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Sunspot activity and associated temperature variations

B. N. BHARGAVA and R. K. BANSAL

Colaba Observatory, Bombay

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ABSTRACT. From an investigation of daily relative sunspot numbers and maximum temperatures at 20 stations it is shown that during 1946-47 a significant relationship existed between the two variables continuously over period from about 60 to 300 days. In the Indian region north of about Lat. 22°N the temperature changes followed the changes in sunspot numbers by intervals of 12 to 18 days. The response time was much shorter in the peninsular India, the interval being only 2 to 4 days. At some stations in the interior Mysore, Rayalaseema and Telengana, the relationship was exceedingly strong, and lasted over long intervals. Recurrent sunspot activity similar to 1946-47 is not encountered often and when present it lasts only for a few solar rotations. At other times the activity is highly sporadic. However, the results of the present investigation suggest that analysis of temperature data of stations where the response time is only of the order of 1 to 2 days may yield valuable information on the short-period (2 to 10 days) relationships between sunspot activity and air temperatures even during periods of sporadic sunspot activity.

1. Introduction

In the course of numerous investigations of solar activity-weather relationships a search has been made during last several decades for an association between phases of sunspot activity cycles and temperatures at the earth's surface. Shaw (1965) has briefly reviewed the earlier work. From spectrums of temperature series of England, Netherlands and New York city over a period of 134 to 257 years he concluded that there was no definite connection between mid-latitude temperatures and sunspots. Mitchell and Landsberg (1966), who differed from Shaw, showed that the cross-spectrum analysis of summer seasonal mean temperatures of New York city and sunspot number series was suggestive of a relationship sufficiently encouraging to warrant further investigation. While the results of long period solar cycle phase-temperature relationship remain inconclusive, short-period relationships between solar activity and temperatures such as those over periods of a solar synodic rotation, have remained relatively unexplored. One reason for this is that there are large and random variations in day-to-day sunspot number and when a 27-day periodicity is present, it lasts for two or three solar rotations. Visser (1958) observed a significant relation between daily maximum temperatures at a number of stations in the United States and Europe and sunspot activity in 1947, a year when the activity underwent regular 27-day oscillations over a period of many solar rotations. According to him, eight well developed 27-day periods of sunspot activity were followed by significant heat waves in Central Europe. Sunspot activity data published by Waldmeir (1961) shows that the activity between September 1946 and November 1947 was not only high but a major part of the variance in the sunspot number series was contributed by frequencies near 1/27 cycles per day. In the present investigation maximum air temperatures ($T_{\max}$) at selected Indian stations and sunspot numbers (SSN) during this period, have been examined for a possible association by the traditional regression method as well as by cross spectral method.

2. Data and analysis

In selecting 20 stations, including a few coastal stations, whose daily maximum temperatures were analysed, an attempt was made to sample broadly the entire sub-continent. The series of daily maximum temperature were smoothed and the seasonal variation or 'trend' was removed by digital filters. Since the principal wavelength of interest was 27 days, a data window with a 25-day width, from 10 to 35 days, was used for the filter. Following Behanon and Ness (1966) two symmetrical zero phase shift digital filters, each of 101 weights, were designed. The transfer function (ratio of the output spectrum to the input spectrum) of each of the two filters is shown in Fig. 1. The overall response of the filters was within 1 per cent of unity for wavelengths between 35 and 10 days, greater than 0·9 between 46 and 9·7 days and greater than 0·8 between 53 and 9 days. The output series Y_t were computed from the input series X_t by the linear transformation,

$$Y_t = \sum_{k=-n}^{n} W_k X_t + k$$

where W_k is the k^{th} weight of the filtering function and n is 50.

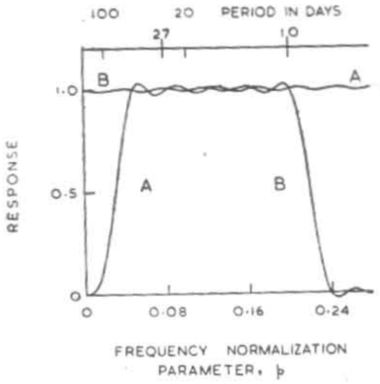

Fig. 1. Frequency response of high-pass filter (A) and low pss filter (B)

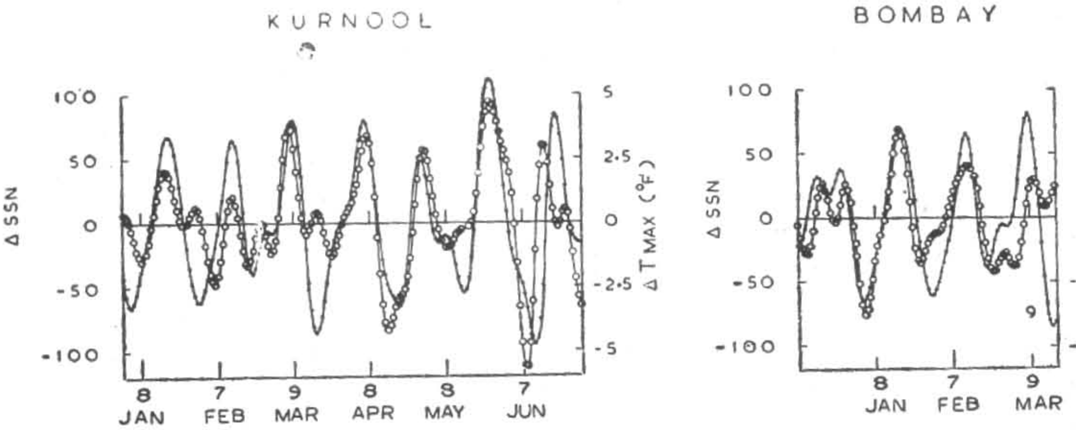

Fig. 2. Daily values of $\triangle$SSN (dotted line) and $\triangle T_{\max}$ (circles) for Kurnool and Bombay. The ordinates give temperatures 2 days later for Kurnool and 15 days later for Bombay

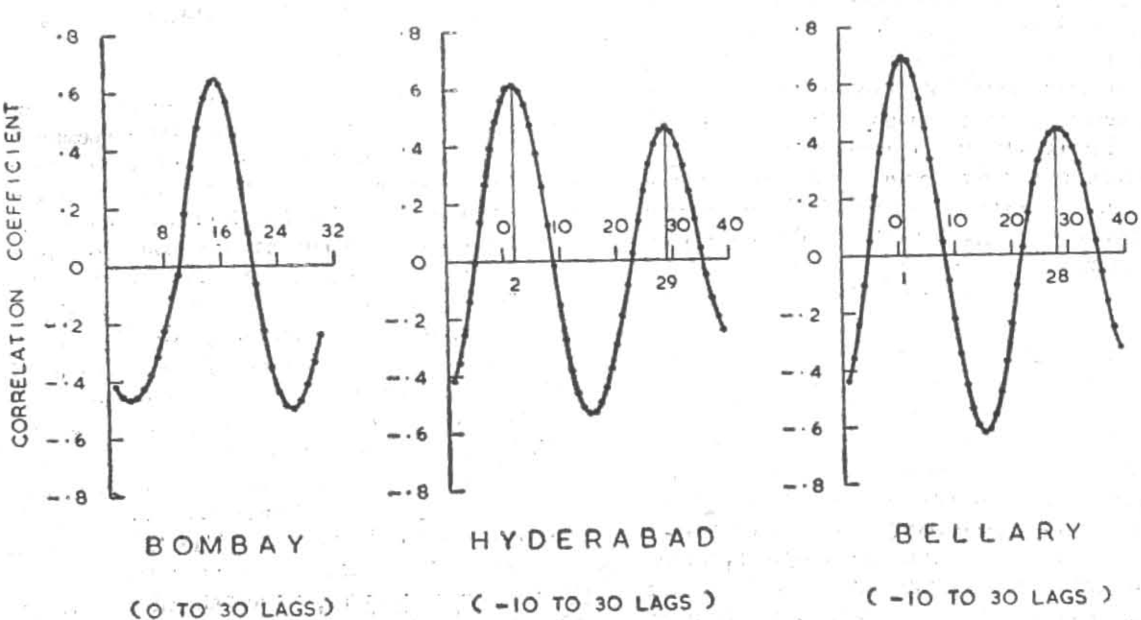

Fig. 3. Correlation coefficient between $\triangle$SSN and $\triangle T_{\max}$

TABLE 1

Station	Period of good linear association between Max. temp. and Sunspot No.	Period of linear association (Days)	Approximate time interval (lag) between Sunspot number and Max. temp. (Days)
Hyderabad	8 Dec 1946 to 9 Oct 1947	306	2
Bellary	18 Dec 1946 to 19 Sep 1947	276	2
Bijapur	8 Dec 1946 to 14 Oct 1947	311	2
Kurnool	7 Jan 1947 to 14 Oct 1947	281	2
Nagpur	8 Dec 1946 to 25 Aug 1947	260	2
Patna	24 Oct 1946 to 7 June 1947	226	15
Kolhapur	8 Dec 1946 to 26 Jul 1947	231	2
Madras	19 Nov 1946 to 23 May 1947	184	2
Ambala	18 Nov 1946 to 7 May 1947	171	2
Lucknow	23 Dec 1946 to 17 May 1947	136	18
New Delhi	28 Dec 1946 to 7 May 1947	131	15
Ahmednagar	26 Feb 1947 to 1 Jul 1947	126	5
Jodhpur	28 Dec 1946 to 17 Apr 1947	116	12
Aurangabad	28 Mar 1947 to 6 Jul 1947	101	3
Poona	28 Mar 1947 to 6 Jul 1947	101	3
Bombay	9 Dec 1946 to 14 Mar 1947	95	15
Bhopal	8 Dec 1946 to 13 Mar 1947	96	18
Indore	23 Dec 1946 to 18 Mar 1947	86	16
Madurai	12 Jan 1947 to 13 Mar 1947	61	2
Trichinapally	12 Jan 1947 to 13 Mar 1947	61	4

As a result of successive applications on the two filters the output series was shorter than the input series by 200 points. The solar cycle trend and short period fluctuations were reduced in the series of daily sunspot also by identical filters. Inspection of trend-free temperatures and sunspot number series hereafter called $\triangle T_{\max}$ and $\triangle$SSN revealed that at almost all stations $\triangle T_{\max}$ showed varying degree of similarity to $\triangle$SSN over intervals which varied from about 60 to 300 days. The lag between $\triangle$SSN and $\triangle T_{\max}$ series also differed considerably from one station to another. Daily values of $\triangle$SSN and $\triangle T_{\max}$ at Bombay between 9 December 1946 and 19 March 1947 and at Kurnool between 1 January 1947 and 30 June 1947 are shown in Fig. 2 where $\triangle T_{\max}$ series have been shifted to the left and by 15 and 2 days respectively. The approximate periods over which a linear association appeared together with the interval in days by which $\triangle T_{\max}$ lagged behind $\triangle$SSN are given in Table 1 for each one of the stations.

3. Lagged correlation

For a few stations a series of correlation between the two variables were computed, successively correlating and lagging in one day steps pairs of daily values of sunspot number and maximum temperatures. For Colaba, Bombay where each C.C. (Correlation Coefficient) was computed from 100 pairs of daily $\triangle$SSN and $\triangle T_{\max}$ the coefficient are shown as a function of lag, in Fig. 3. The strongest linear relationship with C.C. equal to $0\cdot640 \pm 0\cdot059$ is observed for a lag of 15 days. The values of C.C. for different levels of significance (Fisher and Yates 1943) show that for $n = 98$, the probability of C.C. being $0\cdot3211$, a figure about half of the observed C.C., by chance is $0\cdot001$. The C.C. between the two series is therefore highly significant. The C.C. of $0\cdot64$ suggests that about 41 per cent of the variation in the temperatures was accounted for by the change in SSN.

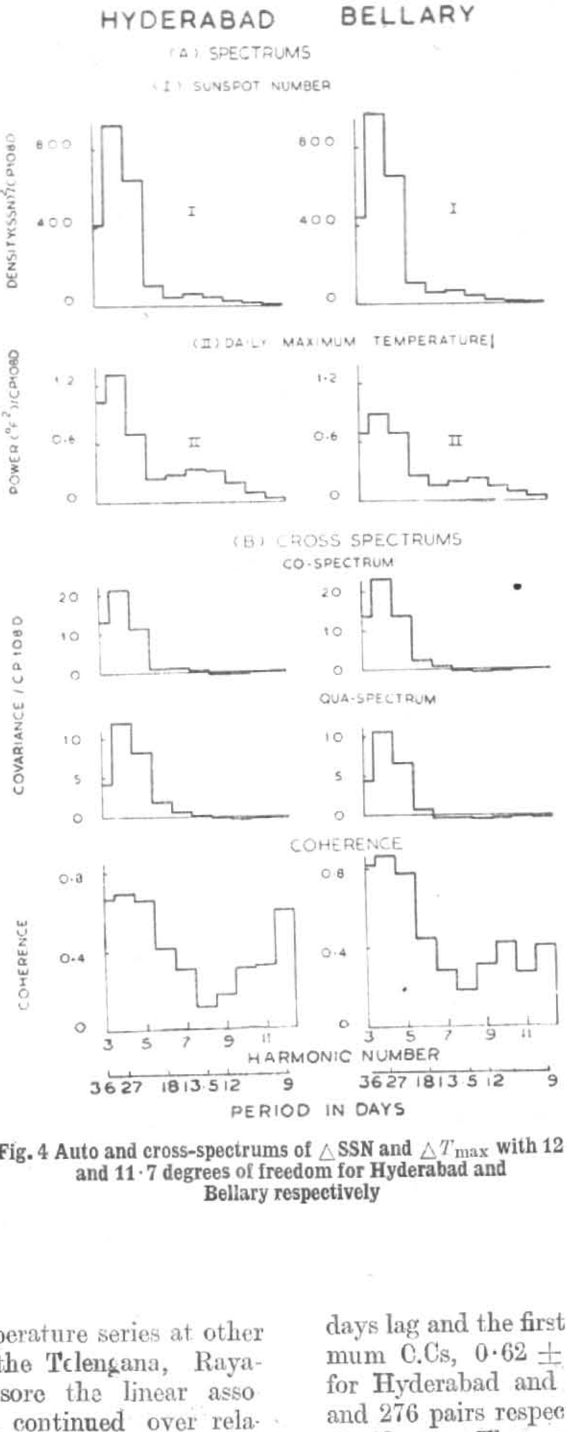

Fig. 4 Auto and cross-spectrums of $\triangle$SSN and $\triangle T_{\max}$ with 12·8 and 11·7 degrees of freedom for Hyderabad and Bellary respectively

Examination of the temperature series at other stations revealed that in the Telengana, Rayalaseema and interior Mysore the linear association was strongest and continued over relatively long intervals of about 300 days. For two of the stations, Hyderabad and Bellary, 50 values of C.Cs were computed successively for lags from —10 to +39 using 306 and 276 pairs of daily values respectively. The results are shown in Fig. 3. The highest correlation occurred when the lag was about 2 days. The period related to solar rotation is noticed in the corralogram as separation in days between dominant peak at 2 days lag and the first subsidiary peak. The maximum C.Cs, 0·62 ± 0·035 and 0·69 ± 0·032 for Hyderabad and Bellary computed from 306 and 276 pairs respectively are statistically highly significant. The maximum negative C.Cs are also high and significant.

4. Estimation of relation between $\triangle$SSN and $\triangle T_{\max}$ series from cross spectrums

The spectral methods have distinct advantages over the traditional regression methods. The degree of association, coherence, is obtained as a function of frequecy irrespective of time dis-

TABLE 2

Station	Coherence	(Coh)^2	υ	$4/\upsilon$	Limiting values of Coh for 1% confidence limit
Hyderabad	0·692	0·479	12·82	0·312	0·582
Bellary	0·865	0·748	11·70	0·342	0·610

TABLE 3

Hamonic No.	Period	Phase (lead of $\triangle$SSN relative to $\triangle T_{max}$) days	
	(Days)	Hyderabad	Bellary
3	36·0	1·79	1·80
4	27·0	2·18	1·85
5	21·6	2·12	1·56
6	18·0	2·14	0·71

placement between the two series. The time displacement itself of one series relative to another is computed as phase lead or lag of the second series relative to the first series, also as a function of frequency. The methods take account of the variation of signal to noise ratio with frequency. While a major fraction of the variance of the two series, examined here, was contained in a band of frequencies close to 1/27 cpd the data window provided by the numerical filters was sufficiently wide to justify an examination of relationship as a function of frequency.

The results of the autospectrum analysis are shown at the top of Fig. 4. Both the spectrums have a peak at 27 days. The amplitudes in $\triangle$SSN and $\triangle T_{max}$ at Hyderabad and Bellary, computed from spectral estimates for wavelength of 27 days, are 62·4, 1·88°F and 2·30°F respectively. The variations of about 130 in the series of sunspot numbers within a period of half a solar rotation were very common during 1946-47. The corresponding changes in temperatures of about 4°F within a period of about 13·5 days are therefore appreciable. The two plots in the centre of Fig. 4 show the co-spectrum and quadrature spectrum respectively which also have peaks at 27 days. The bottom part of the figures shows the coherence which is highest for the 4th harmonic (wavelength for 27 days). Table 2 shows the coherence, (coherence)^2 and v, $4/v$, v being the number of degrees of freedom.

It is noticed that the condition for significance of coherence (Munk and MacDonald 1960) that $(coh)^2 > (4/v)$ is satisfied with a large margin for both the stations. Limiting values of coherence (Panofsky and Brier 1958) for 12·82 and 11·70 degrees of freedom, for 1 per cent confidence limit being 0·582 and 0·610 respectively for the two stations, the chances are 1 in 100 that coherence of 0·582 and 0·610 or better will be found by chance. The computed coherence being far in excess of these figures, the analysis establishes a significant similarity between the $\triangle$SSN and $\triangle T_{max}$ series.

The coherence is minimum at a wavelength of 13·5 days which corresponds to half the period of solar synodic rotation. An increase in coherence at about 9 days, suggests a shorter period association between $\triangle$SSN and $\triangle T_{max}$. The phases (lead of $\triangle$SSN relative to $\triangle T_{max}$) for harmonic number 3 to 7 for the two stations are given in Table 3. At a wavelength of 27 days, temperature changes at Hyderabad follow $\triangle$SSN after an interval of 2·18 days and at Bellary after 1·85 days.

5. Conclusions

During a period of high and significantly recurrent sunspot activity the results establish an association of maximum temperatures with sunspot numbers at almost all the 20 stations. The intervals over which this association existed varied from station to station. In the region north of about Lat. 22°N, with few exceptions, the temperature variations followed the sunspot activity after intervals of 12 to 18 days. In the peninsular India the response time in temperature was shorter, the corresponding intervals being between 1 and 4 days. In the region between Lat. 15°N and 21°N and Long. 76°E and 79°E the association between sunspot activity and maximum temperatures was most remarkable and lasted over continuous intervals of the order of 300 days. The linear correlation coefficients between $\triangle$SSN and $\triangle T_{max}$, computed from 306 and 276 daily values of $\triangle T_{max}$ at Hyderabad and Bellary are 0·62 and 0·69, with temperature maximum following the sunspot peak after about 2 days. Cross-spectral analysis yields statistically significant coherence between the time series at a frequency of 1/27 cpd. The results suggest that during high and recurrent solar activity a 27-day cyclic change in maximum temperatures follows the sunspot activity in the lower middle and equatorial region in India. In view of the fact that regular 27-day variations in sunspot activity cannot be forecast, the prediction value of relationships is extremely limited. It should, however, be noted that the response time being relatively small in some of the regions, there is a good possibility of detecting similar relationships at wavelengths much shorter than 27 days. The results of the present investigation appear to be sufficiently encouraging for further work with emphasis on periods of moderate, and low sunspot activity as well as for intervals when the sunspot activity is relatively more sporadic.

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