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Solar semi-diurnal variation of Pressure

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ABSTRACT. A statistical study has been made of the year to year variation of solar semi-diurnal wave of atmospheric pressure over Delhi for the period 1948—1960. It has been found that there has been a slight decrease of amplitude during the period 1954—1960 as compared with the previous period. There has also been a tendency for positive anomalies and the negative anomalies longer than two months to persist. These have been compared with the results of a similar study of Singapore.

1. Introduction

In the previous communication (Jagannathan and Alvi 1961) the study of the mean diurnal curve of pressure at a network of 37 meteorological observatories in India was made by separating out the S_1 and S_2 variations. The study has brought to light considerable local and seasonal variation in the components of the S_2 – vector throwing further light on the possible thermal influence on the semi-diurnal variation of pressure. While analysing the general problem of pressure variations over Malaya, Frost (1961) calculated the amplitude of the semi-diurnal variation of atmospheric pressure at Changi (Singapore) for the years 1948—57. He noted a marked discontinuity about August-September 1952, the mean amplitude for the period 1948 to August 1952 being approximately 0·12 mb below the corresponding 10-year mean and that after that date 0·12 mb above the corresponding 10-year mean. He suggested that this may be reflected in the corresponding fluctuations in the temperatures of the upper troposphere over Singapore. In this connection he quoted the yearly differences from the mean annual upper air temperatures at New Delhi at 200, 300 and 500 mb from Vervard and Ebdon (1960) and suggested that the amplitudes of the pressure waves at New Delhi might throw further light on the subject. Frost's findings were naturally instrumental for kindling our interest leading to the present investigation.

2. Atmospheric tides

At this stage it is necessary to sketch in brief the present state of knowledge on atmospheric tides.

In the tropics the normal pressure variations show a systematic rise and fall of pressure during the day with a range of 2 to 3 mb almost as simple and regular as the tidal changes in the sea level. However these tides unlike the sea tides, occur at about the same local solar time with high pressure at 10 A.M. and 10 P.M. L.M.T.

Though very small in magnitude, the worldwide and persistent character of this oscillation practically with a stronger solar tide as against a weaker lunar tide has attracted the attention of mathematical physicists right from the days of Laplace.

The solar semi-diurnal oscillation(S_2) is the most predominant and interesting part of the tidal oscillation. It is remarkably simple and regular in its distribution. Schmidt (1890) found that near the poles the maxima for the 12 hour component occurs at the same time (GMT) while near the equatorial and temperate regions, it occurs at the same local mean time. Hence he put forward the hypothesis that the tidal oscillation should be regarded as being made up of two components—one a travelling wave which follows the Sun round the earth and the other a stationary wave in which the pressure is alternately high at the poles and the equator. Simpson (1918) showed that the S_2 variation could be represented as the sum of two sinusoidal components as follows—

$$S_2 = 0\cdot937 \cos^3\phi \sin(2wt + 154°) + \\ + 0\cdot137 (\sin^2\phi - \tfrac{1}{3}) \times \\ \times \sin(2wt - \lambda + 105°)$$

Up to 60° latitude the stationary wave is of minor importance but is pronounced in the higher latitudes. In the lower latitudes, it is only the progressive wave that is predominant.

Kelvin suggested that the atmosphere may possess a natural free period of nearly 12 solar hours and it was Pekeris (1937), continuing the work of Taylor, who proved that the atmosphere with a distribution of temperature up to 80 km as was known to exist has essentially two modes of free vibration, one of which is of period of nearly 12 hours. The important conclusion reached by Pekeris on this basis was that at high levels pressure variation may be reversed in phase and highly magnified. This fitted well with Chapman's (1919) dynamo theory for the diurnal variation of the earth's magnetic field providing the intense periodic winds of velocities approaching 200 km/hr over height of 100 km and 180° out of phase with the observed pressure oscillation as also for the analogous variation in heights and ionisation densities of the ionospheric regions (Mitra 1952). However the fact that the free period of the atmosphere could not be proved to be within 2-3 minutes of 12 hours as would be required for the resonance amplification of observed order has been deterrent to its acceptance as such. Up-to-date knowledge of the thermal structure of the atmosphere takes the free period further away. Refinements involving temperature variations with latitude, existence of zonal winds etc. could not remove the difficulty at present standing in the way of the resonance theory (Wilkes 1963). However, the fact that there is still considerable local variation and that the maximum phase precedes the solar transit, lends support to the thermal influence. Even though exact theory for a combined tidal-thermal action is still lacking, endeavours in this direction are gaining ground (Harris 1955 and Frost 1960).

3. Scope of the study

The hour-to-hour variation of the mean hourly values of atmospheric pressure in India in each month have been found by the authors (*loc. cit*) to be adequately represented as the sum of two harmonics, the first of period 24 solar hours (S_1) and the second of 12 solar hours (S_2)

$$S_1 = a_1 \sin(wt + \alpha_1)$$
$$S_2 = a_2 \sin(2wt + \alpha_2)$$

where a_1 and a_2 are the amplitudes of the two oscillations and α_1 and α_2 are the phase angles. Here we propose to study the year to year variation of the S_2 vector at Delhi (Safdarjung) (28°35'N, 77°12'E, 216·4 m.a.s.l.) during the 13 years 1948—1960.

4. Year to year variation of S_2

Tables 1 (a) and 1 (b) show the variation in the amplitude and phase angles of the S_2 vector of pressure for each year of the period 1948 to 1960.

While the seasonal features revealed here are practically the same as indicated in our previous paper, the tables reveal some noteworthy year to year variations. Fig. 1 shows the contrasting features of the seasonal patterns of the amplitude during the different years.

The abnormal features of the 1948 pattern threw some doubt on the accuracy of the observations. On a closer examination of the mean pressure as obtained from the autographic records *vis-a-vis* the mean hourly values of pressure obtained from eye-readings at the several synoptic hours, it was found that the instrument was having a slight magnification error. The data for 1948 were, therefore, omitted from further consideration.

TABLE 1(a)

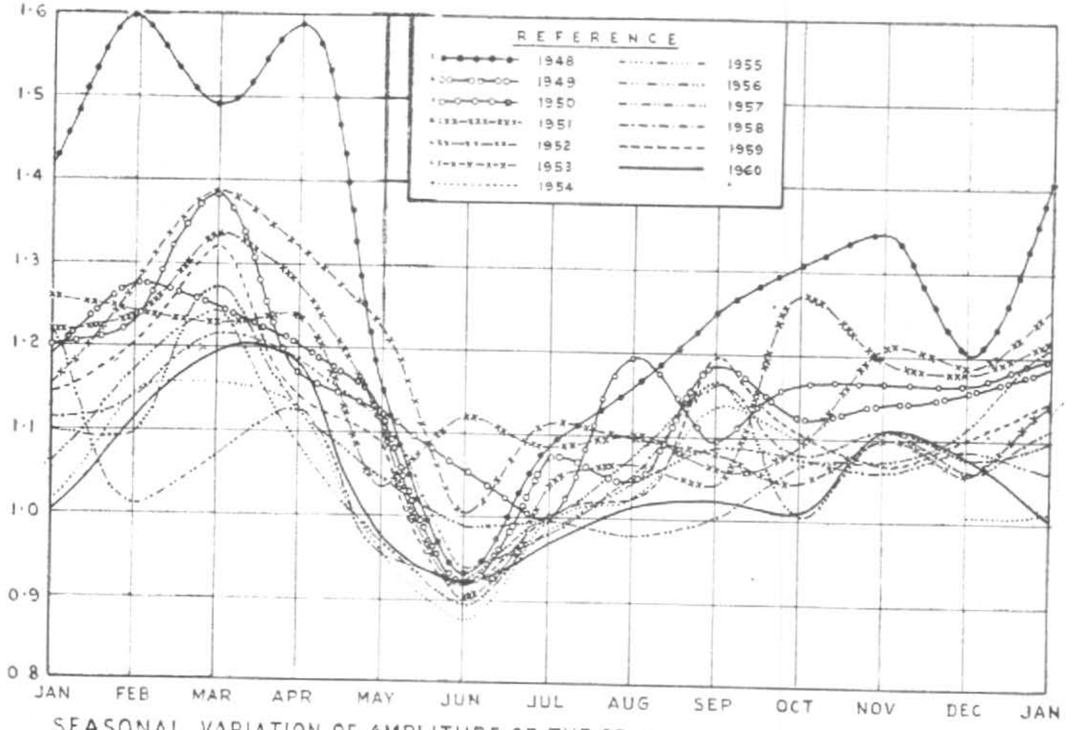
Yearly variation of amplitude (millibars) of semi-diurnal variation of pressure at New Delhi

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1948	1·41	1·60	1·49	1·59	1·15	0·93	1·09	1·16	1·25	1·31	1·35	1·20
1949	1·19	1·28	1·25	1·20	1·14	0·92	1·07	1·04	1·19	1·12	1·14	1·16
1950	1·20	1·23	1·39	1·17	1·13	1·05	1·00	1·19	1·09	1·17	1·17	1·16
1951	1·22	1·24	1·34	1·22	1·12	0·90	1·04	1·07	1·04	1·27	1·19	1·18
1952	1·26	1·25	1·23	1·24	1·03	1·12	1·08	1·10	1·06	1·09	1·21	1·19
1953	1·15	1·27	1·38	1·31	1·22	1·00	1·11	1·10	1·08	1·05	1·10	1·06
1954	1·01	1·15	1·16	1·13	0·95	0·87	1·00	1·03	1·14	1·10	—	1·01
1955	1·10	1·10	1·27	1·13	1·04	0·99	0·99	1·07	1·16	1·01	1·11	1·07
1956	1·06	1·17	1·24	1·08	0·97	0·89	0·98	1·04	1·09	1·07	1·06	1·09
1957	1·21	1·01	1·07	1·12	0·95	0·92	0·97	0·98	1·06	1·07	1·07	1·11
1958	1·14	1·14	1·22	1·18	1·11	0·94	0·97	1·05	1·16	1·07	1·11	1·06
1959	1·15	1·20	1·32	1·14	1·09	0·92	1·00	1·03	1·19	1·10	1·07	1·10
1960	1·00	1·11	1·19	1·19	0·97	0·92	0·97	1·02	1·03	1·00	1·11	1·08
1949-53	1·19	1·25	1·31	1·24	1·10	1·00	1·06	1·11	1·09	1·13	1·17	1·15
1954-60	1·09	1·13	1·20	1·13	1·01	0·90	0·99	1·04	1·13	1·07	1·09	1·08

TABLE 1(b)

Yearly variation of Phase Angle (L.M.T.) of semi-diurnal variation of pressure at New Delhi

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1948	128° 53′	128°07′	126°52′	125°26′	134°46′	128°03′	142°22′	131°58′	131°42′	134° 59′	137°36′	140°06′
1949	140 12	134 26	134 01	133 40	136 58	130 12	133 26	128 21	134 41	152 54	149 58	154 55
1950	145 33	140 33	137 26	136 55	136 00	133 32	131 19	136 21	143 11	154 24	151 19	152 39
1951	144 19	137 53	140 01	135 53	137 11	141 56	132 15	138 49	144 57	155 27	160 08	151 08
1952	144 59	138 18	140 51	138 10	141 29	136 52	138 34	139 26	144 57	152 49	155 57	147 08
1953	145 26	142 00	139 37	139 49	145 57	139 42	131 21	134 14	140 24	155 57	154 10	148 40
1954	145 46	136 22	134 41	132 55	128 30	124 56	134 06	139 34	146 43	151 33	—	152 15
1955	142 46	129 49	134 38	129 06	135 19	134 24	133 14	142 11	144 30	153 59	157 01	151 37
1956	142 47	137 11	140 54	134 56	138 06	139 10	136 40	136 48	145 31	149 37	156 25	149 19
1957	144 01	142 59	137 04	136 41	127 37	138 32	133 35	133 06	142 57	155 25	150 52	149 27
1958	150 00	136 46	136 25	127 08	136 49	132 21	131 32	133 29	145 25	152 28	149 13	144 25
1959	145 05	136 29	138 08	132 23	134 57	129 51	132 37	135 21	144 01	151 52	157 05	149 09
1960	145 02	137 50	138 35	135 41	131 57	126 22	126 29	137 05	142 29	153 17	155 50	148 40
1949-53	144 32	137 32	138 10	137 32	138 56	135 11	132 31	136 01	141 35	154 28	153 37	151 56
1954-60	144 52	137 29	137 29	132 59	133 43	132 44	132 50	136 46	144 17	150 10	154 40	149 02



SEASONAL VARIATION OF AMPLITUDE OF THE SEMI DIURNAL WAVE OF PRESSURE

FIG 1

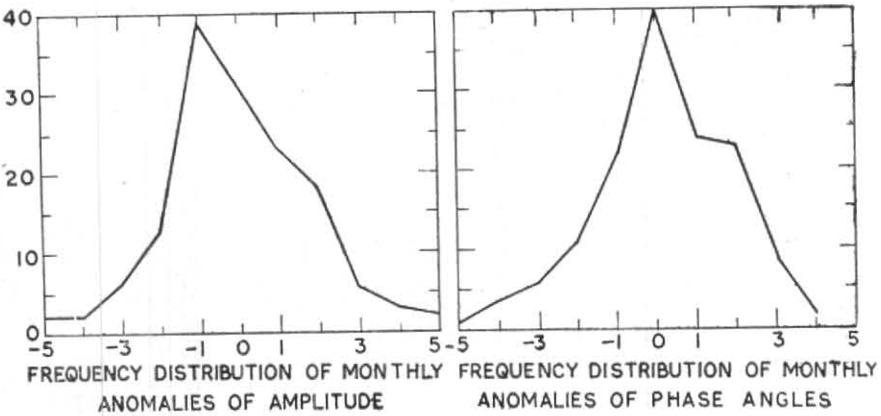


Fig. 2

The nature of the trend, if any can be brought out more clearly from an examination of the anomalies after elimination of the annual variation. Tables 2 (a) and 2 (b) shew the departures of the monthly amplitudes and phase angles calculated for the different years form those calculated for the 12 years (1949—1960) as a whole. It is seen that negative anomalies are most frequent for 1954 and thereafter, while prior to this year, the positive departures are most frequent. Combining the monthly anomalies, the yearly anomalies are given in the last column which show more strikingly the change in the sign of the anomalies from 1954 onwards; the anomaly prior to 1954 averaging to $+0 \cdot 050$ mb and that from 1954 onwards averaging to $-0 \cdot 030$ mb. In respect of phase angles, those prior to 1954 average to $-0° 48'$ and those from 1954 average to $+0° 40'$.

The mean monthly amplitude and phase angles calculated for the two periods, *viz.*, 1949—1953 and 1954—1960 respectively are also given at the bottom of Tables 1 (a) and 1(b). It is seen that the monthly amplitudes in the latter are almost consistently lower than those in the former by 5—10 per cent except in the case of September where it shows an increase of about 5 per cent. Each of the amplitudes in the first period is calculated from about 3600 observations and in the second period from about 5000 observations. Since the standard deviation of the individual observation is of the order of 2 mb the standard deviation of the harmonics is $0 \cdot 03$ to $0 \cdot 04$ mb. As such, the monthly deviations except those for July to October are just significant at the 5 per cent level. Unlike the amplitudes, the monthly phase angles show no systematic variation from year to year; the largest deviation from the first to the second period occurring in the months May, April and October, the maximum of the oscillation occurring about 9-10 minutes later than in the first.

The distribution of the monthly anomalies of amplitudes and phase angles for the 12-year period as a whole show that they are distributed according to the "Normal Law of Error". Fig. 2 shows the curves of distribution.

5. Tests of randomness

The mean amplitude and phase angles in the different years are in a particular order and the values are bounded as they do not increase or decrease indefinitely. It would be worthwhile at this stage to examine if the year to year sequence of the amplitudes

TABLE 2(a)

Departures of the monthly amplitudes (S_2 for New Delhi) for the different years from the monthly values calculated for the period 1949—1960

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1949	·04	·10	·00	·03	·10	—·02	·07	—·01	·08	·03	·02	·05	0·04
1950	·05	·05	·14	·00	·09	·11	·00	·14	—·02	·08	·05	·05	0·06
1951	·07	·06	·09	·05	·08	—·04	·04	·02	—·07	·18	·07	·07	0·05
1952	·11	·07	—·02	·07	—·01	·18	·08	·05	—·05	·00	·09	·08	0·05
1953	·00	·09	·13	·14	·18	·06	·11	·05	—·03	—·04	—·02	—·05	0·05
1954	—·14	—·03	—·09	—·04	—·09	—·07	·00	—·02	·03	·01	—	—·10	—0·05
1955	—·05	—·08	·02	—·04	·00	·05	—·01	·02	·05	—·08	—·01	—·04	—0·01
1956	—·09	—·01	—·01	—·09	—·07	—·05	—·02	—·01	—·02	—·02	—·06	—·02	—0·04
1957	·06	—·17	—·18	—·05	—·09	—·02	—·03	—·07	—·05	—·02	—·05	·00	—0·06
1958	—·01	—·04	—·03	·01	·07	·00	—·03	·00	·05	—·02	—·01	—·05	—0·01
1959	·00	·02	·07	—·03	·05	—·02	·00	—·02	·08	·01	—·05	—·01	0·01
1960	—·15	—·07	—·06	·02	—·07	—·02	—·03	—·03	—·08	—·09	—·01	—·03	—0·05

TABLE 2(b)

Departures of the monthly phase angles (S_2 for New Delhi) for the different years from the monthly values calculated for the period 1949—1960

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
1949	—4°36′	—2°25′	—3°29′	—1°31′	0°44′	—2°17′	1°56′	—7°57′	—9°12′	—0°48′	—4°23′	4°57′	—2°26′
1950	0 45	3 42	—0 04	1 44	—0 14	1 03	—0 11	0 03	—0 42	0 42	—3 02	2 41	0 32
1951	—0 29	1 02	2 31	0 42	0 57	9 27	0 45	2 31	1 04	1 45	5 47	1 10	2 16
1952	0 11	1 27	3 21	2 59	5 15	4 23	7 04	3 08	1 04	—0 53	1 36	—2 50	2 14
1953	0 38	5 09	2 07	4 38	9 43	7 13	—0 09	—2 04	—3 29	2 15	—0 11	—1 18	1 13
1954	0 58	—0 29	—2 49	—2 16	—7 44	—7 33	2 36	3 16	2 50	—2 09	—	—2 17	—1 25
1955	—2 02	—7 02	—2 52	—6 05	—0 55	1 55	1 44	5 53	0 37	0 17	2 40	1 39	—0 21
1956	—2 01	0 20	3 24	—0 15	1 52	6 41	5 10	0 30	1 38	—4 05	2 04	—0 39	1 13
1957	—0 47	6 08	—0 26	1 30	—8 37	6 03	2 05	—3 12	—0 56	1 43	—3 29	—0 31	—0 02
1958	5 12	—0 05	—1 05	—8 03	0 35	—0 08	0 02	—2 49	1 32	—1 14	—5 08	—5 33	—1 23
1959	0 17	—0 22	0 38	—2 48	—1 17	—2 38	1 07	—0 57	0 08	—1 50	2 44	—0 49	—0 32
1960	0 14	0 59	1 05	0 30	—4 17	—6 07	—5 01	0 47	—1 24	—0 25	1 29	—1 18	—1 07

and phase angles have occurred at random or according to some cyclical effects. To test this the following two tests of randomness by Kendall (1946) and Wallis and Moore (1941) have been applied.

(*i*) In a series of N randomly ordered terms the expected number of *turning points** is $\frac{2}{3}(N-2)$. For sufficiently large N the number of turning points may be taken as normally distributed about the mean of $\frac{2}{3}(N-2)$ with a standard deviation of $[(16N-29)/90]^{\frac{1}{2}}$. Any significant deviation from this can be considered as indicating the possibility of some cyclical effects. Considering the entire sequence of monthly anomalies the deviation for randomness is not significant as seen from the following—

	Amplitude	Phase angles
A	93	101
E	94·66	94·66
S.D.	5·03	5·03

The actual number of turning points in the different monthly series, the number expected on the assumption of randomness and their standard deviations are given in Tables 3 (a) and 3 (b). It is seen that the number of turning points in the case of July and September for amplitude and of March and August for phase angles, are significantly (5 per cent level of significance) smaller than the number expected on the assumption of randomness, the deviations being just more than twice the standard deviation, indicating that the variations in these months are not quite random but have a persistence tendency.

(*ii*) If d is the phase length, the distribution of d in a series of N randomly ordered terms has a probability density given by

$$\frac{6(d^2+3d+1)\ \ (N-d-2)}{(d+3)\,!\ \ (2N-7)}$$

Wallis and Moore's (1941) test based on the distribution of phase lengths d states that χ^2 derived from the observed distribution for $d=1$, $d=2$ and $d \geqslant 3$ in accordance with the above hypothesis can be used to test the randomness by a comparison with the standard χ^2 tables. The probability of a value of χ^2 larger than the calculated, can be read off from the table of χ^2 against $2\frac{1}{2}$ degrees of freedom, if the calculated value of $\chi^2 \geqslant 6\cdot3$ and for values of $\chi^2 < 6\cdot3$ against 2 degrees of freedom for $6/7\ \chi^2$. Considering the entire sequence of monthly anomalies as a whole the frequencies in respect of $d=1$, $d=2$ and $d \geqslant 3$, together with expected values on the hypothesis of randomness and the χ^2 are given below—

		Amplitude	Phase angles
$d=1$	A	56	101
	E	57·96	63·00
$d=2$	A	22	23
	E	22·08	24·00
$d \geqslant 3$	A	14	8
	E	12·96	14·00
χ^2		0·43	3·17

There is no significant deviation for randomness. The actual and expected frequencies of phase length in respect of the different monthly sequence and the χ^2 are given in Tables 3 (a) and 3(b). It is seen that in the case of April and July for amplitude and of January and February for phase angle, the χ^2 are high indicating significant deviation (at the 5 per cent level) from randomness. This is due to the preponderance of phase lengths 3 and more years and a corresponding lack of 1 year phase lengths. Thus in these months there is an indication of a cyclical tendency with a period of about 8-12 years. However, the determination of the exact

*A *peak* is a point where the value is higher than the neighbouring values on either side and a *trough* is a point where the value is lower than the neighbouring values on either side. These *peaks* and *troughs* are called *turning points* and the distance d between two consecutive turning points is the *phase length*

TABLE 3 (a)

Amplitudes

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
						(i) Turning Points in the series						
A	7	6	7	5	6	7	4	7	4	5	6	5
E	6·7	6·7	6·7	6·7	6·7	6·7	6·7	6·7	6·7	6·7	6·7	6·7
S.D.	1·35	1·35	1·35	1·35	1·35	1·35	1·35	1·35	1·35	1·35	1·35	1·35
						(ii) Frequencies of Phase Lengths						
						$d=1$						
A	5	2	3	1	4	4	1	4	0	2	3	2
C	4·00	3·33	4·00	2·67	3·33	4·00	2·00	4·00	2·00	2·67	3·33	2·67
						$d=2$						
A	1	2	3	1	1	2	0	2	2	1	2	1
C	1·50	1·25	1·50	1·00	1·25	1·50	0·75	1·50	0·75	1·00	1·25	1·00
						$d \geqslant 3$						
A	0	1	0	2	0	0	2	0	1	1	0	1
C	0·50	0·42	0·50	0·33	0·42	0·50	0·25	0·50	0·25	0·33	0·42	0·33
χ^2	0·91	1·78	2·25	9·37	0·80	0·66	13·50	0·67	6·33	1·49	0·90	1·50

TABLE 3 (b)

Phase Angles

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
						(i) Turning Points in the series						
A	5	6	4	6	6	5	8	4	7	8	6	8
E	6·7	6·7	6·7	6·7	6·7	6·7	6·7	6·7	6·7	6·7	6·7	6·7
S.D.	1·35	1·35	1·35	1·35	1·35	1·35	1·35	1·35	1·35	1·35	1·35	1·35
						(ii) Frequencies of Phase Lengths						
						$d=1$						
A	2	1	1	2	3	3	5	1	6	6	2	7
C	2·67	3·33	2·00	3·33	3·33	2·67	4·67	2·00	4·00	4·67	3·33	4·67
						$d=2$						
A	0	4	1	3	1	1	2	2	0	1	2	0
C	1·00	1·25	0·75	1·25	1·25	1·00	1·75	0·75	1·50	1·75	1·25	1·25
						$d \geqslant 3$						
A	2	0	1	0	1	0	0	0	0	0	1	0
C	0·33	0·42	0·25	0·42	0·42	0·33	0·58	0·25	0·50	0·58	0·42	0·58
χ^2	9·49	8·10	2·83	3·40	0·92	0·37	0·63	2·92	3·00	1·11	1·82	2·47

A—Actual *E*—Expected *C*—Calculated

period of oscillation, if any, requires further examination.

In order to appreciate the effect of persistence, we must consider the number of runs of different lengths. The frequencies of length of n or more months of positive and negative anomalies for the entire period of 12 years 1949—1960 are given below.

	Frequencies of runs				
	1	2	3	4	5
Positive anomalies					
S_n	23	14	8	5	5
Ratio S_{n+1}/S_n	—	0·61	0·57	0·63	1·00
Negative anomalies					
S_n	23	8	8	6	5
Ratio S_{n+1}/S_n	—	0·35	1·00	0·75	0·83

It is seen that the ratios fluctuate considerably. However, all except n=2 for negative anomalies, the ratios exceed the probability 0·5 for the random event. This suggests that negative anomalies after two consecutive months and positive anomalies tend to persist

6. S_2-variation *vis-a-vis* temperature of the upper troposphere

In as much as there is a marked discontinuity from about September 1953, this points to the genuineness of the changes observed by Frost for Singapore. The essential points of difference, however, are—(*i*) the amplitude of annual S_2 wave for Delhi (28½°N lat.) shows a decrease after 1953, while those for Singapore on the equator showed an increase after 1952, (*ii*) the magnitude of the change at Delhi is of the order of 0·08 mb while for Singapore it is 0·24 mb.

Further, the suggestion of a cyclical tendency of probably 8-12 years duration appears to indicate that the changes may have some connection with solar activity. 1953 was the year of sunspot minimum and one could naturally look to that as a possible cause of that change. Sen Gupta (1960) observed that there was an increase of 3°C in the temperature of 200-mb levels over India during sunspot maximum from that during sunspot minimum and that during sunspot maximum the high pressure cell over the Bay of Bengal at 10-12 km shifts further south. The importance of solar activity to determine the thermal characteristics of the atmosphere is well known. In a recent study Jagannathan (1963) showed the differential character of the seasonal variation of temperature at a number of stations over the arid and semi-arid regions of the world with respect to epochs of sunspot maxima as against those of sunspot minima.

Veryard and Ebdon (1960) also observed marked discontinuity round about 1953 in the upper tropospheric temperature series at a number of stations Aden, Bahrein, Hongkong, Nairobi and Kagoshima. They also observed similar discontinuity at Lerwick and Hemsby at the 300 and 500-mb levels, while at the 200 and 100-mb levels the character of variation was rather different due probably to the fact that tropopause is lower than this level.

Whether a similar discontinuity in the amplitude of the S_2 wave of pressure occurs at other stations particularly over different latitudinal belts and if so what are the character and magnitude of the changes, are problems which need to be further investigated, as any speculation about the possible cause of such a change will have to be consistent. Studies since made of Madras (13°N) and Nagpur (21°N) have also revealed similar features as those for Delhi. Results in respect of all the selected representative stations will be discussed in a future communication.

If the connection with the sunspottedness and the thermal structure of the upper troposphere could be established, they may help in the establishment of a consistent theory of possible tidal thermal action for the "atmospheric tide".

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