.90	+0.80	1.0

(c) The mean percentage area of the country with deficient area (DA) rainfall condition is 15.1 with an S of 16.3 and CV 108%, respectively and those for the Excess Area (EA) are 15.3, 12.0 and 78%, respectively.
(d) On the basis of different classifications there are mainly 18 large-scale dry years and 15 large-scale wet years. Many dry years are bunched during 1899–1925 while many wet years during 1933–1961.
(e) The ISMR index was continuously negative for three decades 1901–30, positive 1931–60 and again became negative during the current period 1961–90.

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Tropical cyclones in the south-west Indian Ocean — track prediction and verification 1989–91

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Summary

The skill of the United Kingdom Meteorological Office weather prediction model in forecasting cyclone tracks in the south-west Indian Ocean is evaluated for the period 1989–91. The track predictions of the model are shown to be useful up to day 3. Mean track errors grow from an initialization value of 172 km to over 500 km by day 3. Cyclones which cross the highlands of Madagascar are not well handled by the model, recurving poleward while predictions maintain westward movement due to model resolution, the steep topography, and consequent entrainment of flow around Madagascar. The forecasting skill of the model is affected by the background flow patterns. Tropical westerlies increased in the 15° S zone in the first season and model errors were smaller.

1. Introduction

On average, ten tropical cyclones (TCs) form and move across the south-west Indian Ocean (5–30° S, 30–90° E) each summer from November to April (Crutcher and Quayle 1973). Approximately two reach the intense cyclone stage causing destruction to the islands of Mauritius, Rèunion and Madagascar and posing a threat to busy shipping lanes (Padya 1989). TCs form most frequently along the Inter-Tropical Convergence Zone (ITCZ) near 13° S, 63° E where low-level horizontal shear between equatorial monsoon westerlies and subtropical trade winds is overlain by an anticyclonic circulation above 200 mb. Sea surface temperatures (SSTs) average 28 °C in the December–March period (Halpert and Ropelewski 1989) and zonal upper-level flow is often absent (Arkin *et al.* 1986). Pre-existent forcing of cyclogenesis by easterly waves and by surges of the north-west monsoon has been noted (Jury *et al.* 1991, Jury 1992). TCs usually move in a south-westerly direction north of 20° S and east of 50° E (Neumann and Randrianarison 1976). To the south-west, the encroachment of subtropical westerlies, the highlands of Madagascar and a semi-permanent subtropical trough all contribute to poleward recurvature (Jury and Pathack 1991).

In recent years numerical weather prediction systems such as the United Kingdom Meteorological Office (UKMO) model have shown increasing usefulness in forecasting the evolution of large-scale weather systems, primarily in the extratopical baroclinic zone. The accurate prediction of TC intensity and track remains elusive, as evidenced by comparisons of numerical forecast errors in the tropical zone and persistence errors (Flood 1985). Towards improving forecasts for these small-scale tropical systems, the model data assimilation and analysis scheme, and spatial resolution are continually being upgraded (Bell and Dickinson 1987). Such improvements may not become immediately evident owing to the interannual variability of tropical circulation. Brankovic *et al.* (1988) point out that model skill response to climatic fluctuations may be more variable than the improvement in skill brought about by model reformulation or resolution change. Over the 1989–91 period considered here, it can be noted that the UKMO model data assimilation and meteorological analysis scheme remained unchanged.

Morris (1989) reviews the capabilities and attributes of the UKMO numerical weather prediction model. The model has a horizontal resolution of about 200 km in the tropics and is thus only able to resolve the large-scale structure of tropical cyclones. In the physics parametrization, radiation is non-interactive and convective processes are crudely represented. The specification of upper winds by geostationary satellite presents a significant problem in the Indian Ocean region. Meteosat provides SATOB data to 60° E while GMS data begins at 90° E. INSAT data have thus far proved unreliable. Hence the quality of model analyses in the central Indian Ocean is compromised, not only by lack of geostationary satellite coverage, but also by the reduced volume of shipping and aircraft reports.

A bogusing procedure is implemented for TCs which makes use of local TC Warning Centre data and satellite imagery to correct the position of or locate a warm-core vortex through the input of winds in the 850–500 mb layer. In the UKMO numerical model, TC motion appears to be controlled by the interaction of the mean flow and the vorticity advection above 500 mb. The model assumes an in-phase and predominantly symmetrical relationship between wind and temperature fields below 500 mb (Morris and Hall 1987). The TC steering level is typically around 500 mb, but can be higher for intense systems with convection overshooting the tropopause (Padya 1989).

2. Background

The aim of this paper is to evaluate the skill of TC track predictions of the UKMO model for the 1989–90 and 1990–91 seasons in the south-west Indian Ocean. The TCs include:

Name	Date	Min. pressure (mb)	Max. sustained wind ($m\ s^{-1}$)
Alibera	16 Dec. 89–6 Jan. 90	975	30
Baomavo	3 Jan. 90–8 Jan. 90	945	33
Cezera	3 Feb. 90–9 Feb. 90	990	20
Dety	3 Feb. 90–9 Feb. 90	990	20
Edisaona	2 Mar. 90–8 Mar. 90	955	35
Felana	10 Mar. 90–15 Mar. 90	986	22
Gregoara	15 Mar. 90–24 Mar. 90	930	40
Hanta	13 Apr. 90–14 Apr. 90	1000	10
Ikonjo	14 May 90–21 May 90	984	22
Alison	4 Jan. 91–9 Jan. 91	975	27
Bella	23 Jan. 91–4 Feb. 91	942	35
Cynthia	15 Feb. 91–20 Feb. 91	990	20
Debra	23 Feb. 91–3 Mar. 91	965	27
Elma	28 Feb. 91–2 Mar. 91	970	25
Fatima	23 Mar. 91–2 Apr. 91	975	25
Gritelle	10 June 91–15 June 91	984	20

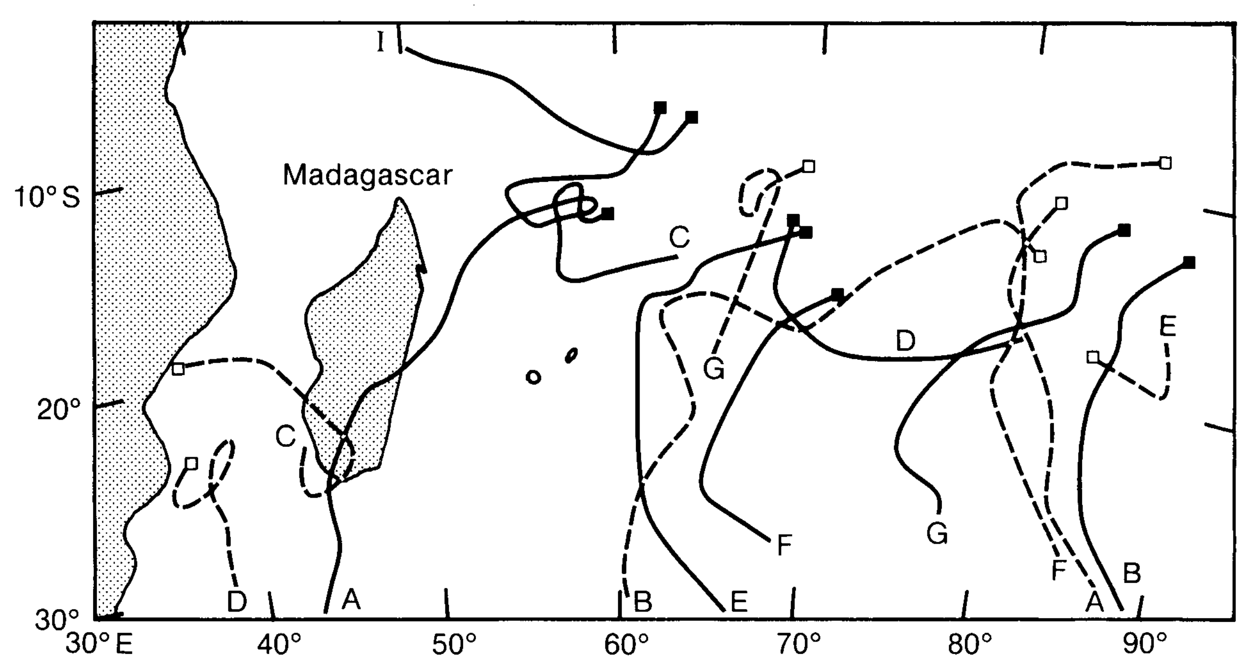

Figure 1. Tropical cyclone (TC) genesis points and tracks for 1989–90 (solid squares and solid lines) and 1990–91 (open squares and dashed lines). Letters refer to alphabetical names of TCs, see text for full names.

The 1989–90 summer is more active with nine TCs; close to the average for the region. The last cyclones of both seasons were quite late (May, June). TC genesis and tracks are shown in Fig. 1 and a general south-westward displacement is evident. The track of the late cyclone, Ikonjo was slightly equatorward. TCs which moved or formed near South Africa include Alibera, the first cyclone of the 1989–90 season, which tracked south-westward over Madagascar in early January 1990 and Debra which developed at 24°S, 37°E, on 23 February 1991. Cezera, Dety, Hanta and Elma have been excluded from further analysis owing to lack of data or limited lifespan.

3. Data

All available weather data on TC track and intensity were analysed by the shipping forecaster at the headquarters of the Weather Bureau of the Republic of South Africa (RSA) in Pretoria at 00 and 12 UTC. The south-west Indian Ocean observations, both direct and indirect, include warnings from TC Warning Centres at Réunion, Mauritius and Madagascar; ship, coastal and island synoptic reports and radiosonde and pibal profiles; Meteosat, NOAA and INSAT satellite images, UKMO advisories and gridded numerical output from the ECMWF and UKMO models. According to forecasters at the south-west Indian Ocean TC Warning Centres at Mauritius and Réunion, the discrepancy between the analysed and observed TC eye is about 55 km. The UKMO model analysed TC positions for 00 and 12 UTC were taken from GTS advisories. The distance or displacement error between the observed and predicted TC position was calculated. Seasonal mean errors were computed by weighting the contribution by each TC according to the number of forecasts. Emphasis is placed on the evaluation of the day 1 forecasts. As shown in Table I, the day 0 initialization error is 163–182 km, and this impacts on subsequent forecast errors. The initialization error is due to the lack of eye in many of the weaker systems, leaving room for subjective errors in the observed position, and to the model resolution as previously mentioned.

4. Results

4.1 Observed climatology, anomalies and seasonal differences

The genesis and tracks for all TCs in the 1989–91 seasons is shown in Fig. 1. The genesis positions can be distinguished by area: two in the Mozambique Channel in February 1992, three near 10°S, 60°E in 1989–90, four in the 70°E longitude, and six to the east of 80°E. A break in cyclone tracks appears in the vicinity of Réunion (21°S, 55°E). The genesis points to the east of Madagascar were more zonally aligned than usual possibly due to the orientation of SST isotherms (Climate Analysis Centre bulletins 1989–1991). During the 1989–90 December–March TC season, the south-west Indian Ocean anticyclone and associated trade winds in the 30°S band were above normal. In addition, tropical monsoon westerlies were persistently above normal to the north-east of Madagascar (contributing to formation of the TC pair Cezera and Dety). Together these circulation features enhanced 850 mb cyclonic

Table I. Mean distance error (km) between the UKMO forecast and the true positions of the cyclones for different forecast periods (days) for all the cyclones. The values in brackets are the number of forecasts used to calculate the mean distance error.

Cyclone names	Forecast period (days) 0	1	2	3	4	5
1989/90 season						
Alibera	172 (15)	395 (13)	614 (12)	792 (11)	969 (9)	924 (8)
Baomavo	180 (10)	274 (9)	356 (7)	493 (5)	777 (4)	965 (2)
Edisaona	267 (8)	255 (7)	296 (8)	311 (8)	454 (8)	464 (5)
Felana	221 (5)	394 (5)	478 (5)	614 (3)	393 (1)	399 (1)
Gegoara	208 (11)	303 (10)	401 (9)	309 (6)	541 (7)	1074 (5)
Ikonjo	117 (15)	161 (14)	265 (13)	250 (7)	344 (3)	248 (1)
Seasonal means	182 (64)	287 (58)	401 (54)	478 (40)	646 (32)	803 (22)
1990/91 season						
Alison	299 (8)	317 (10)	481 (10)	677 (8)	586 (6)	510 (3)
Bella	158 (20)	256 (20)	413 (18)	642 (15)	702 (12)	861 (6)
Cynthia	223 (8)	144 (4)	240 (4)	238 (3)	157 (1)	111 (1)
Debra	138 (17)	231 (12)	344 (7)	503 (4)	917 (3)	—
Fatima	112 (18)	223 (18)	435 (16)	594 (14)	669 (12)	835 (8)
Gritelle	139 (6)	211 (7)	339 (6)	686 (4)	891 (4)	679 (2)
Seasonal means	163 (77)	241 (71)	404 (61)	601 (48)	696 (38)	742 (20)

vorticity during the 1989–90 season. In 1990–91, 850 mb wind anomalies were less intense and the flow pattern was dominated by subtropical Rossby waves of short wavelength. One such trough was located over the Mozambique Channel in February 1991 (Climate Analyses Centre bulletins 1991), spawning two cyclones there. The 200 mb 10 m s^{-1} isotach retreated south of 20°S in January and March 1990 and in February 1991 Outgoing Long-wave Radiation (OLR) anomalies to the north-east of Madagascar were below normal (convective) in December 1989 and February 1990. In the 1990–91 season a low/west–high/east convective dipole moved slowly across the region from southern Africa to the south-west Indian Ocean. In February 1991 the convective part of the dipole, as seen in the OLR pattern, crossed into the Mozambique Channel in association with the eastward movement of the low-level subtropical trough.

4.2 Track errors for individual TCs

Table I and Fig. 2 show the accumulated track errors associated with forecasts from 0 to 5 days for individual TCs. The displacement errors of the UKMO model in forecasting TC position increases after day 2. For individual TCs such as Edisaona, Felana and Ikonjo in 1990 the day 4 and 5 skill is reasonable (i.e. below 400 km error). It is notable that the early season TCs of 1989 were poorly forecast, particularly Alibera the first of the season.

TCs of the 1990–91 season also show the trend of decreasing errors in mid season, with Cynthia forecast best and Alison faring worst in day 2 and 3 forecasts. Debra in the Mozambique Channel, was well forecast up to day 2, but looped back instead of heading poleward, causing day 4 and 5 forecasts to 'explode'. In many cases TCs were dissipated too soon by the UKMO model. Debra lasted 9 days, but was forecast to dissipate after day 4. It would appear that the model drifts to the climatological mean too quickly, possibly due to insufficient observations which impair thermodynamic forcing in the model. The seasonality of forecasting skill is seen after day 3 for TC Gritelle which dissipated quickly after merging with a mid-latitude front in June 1991.

A closer look at Alibera December 1989 and Debra February 1991 is taken in Fig. 3. These two contrasting examples were chosen by virtue of their influence on the weather of south-east Africa. Alibera formed on 16 December 1989 to the north-east of Madagascar and tracked reasonably close to the climatological mean. However, on reaching the highlands of Madagascar, Alibera recurved poleward (996 mb, 20 m s^{-1} winds), while the forecast track was south-westward. Track errors grew to 969 km as a result of the poor handling of orographic friction and interaction with a weak mid-

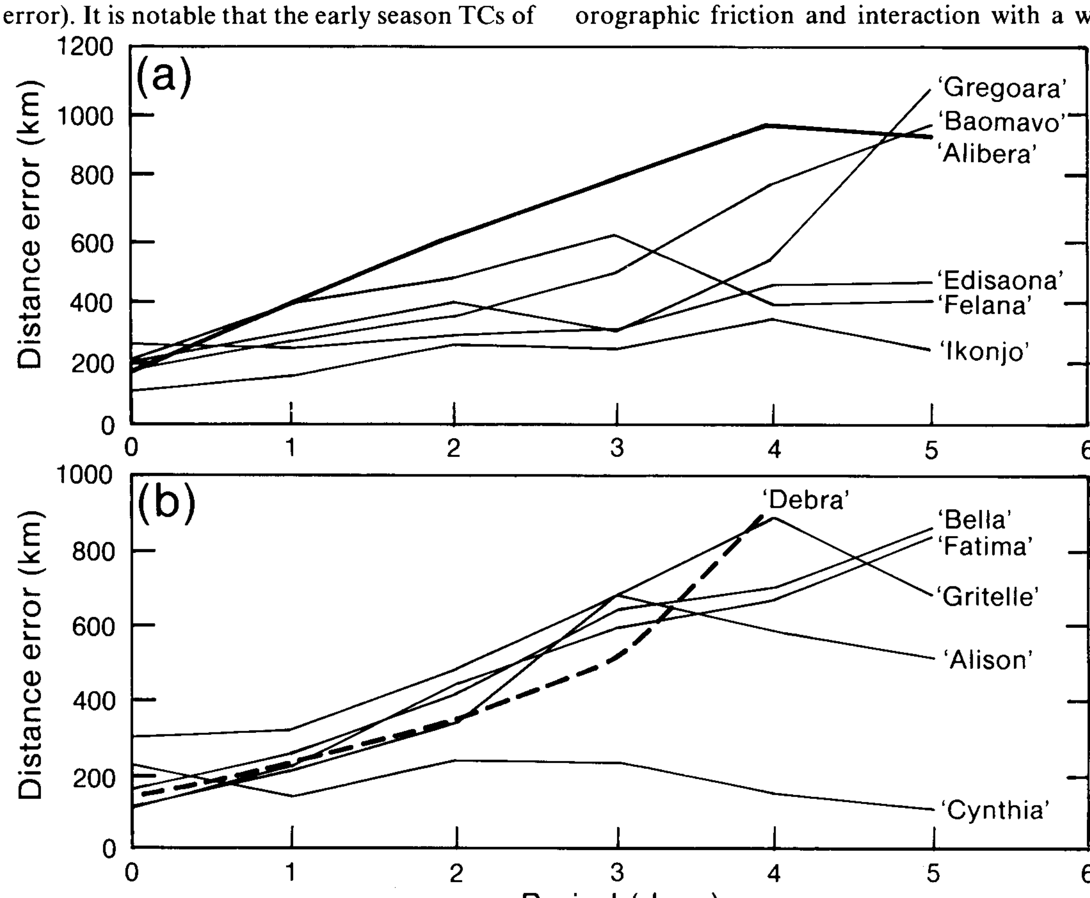

Figure 2. Distance error of predicted versus observed tropical cyclone positions for 0–5 day forecast periods for (a) season 1989–90, and (b) season 1990–91.

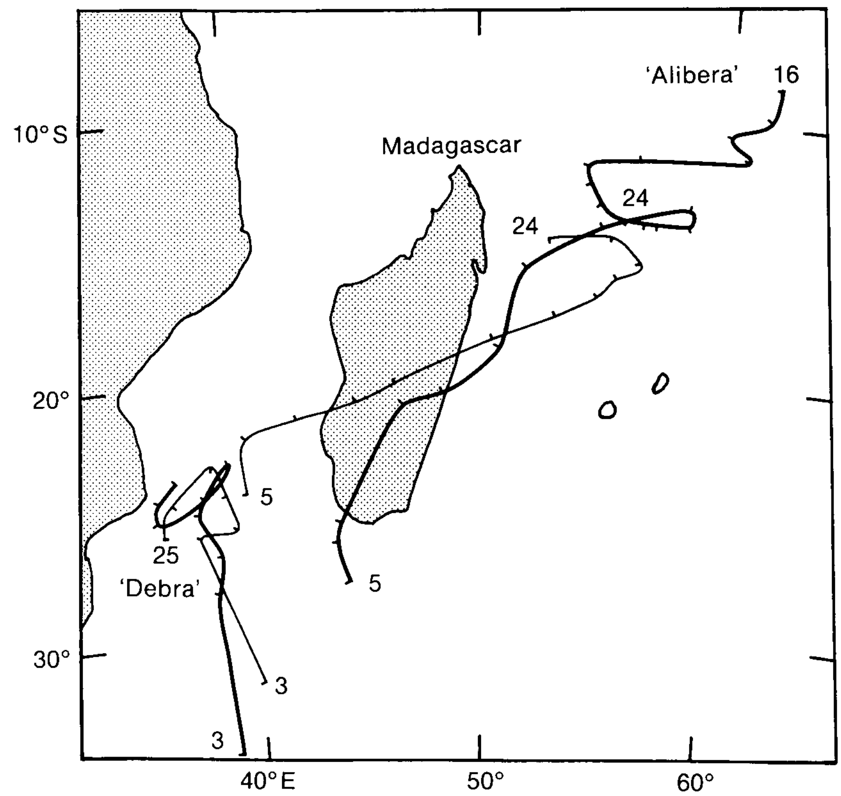

Figure 3. Tropical cyclone observed track (bold line) and 1-day forecast track (thin line) for Alibera and Debra. Numbers refer to dates, tick marks show daily positions.

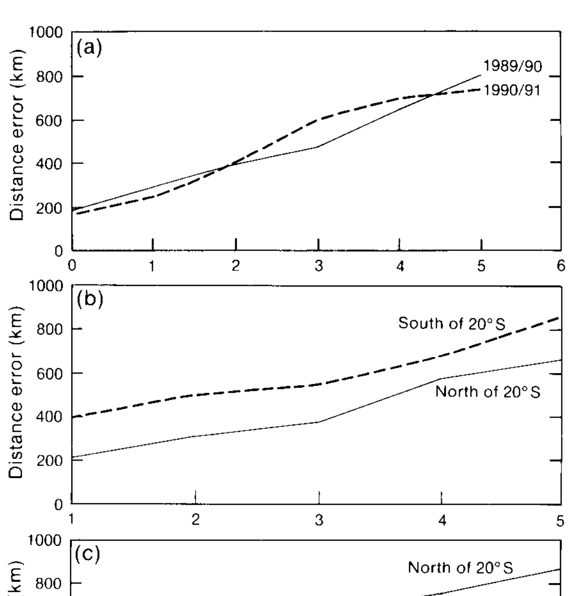

Figure 4. Mean distance error of predicted versus observed tropical cyclone positions for (a) 0–5 day forecast periods for 1989–90 and 1990–91 (dashed) seasons, (b) distance error for 1–5 day forecast periods for zone north and south (dashed) of 20° S for 1989–90 and (c) as in (b) except for 1990–91.

latitude trough. Morris (1989) indicates that the UKMO model often transfers a TC which approaches Madagascar from the north-east in a westerly track across the mountainous island. Debra, in contrast, formed and looped in the subtropical Mozambique Channel (992 mb, 20 m s^{-1} winds) then became extratropical after 4 March 1991. Debra was forecast with reasonable skill up to day 3. The day 1 forecast track handled the looping and poleward acceleration reasonably well (Fig. 3).

4.3 TC track errors by season and latitude zone

The seasonal mean initialization error declined slightly from 1990 to 1991. Errors for day 1 and 2 forecasts in 1989–90/1990–91 grew from 287 km/241 km to 401 km/404 km, respectively. The greatest difference between the seasonal means is at day 3 (Fig. 4(a)) where errors in the second season were 123 km larger than the first. The average difference for all forecast times is only 8 km and the UKMO model performance appears unchanged over the two seasons. The error budget compares well with similar results reported by Morris and Hall (1987) for TCs in the North Atlantic and north Pacific Ocean basins.

The mean recurvature latitude of 20° S for TCs in the south-west Indian Ocean (Neumann and Randrianarison 1976) was utilized to make comparisons of track errors to the north and south (Table II and Figs 4(b) and 4(c)). In the first season, mean errors north of 20° S were much

Table II. As Table I but for demarcation at 20° S

Cyclone names	Forecast period (days) 1	2	3	4	5
1989/90 season		North of 20° S			
Alibera	269 (6)	444 (5)	570 (5)	819 (4)	920 (3)
Baomavo	107 (3)	163 (2)	—	—	—
Edisaona	255 (7)	331 (6)	377 (5)	488 (3)	493 (2)
Felana	351 (1)	—	—	—	—
Gegoara	317 (3)	369 (2)	—	—	—
Ikonjo	161 (14)	265 (13)	250 (7)	344 (3)	248 (1)
Seasonal means	214 (34)	311 (28)	381 (17)	577 (10)	666 (6)
		South of 20° S			
Alibera	504 (7)	737 (7)	977 (6)	1089 (5)	926 (5)
Baomavo	358 (6)	433 (5)	493 (5)	777 (4)	965 (2)
Edisaona	—	194 (2)	201 (3)	434 (5)	444 (3)
Felana	405 (4)	478 (5)	614 (3)	393 (1)	399 (1)
Gegoara	298 (7)	411 (7)	309 (6)	541 (7)	1074 (5)
Ikonjo	—	—	—	—	—
Seasonal means	391 (24)	499 (26)	549 (23)	677 (22)	854 (16)
1990/91 season		North of 20° S			
Alison	453 (5)	548 (6)	571 (4)	440 (2)	—
Bella	273 (12)	580 (10)	859 (7)	954 (3)	1068 (4)
Cynthia	—	—	—	—	—
Debra	—	—	—	—	—
Fatima	183 (13)	406 (11)	552 (9)	632 (7)	618 (4)
Gritelle	211 (7)	339 (6)	686 (4)	1031 (3)	1023 (1)
Seasonal means	254 (37)	472 (33)	667 (24)	751 (15)	863 (9)
		South of 20° S			
Alison	181 (5)	381 (4)	784 (4)	660 (4)	510 (3)
Bella	232 (8)	204 (8)	453 (8)	618 (9)	449 (2)
Cynthia	144 (4)	240 (4)	238 (3)	157 (1)	111 (1)
Debra	231 (12)	344 (7)	503 (4)	917 (3)	—
Fatima	326 (5)	499 (5)	670 (5)	720 (5)	1051 (4)
Gritelle	—	—	—	471 (1)	334 (1)
Seasonal means	198 (39)	322 (28)	535 (24)	660 (23)	643 (11)

lower than to the south (Fig. 4(b)). A Wilcoxon sum of ranks test indicates that the difference between track errors in the two areas is significant at 95% for day 1. In the 1989–90 season nine TCs formed in random positions in the tropical monsoon westerlies, but were subsequently better predicted.

While TC track errors were lower in the tropical zone in the first season, Fig. 4(c) reveals the opposing trend in the second season. The 1990–91 season had seven TCs, most forming east of 80° E. Given the lower intensity of monsoon westerlies (Climatic Analysis Centre bulletins, 1991) it is likely that many TCs formed as an outgrowth of easterly waves. Poor short-term forecasts of TC tracks in the tropical zone could be attributable to the interaction of an eastward-moving low-frequency mode in the subtropics and higher frequency westward-moving barotropic waves in 1990–91. Although the extratropical band was better predicted in the latter season, no statistically significant differences in the two latitude zones could be found.

5. Discussion

A study of TC track prediction based on the UKMO model advisories has been made for the south-west Indian Ocean. The day 1 to 3 forecasts were shown to be useful, keeping in mind the large day 0 displacement error. Little forecasting skill was found beyond day 3. Problems were encountered when TCs moved across the large mountainous island of Madagascar. From statistical analyses, track errors in different latitude zones reveal that differing climatological background patterns can have a varying effect on the forecast skill of the model. The tendency in the model to dissipate cyclones too early may be a drift in the model to background climatology. Other deficiencies in the model (Morris 1989) include the inability to discriminate between depressions and cyclones, and the absorption of a TC pair by the poleward system. A positive attribute is the ability of the model to predict TC genesis in response to upper dynamical forcing.

In general, TC interaction with baroclinic waves and subsequent poleward acceleration appears less easily predicted, in the seasons considered here, than steering by steady tropical flow. In the south-west Indian Ocean predictability is complicated by: low-frequency surges of the north-west monsoon (Wang and Rui 1990), the absence of a background zonal easterly flow in the 500–300 mb layer, the intermittent nature of high-frequency barotropic easterly waves, and a lack of upper-level observations near the ITCZ over the central ocean basin. Further studies are planned using detailed ECMWF and UKMO model analyses to elucidate meteorological processes influencing TC formation and steering, and kinematic–thermodynamic interactions in the south-west Indian Ocean. It is hoped that the upgraded capabilities of the next generation of weather satellites and high-resolution numerical models will assist in this endeavour.

Acknowledgements

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The summer of 1991 in the United Kingdom

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Summary

Despite the very cold and rather miserable June, the summer as a whole was rather warm, rather dry, though with average sunshine.

1. The summer as a whole

Although June was unusually cold, over the summer as a whole temperatures were above average nearly everywhere, except in parts of Wales and south-west England, and ranged from 1 °C above average in western Scotland and on the Norfolk/Suffolk coastal stretch to 0.5 °C below average in parts of south-west England. Rainfall amounts over the summer season were generally below average, although in southern England amounts of rain were generally above average and reached more than 150% of average along the coast of East Sussex, as against only 41% of average in Lincolnshire. Sunshine amounts were about average generally, although it was rather sunny over northern and western Scotland and eastern and central parts of England, but dull over North Wales, north-west England, and much of south-western and central Scotland, ranging from more than 120% in South Yorkshire to less than 80% in North Wales.

Information about the temperature, rainfall and sunshine during the period from June 1991 to August 1991 is given in Fig. 1 and Table I.

2. The individual months

June. Mean monthly temperatures were below normal in all areas of the United Kingdom, ranging from 2.7 °C below normal at Macclesfield, Cheshire to

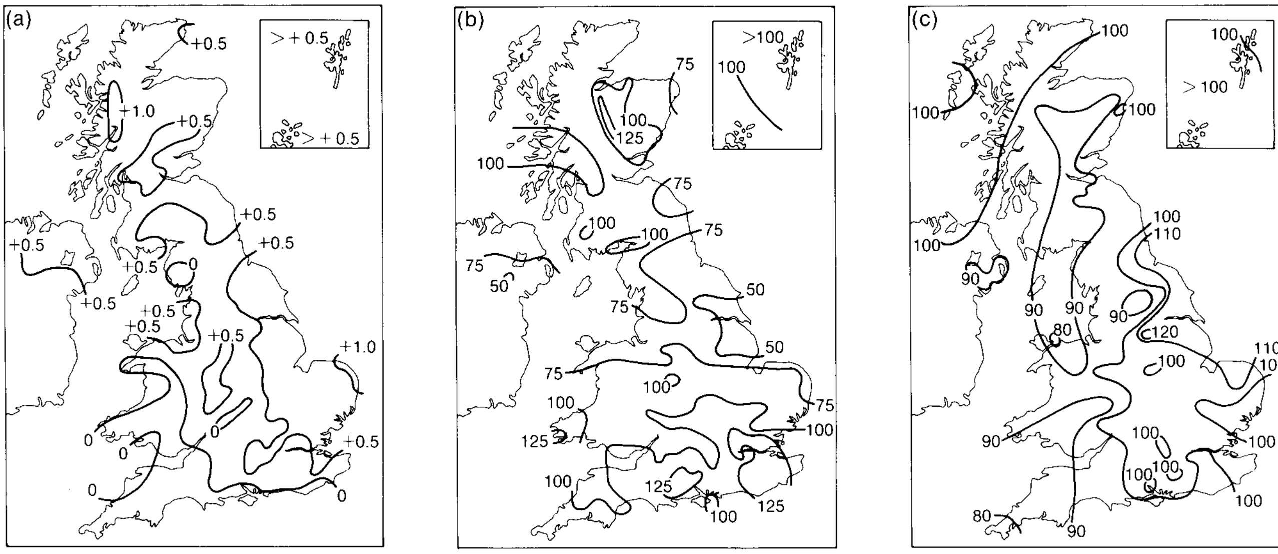

Figure 1. Values of (a) mean temperature difference (°C), (b) rainfall percentage and (c) sunshine percentage for summer, 1991 (June–August) relative to 1951–80 averages.

Table I. District values for the period June–August 1991, relative to 1951–80 averages

District	Mean temperature (°C)	Rain-days	Rainfall	Sunshine
	Difference from average		Percentage of average	
Northern Scotland	+0.7	0	88	103
Eastern Scotland	+0.6	0	96	93
Eastern and north-east England	+0.6	0	70	105
East Anglia	+0.6	+1	94	104
Midland counties	+0.3	0	94	105
South-east and central southern England	+0.2	+2	125	104
Western Scotland	+0.5	+1	97	95
North-west England and North Wales	+0.3	+2	86	90
South-west England and South Wales	+0.3	+3	108	92
Northern Ireland	+0.6	+1	82	98
Scotland	+0.6	0	94	97
England and Wales	+0.3	+2	95	100

Highest maximum: 30.6 °C in East Anglia in July.
Lowest minimum: −3.8 °C in western Scotland in June.

0.7 °C below normal at Lowestoft, Suffolk. Frost occurred quite widely during the first week. Bastreet, Cornwall had a minimum of −1 °C on the 2nd. The temperature over grass at Birmingham Airport fell to −6 °C on the 5th and this was the coldest June night since records began at a number of places; this included the lowest of the month (−3.8 °C) at Carnwath, Strathclyde Region, the lowest for June at that station since the record began in 1952. Monthly rainfall amounts were above normal nearly everywhere apart from a few locations, mainly in western areas where it remained dry; nearly three times the normal in East Sussex contrasted with as little as half the normal in western Scotland. Monthly sunshine amounts were below average everywhere except for a few places, mainly in northern Scotland, where they were above or near normal, and ranged from 109% of average at Tiree, Strathclyde Region to 50% of average at Bexhill, East Sussex. The month was one of the dullest Junes this century over a wide area. Sunny days were mainly limited to the 3rd and 13th in the south-west of England and the 20th more widely across England and Wales, apart from the south-east.

The weather was generally unsettled, with outbreaks of rain or drizzle, and more prolonged rain from time to time, heavy in places, or showers, often thundery and sometimes of hail. Sleet and snow fell on the Grampian Mountains on the 2nd and 3rd, and on the Southern Uplands on the 3rd; snow lay at Cairngorm Carpark for three days. Snow fell on the northern Pennines on the 3rd, hail was reported at Inverness, over North Yorkshire and north Norfolk, and thunder over Salisbury Plain. On the 23rd torrential rain over the south and west caused extensive flooding, particularly in Plymouth and Torquay, Devon and Bridport, Dorset, while in Cornwall some rivers burst their banks.

Thunderstorm frequency was very high during the month, particularly in eastern areas, with thundery activity reported somewhere in the United Kingdom on nearly every day.

July. Mean monthly temperatures were above normal nearly everywhere, ranging from more than 3 °C above normal in the western Highlands to nearly 1 °C below normal in the Isles of Scilly. Scotland had one of the warmest Julys on record. Monthly rainfall totals were above normal in northern Scotland, Shetland and Orkney, the Forth–Clyde Valley, and England and Wales south of a line from Anglesey to Essex, and below normal elsewhere, and ranged from 280% in the Isles of Scilly to as little as 26% in Lincolnshire. Monthly sunshine amounts were above average over westernmost areas of Scotland and the whole of England apart from the south-west peninsula, and below average elsewhere, ranging from 138% at Cromer, Norfolk to just over 50% in west Cornwall.

The weather was changeable, with showers, sometimes accompanied by thunder, and longer periods of rain. Heavy rain fell in parts of Scotland, Northern Ireland and northern England on the 1st. During the afternoon of the 2nd rain spread across Kent and Sussex, where thunder was reported, later spreading across south-eastern England, East Anglia and the Midlands; thunderstorms occurred over North Wales and north-west England, with heavy showers, some of hail. Thunderstorms, some severe with hail, moved northwards over southern England late on the 5th, and crossed parts of Wales and the Midlands during the night; further thunderstorms occurred over Wales and north-west England early on the 6th and again widely on the 7th. Lightning caused structural damage in North Wales and Scotland on the 8th. On the 13th a short-lived tornado caused damage to roofs and power lines at Castle Bytham, south-west Lincolnshire. Thundery outbreaks over south-west England on the 23rd became widespread by the evening, with the south-east being the worst affected. The main thundery activity moved to East Anglia and eastern England on the 24th. Further heavy rain fell over parts of south-east England and the Midlands on the 30th.

August. Mean monthly temperatures were above normal nearly everywhere, ranging from near normal in the Isles of Scilly to 2.0 °C above normal in parts of East Anglia. Monthly rainfall amounts were below normal nearly everywhere, ranging from 112% at Stornoway, Western Isles to as little as 6% at Finningley, South Yorkshire. This was generally the driest August since that of 1976. Apart from parts of Scotland and northern England, most places had no rain after the 23rd. August was the driest at Valley, Gwynedd since 1976, at Coventry, Warwickshire since 1947, and over Northern Ireland since 1983. Monthly sunshine amounts were above average nearly everywhere and ranged from 143% in East Kent to 82% at Benbecula, Western Isles. Sunshine amounts were generally higher than those of August 1990 in north-western areas. Northern Ireland had its sunniest August since 1977.

Very moist air brought cloud and mist and kept sunshine amounts as well as temperatures low in some places in the west, while fronts, although they crossed all areas, soon weakened as they moved south-eastwards, giving negligible amounts of rain in the east. However, thundery showers produced localized heavy rainfall. On 1 August thunderstorms over East Anglia and south-east England caused flooding and disrupted traffic: lightning killed one person in Kent, injured two people in Essex, and caused structural damage in south-east London. Further thundery outbreaks occurred over northern England and Scotland on the 6th, 16th, 17th and 22nd, and over Wales and south-west England on the 23rd. Late on the 30th lightning was observed over Cornwall and the Channel Islands as thunderstorms drifted northwards over the English Channel and on the 31st thunderstorms occurred over Cornwall and South Wales.

Latest Climate Assessment

28 May saw the publication of the authoritative update on climate change which has been produced by the Scientific Assessment Working Group of the United Nations Intergovernmental Panel on Climate Change (IPCC).

For world leaders and officials who attended the UNCED 'Earth Summit' in Rio de Janeiro, Brazil — where a key item on the agenda was the the signing of a convention on Global Climate — the Report provided a timely reminder of the continuing scientific concerns about global warming due to the emission of greenhouse gases.

Climate Change 1992: The Supplementary Report to the IPCC's Scientific Assessment, published by Cambridge University Press, is the result of 12 months of intensive work by IPCC Working Group I.

The Report is an update to the definitive and widely accepted first *Scientific Assessment* published in 1990. Read in conjunction with the 1990 Report, it provides policymakers worldwide with the best available consensus of contemporary scientific opinion on climate change, and essential reading for the Rio delegates and all those who have an interest in the future of global climate.

The 1992 Supplementary Report upholds the major conclusions of the 1990 Assessment but introduces new research which sheds light on such subjects as the climate effects of pollution, ozone depletion by CFCs and volcanoes. Recent UN projections of future world population and economic growth are all incorporated in a range of predictions of global warming.

Under the chairmanship of Sir John Houghton, the Supplementary Report was compiled on the basis of contributions from 118 scientists from 22 countries, and was reviewed by a further 380 specialists from 63 countries and 18 UN and non-governmental organizations.

Review

Mid-latitude weather systems, by T.N. Carlson. 152 mm × 234 mm, pp. xx+507, *illus.* London, Routledge, 1991. Price £19.95 (paperback, ISBN 0 04 551116 0), £75.00 (hardback, ISBN 0 04 551115 0).

In this book the author attempts to fuse together two differing disciplines within meteorology, that of the synoptician and that of the dynamicist. The stated aims are to enable students of dynamical meteorology to relate their knowledge to processes depicted on weather charts and, at the same time, allow those more familiar with chart material to interpret synoptic patterns in terms of dynamics. The author is particularly well qualified to tackle this difficult task, having studied synoptic meteorology under one of the best-ever exponents of the art, the late Professor Ludlam, and having since published many papers involving both aspects of meteorology.

The first three chapters give a rather brief overview of the basic equations of dynamical meteorology, more an *aide-mémoire* for those already familiar with the subject than a formal introduction. Thereafter most aspects of synoptic-scale meteorology are explained in terms of simplified dynamical models based on quasi-geostrophic theory and appropriate to the scale of mid-latitude cyclones. Wherever possible concepts are illustrated by well-documented case-studies. Not surprisingly, a large amount of space is devoted to the role of vorticity advection and thermal advection in cyclogenesis. There are two fairly lengthy chapters devoted to fronts and one on upper fronts and jet streaks. On the synoptic side the concept of warm and cold conveyor belts and the air flow through cyclones and fronts is explained with the use of isentropic analysis. I was disappointed to find that use of isentropic potential vorticity in the diagnosis of cyclone development is not covered, though the other fashionable diagnostic aid, Q-vectors, is explained in some detail.

A comprehensive bibliography is ordered by broad subject headings, perhaps unnecessarily since each chapter has its own list of references often very similar to a subject list in the complete bibliography. There are mathematical and synoptic exercises at the end of each chapter to test the understanding of the student, but I would have liked to have seen some brief solutions as well to help those who may use the book in the absence of guidance from lecturers or tutors.

The book is well presented with the many line diagrams especially clear, though a few of the reproductions of satellite images are less so. The case-studies are taken almost exclusively from the USA and students should be aware that a few aspects may not be completely transportable to other regions. Some readers may find the strange mix of units still used by the US Weather Service irritating if not confusing. For example, vertical velocities in micro-bars per second are combined with rainfall in inches per day! However, there is a clearly defined list of symbols and subscripts, etc. for use in equations, which is adhered to throughout, making interpretation of the quantitative examples relatively easy. On the negative side there are a large number of typographical errors especially within the mathematics, a few of which are not immediately obvious as such and may be a serious drawback for those not very familiar with dynamics.

It is very difficult in writing a book of this sort to avoid falling between two stools and the author is not entirely successful in avoiding this. Those already familiar with dynamics will find the first four chapters largely unnecessary whereas there is probably insufficient explanation included for those tackling the subject for the first time. A knowledge of maths approximately at the level of a first-year science undergraduate is needed to make good use of the dynamical meteorology presented. Because of this, the book is best considered as a text on dynamical mid-latitude meteorology, but a rather novel one in that the theory is at every opportunity related to real synoptic situations. In this way the first aim of the author is achieved but the reciprocal aim will only be realized where the reader already has a reasonably sound if undetailed knowledge of dynamics. Assuming such a prior knowledge most of the chapters are reasonably self-contained and this combined with the independent bibliographies makes the book particularly useful for reference.

In conclusion I would strongly recommend the book to all undertaking a course in dynamical meteorology (though not as a first text because of its deliberate omission of certain aspects such as tropical meteorology and numerical modelling). Those engaged in practical meteorology who wish to pursue the dynamics on which their work is based, and have a sufficient mathematical background, would also find this book useful.

D.A. Mansfield

Book comment

The *New Scientist* Inside Science, published by Penguin at £10 is a useful handbook giving brief résumés (about 12 pages) on 26 topics of current interest. The articles are by research scientists, science teachers and *New Scientist*'s team of science writers and editors. They have tried to steer clear of topics which are well handled in readily available textbooks. As their target audience is probably scientific, but knowing only a little of the topic, they cover a large amount of ground and assume good general knowledge.

Of particular interest are essays on acid rain, the ozone layer, the greenhouse effect and risk assessment, which should go a long way towards answering the questions put to us by non-meteorologists. One difficulty is the use of large two-column footnotes which intrude on the main text to the point of obfuscation. However, the index is as likely to contain the topic of a search as many larger, more costly, encyclopaedias.

R.M. Blackall

Books received

The listing of books under this heading does not preclude a review in the Meteorological Magazine at a later date.

Perfect symmetry, by H.R. Pagels (London, Penguin Books, 1992. £7.99) contains a non-technical account of the origin and evolution of the universe. The text proceeds to the farthest frontiers of scientific thought. ISBN 0 14 015826 X.

Glaciers–Ocean–Atmosphere INTERACTION, edited by V.M. Kotlyakov, A. Ushakov and A. Glazovsky (Wallingford, IAHS Press, 1991. $60.00) contains the proceedings of the International Symposium held at St Petersburg on 24–29 September 1990. A number of glacial phenomena related to large-scale variations are identified, and areas requiring knowledge intensification are described. ISBN 0 947571 33 7.

The year without a summer? World climate in 1816, edited by C.R. Harington (Ottawa, Canadian Museum of Nature, 1992. $42.80) includes 40 papers from experts in many disciplines, and countries, concerned with the unusual weather worldwide around 1816. The data gathering and their interpretation are explained and demonstrated from various viewpoints. ISBN 0 660 13063 7.

GUIDE TO AUTHORS

Content

Articles on all aspects of meteorology are welcomed, particularly those which describe results of research in applied meteorology or the development of practical forecasting techniques.

Preparation and submission of articles

Articles, which must be in English, should be typed, double-spaced with wide margins, on one side only of A4-size paper. Tables, references and figure captions should be typed separately. Spelling should conform to the preferred spelling in the *Concise Oxford Dictionary* (latest edition). Articles prepared on floppy disk (IBM-compatible) can be labour-saving, but only a print-out should be submitted in the first instance.

References should be made using the Harvard system (author/date) and full details should be given at the end of the text. If a document is unpublished, details must be given of the library where it may be seen. Documents which are not available to enquirers must not be referred to, except by 'personal communication'.

Tables should be numbered consecutively using roman numerals and provided with headings.

Mathematical notation should be written with extreme care. Particular care should be taken to differentiate between Greek letters and Roman letters for which they could be mistaken. Double subscripts and superscripts should be avoided, as they are difficult to typeset and read. Notation should be kept as simple as possible. Guidance is given in BS 1991: Part 1: 1976, and *Quantities, Units and Symbols* published by the Royal Society. SI units, or units approved by the World Meteorological Organization, should be used.

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