extend this range if it ever becomes necessary. The numerical results are compiled in Table I and five characteristic figures (Figs. 1–5) are included with appropriate descriptions.

The authors would like to express their gratitude to Dr. B. Lepson, R. M. Mason, and L. E. Davis all of the Naval Research Laboratory. The numerical results were obtained under the guidance of Dr. Lepson while much of the machine programming was performed by Mr. Mason and Mr. Davis.

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Solar Influence on the Anisotropy of Primary Cosmic Radiation. I. Studies at Low Latitudes*

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A study of the daily variation of meson intensity at low latitudes has been conducted with counter telescopes of identical design at Ahmedabad and at the mountain station of Kodaikanal. The analysis of the data shows that the semidiurnal component of variation, like the diurnal component, undergoes significant long-term changes. The appropriateness of a barometric coefficient applicable to the daily variation of meson intensity is discussed. Long-term changes of the daily variation reveal that these are due to the addition or attenuation of a day and a night contribution, both of which are principally diurnal in character and at Ahmedabad have maxima at about 1300 and 0300 hours, respectively.

For corroboration of these findings, data from 1937 to 1952, from the Carnegie Institution stations of Huancayo and Cheltenham have been analyzed. While at the equatorial station of Huancayo, the mechanism of change of daily variation is similar to what is observed at Ahmedabad and Kodaikanal, there are some differences in detail at Cheltenham, which lies in middle latitudes. There is evidence that some characteristics of the daily variation, notably the hour of maximum of the diurnal component and the amplitude of the semidiurnal component, follow the eleven-year solar cycle of activity. However, there is an indication that the nature of the composite daily variation, the hour of maximum of the semidiurnal component, and the pattern of addition and attenuation of the day and night contributions follow a 22-year cycle of change. The activity of the day and night contributions in relation to solar activity is discussed.

I. INTRODUCTION

THE current status of our experimental knowledge concerning the daily variation of meson intensity may be summarized as follows.

(1) It is now fairly clear that the daily variation of barometric pressure is the only terrestrial influence of importance which affects the daily variation of meson intensity. The mean daily variations of atmospheric temperature and of the heights of isobaric levels near the 100-millibar level are both of small magnitude.[1] On account of this, the atmospheric mass absorption effect appears as the principal factor in the total barometric coefficient applicable to the daily variation of meson intensity.[2]

(2) Barring rare exceptions[2–5] which are not yet reconciled, there is high negative correlation between the semidiurnal variations of meson intensity and of barometric pressure. It has been suggested by Sarabhai *et al.*[2,5] that the barometric coefficient derived from the relationship of the semidiurnal components of the daily variations can be applied to correct the daily variation of meson intensity.

The barometric coefficient so derived by them and applied to the daily variation of meson intensity at Ahmedabad is $\beta=-2.4\%$ per cm of Hg. Other workers have used a coefficient derived from day-to-day variations of meson intensity and of barometric pressure, and this coefficient, in general, has a value ranging from -1.5 to -3.0% per cm of Hg.

(3) The solar daily variation of meson intensity, corrected for barometric pressure, may be designated by M. It has, in general, only two principal harmonic components. The diurnal component may be specified by its percentage amplitude M^D and the local time of its maximum $M\phi^D$ expressed as an angle from midnight in a clockwise direction on a 24-hourly harmonic dial. Similarly the semidiurnal component may be specified by M^S and $M\phi^S$ respectively, in terms of a representation on a 12-hourly harmonic dial.

(4) The nature of M depends on the cone of incidence of the measured radiation and the orientation of the axis of the cone with respect to azimuth and zenith. It also depends on the mean energy of the measured radiation, the latitude, and the elevation of the place of observation.

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The amplitude M^D of the variation increases as the cone is made narrow.[5–7] M^D is larger at an equatorial mountain station than at stations at low elevation in high latitudes.[7,8] $M\phi^D$ is earlier at low latitudes than at high.[5,7,8] It becomes earlier still at low latitudes and at mountain elevations.[5,7] Directional studies[9–12] reveal that $M\phi^D$ at intermediate latitudes north of the equator is earlier for north azimuth than for south and for east than for west: M^S is present[12] for south azimuth but not for north to the same degree.

(5) M is known to change with magnetic disturbance. M^D increases and $M\phi^D$ is displaced to earlier hours on days that are magnetically disturbed.[13–16] In contrast to this, M^S decreases markedly.[17] The effect is more pronounced in narrow-angle telescopes than in instruments admitting radiation over a wide cone.

(6) M is known to undergo an annual change.[11,12,18–21] Several attempts have been made to identify in this a true seasonal variation and a distinct contribution of a sidereal time daily variation. However, the two effects are small and the facts have not been clearly established.

(7) M undergoes worldwide changes broadly in step with the eleven-year solar cycle of activity.[22,23] Changes of the time of maximum $M\phi^D$ are highly correlated at widely separated places on the earth.[24] Changes in M^D are not equally consistently correlated. The change of activity of solar coronal emission 5303 A is best related to changes observed in M.

(8) Changes in M have been shown to be related to changes in the nature of the daily variation of cosmic-ray neutron intensity.[25,26]

There is, therefore, weighty evidence to indicate the existence of an anisotropy of the primary cosmic radiation which is under solar control. Of the suggestions put forward to explain this, perhaps two have to be seriously considered. There is the possibility of continuous solar emission of particles of cosmic-ray energies.[22] Then there are processes[27] such as those suggested by Alfvén, by which emission of particles of inferior energy from the sun can disturb the isotropy of primary cosmic radiation, itself originating outside the solar system. Under certain circumstances, both processes may be operative. Further progress in our understanding of this important problem is now dependent on a closer examination of the finer features of changes in M occurring with time, and of the nature of M observed at different stations and under differing experimental conditions.

The influence of the anisotropy of the primary cosmic radiation on an apparatus fixed to the spinning earth is best observed with directional telescopes. A project was therefore commenced some years ago at the Physical Research Laboratory, Ahmedabad, for continuous measurement of the meson intensity with counter telescopes of standardized geometry at stations in low latitudes. One station has been in operation at Ahmedabad (latitude 23° 02′ N, longitude 72° 38′ E, geomagnetic latitude 13° N, altitude 180 ft above sea level) since September, 1950. Another was started in June, 1951 at the mountain station of Kodaikanal (latitude 10° 14′ N, longitude 77° 28′ E, geomagnetic latitude 1° N, altitude 7688 ft above sea level). A third has recently been started at Trivandrum (latitude 8° 30′ N, longitude 76° 55′ E, geomagnetic latitude 1° N, altitude sea level). Details of the apparatus and early results from the first two stations have been previously reported.[5] We are now able to present a more comprehensive picture of the daily variation of meson intensity at low latitudes. Changes in M observed during the past four years reveal new and interesting features and we have attempted to find corroboration for our findings in the Carnegie Institution data extending over a much longer period of time.

II. EXPERIMENTAL METHOD AND NOMENCLATURE

The standardized instrument, consisting of duplicate independent sets of two triple-coincidence counter telescopes in each set, has been described elsewhere.[2] The telescopes subtend a semiangle of 22° in the E-W plane and a semiangle of 37° in the N-S plane. Each counter tray has a sensitive area of about 600 sq cm and the mean bihourly rate of a telescope is about 3400 counts at Ahmedabad and about 4000 counts at Kodaikanal. The monthly mean solar daily variation of meson intensity is denoted by $^*M$. It relates to the percentage bihourly deviations from the monthly mean cosmic-ray intensity measured with an absorber equivalent in thickness of lead from 7 to 15 cm. For

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TABLE I. Meaning of symbols.

M	The monthly mean daily variation of meson intensity, corrected for barometric pressure, and expressed as bihourly percentage deviations from monthly mean intensity.
P	The monthly mean daily variation of barometric pressure expressed as bihourly deviations in mm of mercury from monthly mean barometric pressure.
M^D	The percentage amplitude of the diurnal component of M.
$M\phi^D$	The time of maximum of M^D given by the angle in a clockwise direction between the direction of midnight and of the vector for M^D on a 24-hourly harmonic dial.
M^S	The percentage amplitude of the semidiurnal component of M.
$M\phi^S$	The time of maximum of M^S given by the angle in a clockwise direction between the direction of midnight and of the vector for M^S on a 12-hourly harmonic dial.
M_X	The determination of M made at station X. For the stations we use the following symbols: A—Ahmedabad, K—Kodaikanal, H—Huancayo, C—Cheltenham, C'—Christchurch, G—Godhavn.
$^*M$	The daily variation M before applying correction for barometric pressure.
${}_{x.y}M$	Value of M for year x and month y.
${}_{x.y}\bar{M}$	12-monthly mean value of M centered at year x and month y.
$^\circ M$	Smoothed M obtained by superposition of its first and second harmonic components.
$\Delta^\circ\bar{M}(x.y-x'.y')$	The difference between ${}_{x.y}{}^\circ\bar{M}$ and ${}_{x'.y'}{}^\circ\bar{M}$.

Ahmedabad and Kodaikanal, it is specified by $^*M_A$ and $^*M_K$, respectively.

Both at Ahmedabad and at Kodaikanal, one to four identical telescopes have been in operation at various times. $^*M_A$ and $^*M_K$ represent the mean daily variations of as many telescopes as were in operation on various days during each month. When a bihourly deviation from mean daily counting rate exceeds three times the standard error, the data for the particular telescope for the day are neglected.

$^*M^D$ and $^*M\phi^D$ signify the percentage amplitude and the angle corresponding to the time of maximum of the first harmonic or diurnal component of $^*M$. Similarly, $^*M^S$ and $^*M\phi^S$ relate to the second harmonic or semidiurnal component of $^*M$. β is the barometric coefficient that is applied to the data to correct for the influence of the daily variation of barometric pressure. The daily variation of meson intensity after applying this correction for barometric pressure is indicated by the corresponding symbols M, M^D, $M\phi^D$, etc. without asterisks.

The year and the month of the observation is indicated by small figures preceding the symbol. Thus ${}_{52.\text{xi}}M_A{}^D$ indicates the percentage amplitude of the diurnal component of the mean daily variation of meson intensity at Ahmedabad during the eleventh month of 1952. The 12-monthly mean variation is denoted by $\bar{M}$. The year and month of the epoch at which this period is centered is indicated by small figures preceding the symbol. Thus ${}_{52.\text{xi}}\bar{M}_A{}^D$ indicates the mean of 12 values commencing with ${}_{52.\text{vi}}M_A{}^D$ and ending with ${}_{53.\text{v}}M_A{}^D$.

Even though the number of telescope days differs from month to month, equal weight is given to the mean M for each month in calculating the 12-monthly mean $\bar{M}$. However, where there is complete absence of data in a particular month as at Ahmedabad in the month of August, 1952, the 12-monthly means involving this month relate only to data for eleven months instead of the usual 12 months.

In discussing the characteristics of the daily variation of meson intensity, it is advantageous to smooth out random irregularities in M. Since the main contribution to M is known to be due to only the first two harmonic components, we frequently derive a smoothed $^\circ M$ by building up bihourly percentage deviations from mean by superposition of the first and the second harmonic components.

Changes of the daily variation may be considered by looking at either the composite variation $^\circ\bar{M}$ or the amplitudes and times of maximum of its first two harmonic components. We express by $\Delta^\circ\bar{M}$ (49.VI −48.VI) the difference between 12-monthly mean daily variations centered at June, 1949 and at June, 1948. This is obtained by subtracting respective bihourly percentage deviations from mean for ${}_{48.\text{VI}}{}^\circ\bar{M}$ from those for ${}_{49.\text{VI}}{}^\circ\bar{M}$.

For the daily variation of barometric pressure, we use the letter P in place of the letter M. The conventions adopted in this terminology are summarized in Table I.

III. BAROMETRIC PRESSURE CORRECTION FOR THE DAILY VARIATION OF MESON INTENSITY

Sarabhai *et al.* have earlier drawn attention to the high negative correlation between the semidiurnal components of $^*M_A$ and P_A. On the assumption that the principal effect of an anisotropy of the primary radiation would be to produce a diurnal variation of the meson intensity, they attributed the semidiurnal variation entirely to the semidiurnal oscillation of the atmosphere. A barometric coefficient was then derived by them from the semidiurnal components of $^*M_A$ and P_A.

In Fig. 1, we indicate the 12-monthly mean values $^*\bar{M}^S$, $^*\bar{M}\phi^S$, $\bar{P}^S$, and $\bar{P}\phi^S$ centered at successive months. Figure 1 refers to observations made at Ahmedabad during the period October, 1950 to June, 1953, and to observations made at Kodaikanal from May, 1952 to June, 1954. The correlation coefficient r between the semidiurnal components of $^*\bar{M}$ and $\bar{P}$, and the apparent barometric coefficient β calculated from them, are also shown in the figure.

Since we are now considering 12-monthly mean values centered at successive months, seasonal changes would not be revealed. As is to be expected according to the theory of atmospheric tides, there is great constancy of the semidiurnal oscillation of barometric pressure represented by $\bar{P}^S$ and $\bar{P}\phi^S$. However, $^*\bar{M}^S$ and $^*\bar{M}\phi^S$ show significant and large changes. In consequence, r as well as the apparent barometric coefficient β undergo long term changes. At Ahmedabad, the correlation coefficient r ranges from -1.00 to -0.79 and β has values ranging from -4.6% to -2.1% per cm of mercury. At Kodaikanal similarly, values of r range from -1.00 to -0.93 and of β from -6.4 to -3.5% per cm of mercury. Since on physical considerations, it is difficult to imagine long term changes of the 12-monthly mean barometric coefficient of meson intensity, it is clear that contrary to our original belief, the semidiurnal variation of $^*M$ cannot be completely ascribed to the semidiurnal oscillation of P. We must conclude that there is a significant semidiurnal contribution in $^*M$ which is not of meteorological origin and may be ascribed to the anisotropy of primary cosmic rays. This agrees with the observation of Elliot and Dolbear[12] from directional studies made at Manchester. We can further state that like the diurnal component of $\bar{M}$, the semidiurnal component also undergoes significant changes with time. The observation by Sekido and Yoshida[17] of the change in the semidiurnal component of the daily variation of meson intensity during magnetically disturbed days fits in with this view.

Sarabhai *et al.*[5] have reported a nonsignificant positive value $r=+0.29$ for Kodaikanal for the data of 4 months from July to October, 1951. In Table II, we give the values of the three-monthly mean r and β at Kodaikanal. These have been obtained after taking moving averages of three successive monthly values of the semidiurnal components of $^*M_K$ and P_K. Not only are these three-monthly mean values subject to larger random errors than the 12 monthly means, but they also include 12-monthly changes in addition to long-term changes. The table reveals the interesting fact that there are periods during which r has a low negative value.

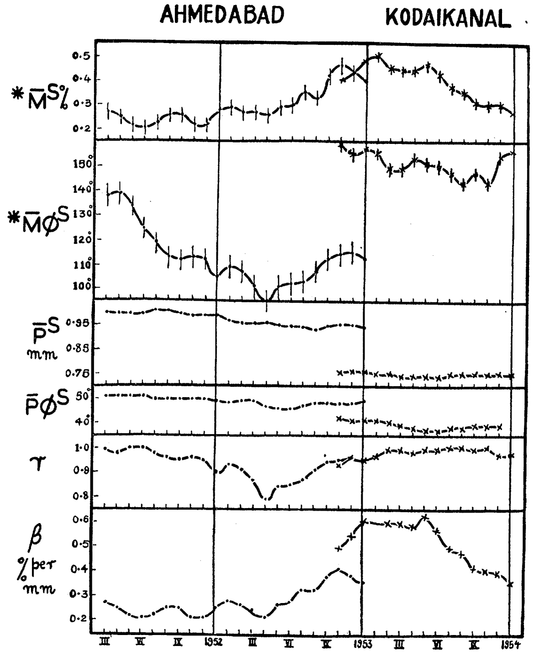

FIG. 1. Time series for 12-monthly means of (1) the amplitude $^*\bar{M}^S$ and the time of maximum $^*\bar{M}\phi^S$ of the semidiurnal component of meson intensity before applying correction for barometric pressure, (2) the amplitude $\bar{P}^S$ and time of maximum $\bar{P}\phi^S$ of the semidiurnal component of the barometric pressure, (3) the correlation coefficient r derived from the semidiurnal components of meson intensity and pressure, and (4) the barometric coefficient β derived from the same. The results at Ahmedabad are shown at the left side while those at Kodaikanal are shown on the right.

TABLE II. Correlation coefficient r and barometric coefficient β calculated from three-monthly mean values of the semidiurnal components of $^*M_K$ and P_K.

Period centered at	r	$\beta\%$ per cm of Hg
52.VI	-0.52	-1.5
VII	-0.91	-4.3
VIII	-0.96	-6.4
IX	-0.97	-6.1
X	-0.85	-4.3
XI	-0.79	-3.7
XII	-0.87	-5.1
53.I	-0.96	-7.1
II	-1.00	-7.1
III	-0.99	-5.9
IV	-1.00	-5.5
V	-0.96	-6.3
VI	-0.98	-8.0
VII	-0.98	-6.9
VIII	-0.90	-6.6
IX	-0.97	-4.5
X	-0.87	-5.0
XI	-0.73	-2.2
XII	-0.99	-1.8

Our present work clearly demonstrates that the barometric coefficient β, derived from the semidiurnal components of $^*M$ and P, can be in error due to a semidiurnal contribution of the anisotropy of cosmic radiation. Experimental studies by Dolbear and Elliot,[28] Duperier,[29] and Trumpy and Trefall[30] and theoretical calculations by Olbert[31] reveal that β is related to a mass absorption coefficient μ, a decay coefficient μ', and a temperature coefficient α. Hence values of β alter as a result of variation in the pattern of changes in the vertical distribution of atmospheric temperature that accompany changes of barometric pressure.

While the daily variation of barometric pressure results from the diurnal heating of the layers near the ground and the excitation of resonant oscillations of the atmosphere, the nonperiodic changes of pressure are accompanied by quite different alterations of the temperature distribution of the atmosphere. On physical ground therefore, there is little justification to apply, to the daily variation, a β derived from day-to-day or nonperiodic changes of meson intensity and of barometric pressure.

In the absence of an experimental determination of a β appropriate for correcting the daily variation of meson intensity, we have to fall back on making an estimate of its value, partly on experimental and partly on theoretical considerations, from a knowledge of the

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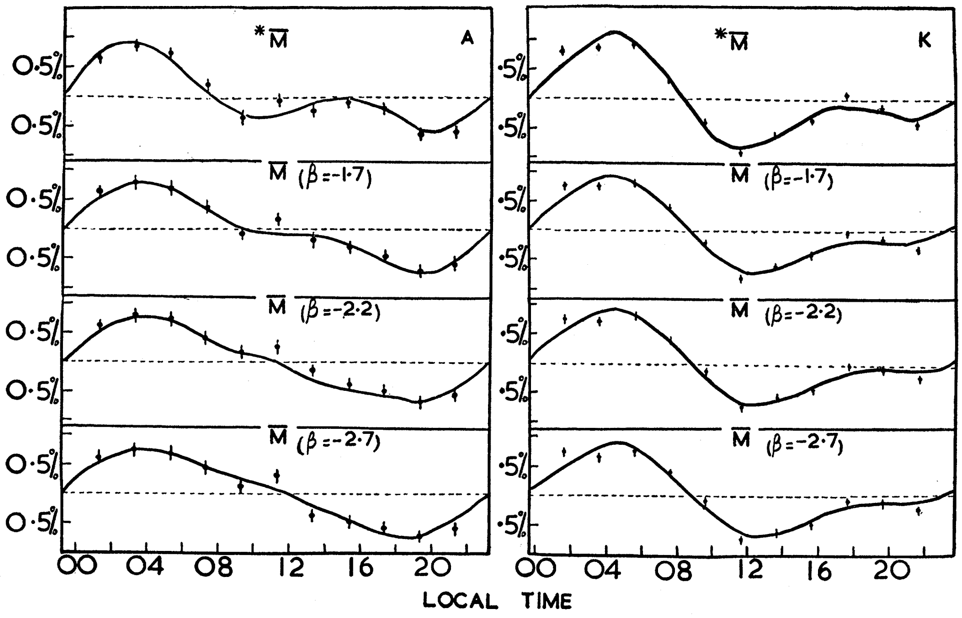

(a) (b)

FIG. 2. The 12-monthly mean daily variation $*\bar{M}$ centered at December, 1952, before applying barometric correction and the same after applying barometric correction, using for β, the barometric coefficient, the values -1.7, -2.2, and -2.7% per cm of Hg. Figure 2(a) refers to Ahmedabad and Fig. 2(b) to Kodaikanal.

daily changes of temperature, barometric pressure, and heights of isobaric levels in the atmosphere. There is experimental evidence to indicate that the diurnal change of air temperature near the 100-millibar level is insignificant. Further, calculations by Nicolson and Sarabhai[32] show that due to atmospheric oscillation the amplitude of the vertical semidiurnal movement of isobaric levels near the 100-millibar level is no more than 12 meters at the equator.

There is therefore reason to adopt for the correction of $*M$ a β which has a negligible contribution of the temperature coefficient α, a small contribution of the decay coefficient μ', and a principal contribution from the mass absorption coefficient μ. Various determinations of these individual coefficients from studies of nonperiodic changes of meson intensity and meteorological elements at different levels in the atmosphere have been made. These are shown in Table III.

Determinations of μ, μ', and α have not been possible either at Ahmedabad or at Kodaikanal on account of the absence of radiosonde data. We have however taken $\beta=-2.2\%$ per cm of Hg for the pressure correction of $*M$ at both places. The arbitrariness in making this choice is unsatisfactory. However, it is well to realize the implications of an error in making this estimate. In Fig. 2, we indicate for a 12-monthly period centered at December, 1952 the mean daily variation curves of $*\bar{M}$ as well as of $\bar{M}$ using barometric coefficients $\beta=-1.7$, $\beta=-2.2$, and $\beta=-2.7\%$ per cm of Hg. Figure 2(a) relates to Ahmedabad and Fig. 2(b) to Kodaikanal. Values of -1.7 and -2.7% per cm of

TABLE III. Absorption coefficient μ, decay coefficient μ', and positive temperature coefficient α.

Coefficient	Duperier[a]	Dolbear and Elliot[b]	Trumpy and Trefall[c] I[d]	II[e]
$\mu\%$ per cm Hg	-1.05	-2.07	$-1.69\ \pm0.11$	$-1.49\ \pm0.14$
$\mu'\%$ per km	-3.90	-4.22	$-4.45\ \pm0.53$	$-3.48\ \pm0.60$
$\alpha\%$ per °C	$+0.12$	$+0.14$	$+0.036\pm0.021$	$+0.038\pm0.019$

[a] See reference 29.
[b] See reference 28.
[c] See reference 30.
I[d] refers to hard componetn penetrating 10-cm lead absorber and II[e] to component penetrating 22-cm lead absorber.

TABLE IV. First and second harmonics of 12-monthly mean daily variation of meson intensity at Ahmedabad, corrected for barometric pressure.

Year and month	$\bar{M}_A{}^D$ %	$\bar{M}\phi_A{}^D$	$\bar{M}_A{}^S$ %	$\bar{M}\phi_A{}^S$
51.III	0.22	174°	0.07	172°
IV	0.23	164°	0.05	$\pi+11°$
V	0.26	165°	0.02	$\pi+63°$
VI	0.27	153°	0.02	0°
VII	0.26	152°	0.04	44°
VIII	0.30	159°	0.08	60°
IX	0.28	164°	0.09	54°
X	0.24	157°	0.06	34°
XI	0.31	150°	0.08	45°
XII	0.38	141°	0.13	58°
52.I	0.40	130°	0.12	66°
II	0.47	130°	0.12	59°
III	0.46	121°	0.13	48°
IV	0.48	118°	0.16	40°
V	0.48	114°	0.16	55°
VI	0.53	116°	0.16	60°
VII	0.56	106°	0.11	56°
VIII	0.58	91°	0.16	76°
IX	0.72	91°	0.23	95°
X	0.74	89°	0.26	101°
XI	0.71	85°	0.23	100°
XII	0.66	88°	0.21	93°

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Hg for β may be considered to be the reasonable limits within which the true coefficient applicable to the daily variation of meson intensity is expected to lie. This is because β is expected to be greater than μ, but less than the value of the barometric coefficient measured in day-to-day changes where all the three factors are operative. It is seen that at both places, the limiting values of β make little difference to the resulting $\bar{M}$. Without making a distinction between applicability to day-to-day changes and to daily changes, Forbush has justified the use of $\beta = -3.0\%$ per cm of Hg at Huancayo, and $\beta = -1.8\%$ per cm of Hg at Cheltenham, Christchurch, and Godhavn.

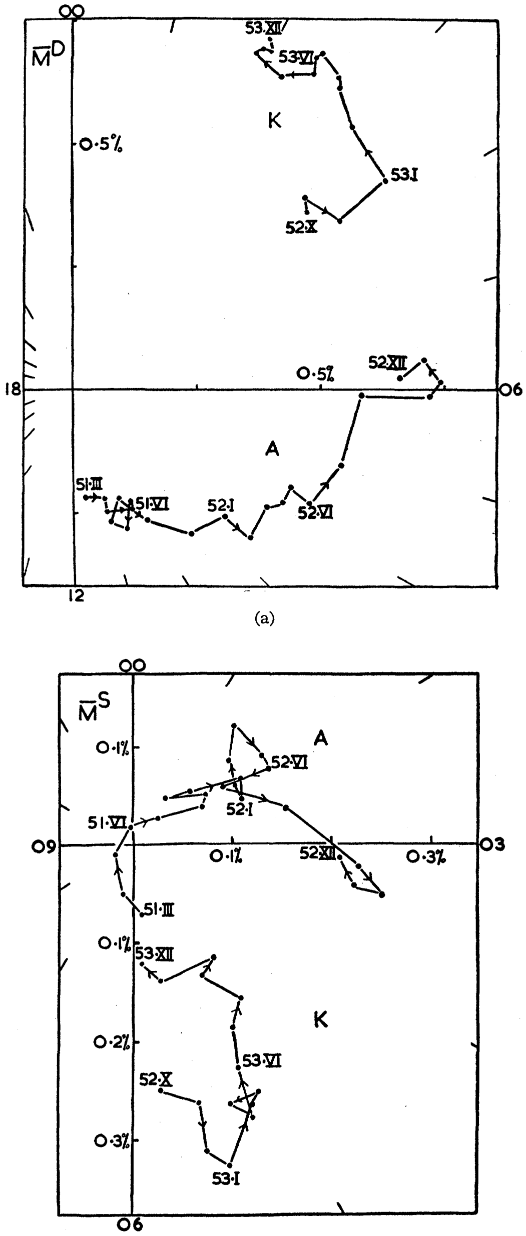
Until a better evaluation is possible, we consider it reasonable to apply $\beta = -2.2\%$ per cm of Hg to our data. In what follows, we have used this value for observations at Ahmedabad as well as at Kodaikanal.

TABLE V. First and second harmonics of 12-monthly mean daily variation of meson intensity at Kodaikanal, corrected for barometric pressure.

Year and month	$\bar{M}_K{}^D$ %	$\bar{M}\phi_K{}^D$	$\bar{M}_K{}^S$ %	$\bar{M}\phi_K{}^S$
52.X	0.60	52°	0.25	173°
XI	0.61	50°	0.27	165°
XII	0.64	57°	0.32	166°
53.I	0.76	56°	0.34	163°
II	0.78	46°	0.29	155°
III	0.82	41°	0.28	153°
IV	0.83	40°	0.28	159°
V	0.85	36°	0.30	156°
VI	0.84	36°	0.25	154°
VII	0.81	37°	0.21	151°
VIII	0.77	33°	0.19	144°
IX	0.78	28°	0.15	152°
X	0.79	29°	0.14	144°
XI	0.80	30°	0.14	168°
XII	0.82	29°	0.12	175°

IV. LONG-TERM CHANGES OF THE HARMONIC COMPONENTS OF THE DAILY VARIATION OF MESON INTENSITY, CORRECTED FOR BAROMETRIC PRESSURE

We have reported earlier[23] the characteristics of long-term changes in $\bar{M}^D$ and $\bar{M}\phi^D$ at the Carnegie Institution stations of Huancayo, Cheltenham, and Christchurch, and the relationship of these changes to the solar cycle of activity. Where M is measured with directional telescopes, the diurnal and semidiurnal components have greater amplitudes than are observed with ionization chambers and it is therefore of interest to look for similar changes in our data. In Tables IV and V we give values of $\bar{M}^D$, $\bar{M}\phi^D$, $\bar{M}^S$, and $\bar{M}\phi^S$ during the entire period of observation at Ahmedabad and at Kodaikanal. In Figs. 3(a) and 3(b), we show, with the aid of harmonic dial representation, the changes in the diurnal and semidiurnal components of $\bar{M}$ at the two stations. Because of shifting the laboratory at Ahmedabad towards the latter part of 1953, there is an unfortunate break of continuous data. 12-monthly mean values at Ahmedabad are available for periods centered up to December, 1952, while at Kodaikanal they commence from October, 1952. Thus, even though the units at Ahmedabad and at Kodaikanal were simultaneously in operation for a period of 14 months, there is overlapping data for 12-monthly means for only 3 months. We are hence unable to compare the time series at the two places.



(a)

(b)

FIG. 3(a). Harmonic dial showing the movement of the first harmonic of the 12-monthly mean daily variation of meson intensity $\bar{M}_A{}^D$ at Ahmedabad and $\bar{M}_K{}^D$ at Kodaikanal. (b) Harmonic dial showing the movement of the second harmonic of the 12-monthly mean daily variation of meson intensity $\bar{M}_A{}^S$ at Ahmedabad and $\bar{M}_K{}^S$ at Kodaikanal.

It is nevertheless interesting to observe in Figs. 3(a) and 3(b) that the amplitudes of the diurnal and semidiurnal daily variations at Ahmedabad and at Kodaikanal are comparable for the overlapping period centered at December, 1952. However, the diurnal time of maximum is about two hours later and the semidiurnal time of maximum about three hours earlier at Ahmedabad than at Kodaikanal. Comparison of some preliminary results[5] during 1951 had shown on the other hand that $M_K{}^D$ was significantly greater than $M_A{}^D$. $M\phi_A{}^D$ was then later by about one hour than $M\phi_K{}^D$, as it is during the present overlapping period of observation. The available evidence thus indicates that while the time of maximum of the diurnal component is earlier at the mountain station near the equator than it is at the sea level station at higher latitude, the amplitude is not always greater at the former location.

Carnegie Institution data[23] reveal that the changes of the diurnal time of maximum are worldwide in character. The correlation between time series for $\bar{M}\phi_H{}^D$ and $\bar{M}\phi_C{}^D$ from 1938 to 1952, is found to be +0.92. There is an overlapping period from March, 1951 to June, 1952 during which changes at Ahmedabad can be compared with changes at Huancayo and Cheltenham. In Fig. 4, the time series of $\bar{M}\phi_A{}^D$, $\bar{M}\phi_H{}^D$, and $\bar{M}\phi_C{}^D$ are shown for these 15 months. The scale for the time of maximum has been considerably expanded for the two Carnegie Institution stations. Curiously, during this period, Cheltenham does not exhibit the progressive decrease of $\bar{M}\phi^D$ that is so marked at the two stations in the tropics. Between the changes at Huancayo and at Ahmedabad there is indeed very close resemblance. The correlation between the two is +0.93. Changes in $\bar{M}\phi^D$ at the two stations can be related by means of the regression equation:

$$\delta(\bar{M}\phi_A{}^D) = 2.8\delta(\bar{M}\phi_H{}^D).$$

This means that changes observed in the diurnal time of maximum are about three times as great at Ahmedabad, where a directional telescope is used, than at Huancayo where an omnidirectional ionization chamber records the meson intensity. The magnified changes observed with the counter telescope may well have been larger if the instrument was at a mountain station like Huancayo instead of being at sea level. It is clear from this evidence that changes of $\bar{M}\phi^D$ from different types of instruments cannot be directly compared. The putting together of data, on a common diagram without appropriate normalization, from counter telescopes and ionization chambers as has been done by Thambyahpillai and Elliot[24] is therefore not justified.

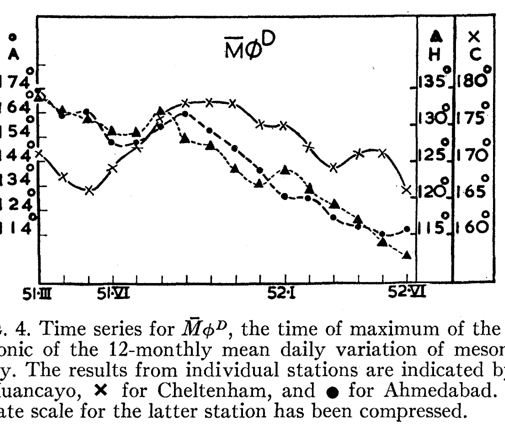


FIG. 4. Time series for $\bar{M}\phi^D$, the time of maximum of the first harmonic of the 12-monthly mean daily variation of meson intensity. The results from individual stations are indicated by ▲ for Huancayo, × for Cheltenham, and ● for Ahmedabad. The ordinate scale for the latter station has been compressed.

V. THE CHANGE OF 12-MONTHLY MEAN DAILY VARIATION OF MESON INTENSITY AT AHMEDABAD AND KODAIKANAL

The change taking place in $\bar{M}_A$ during the period March, 1951 to December, 1952 is quite remarkable. Reference to Table IV reveals that the notable increase of $\bar{M}_A{}^D$ from 0.24 to 0.70% is accompanied by an almost parallel increase of $\bar{M}_A{}^S$ from 0.07 to 0.21%. Simultaneously $\bar{M}\phi_A{}^D$ advances to an earlier time by as much as six hours, and $\bar{M}\phi_A{}^S$ becomes later by nine hours. We can get a better insight into the phenomenon if instead of considering changes in the harmonic components of the daily variation, we look at changes in the nature of the unresolved daily variation after correcting for barometric pressure. We could for this purpose use $\bar{M}$, but in order to smooth out random fluctuations we use $\bar{M}°$ formed by the superposition of the first two harmonic components of $\bar{M}$. In Fig. 5, we show $°\bar{M}_A$ centered at successive epochs separated by 3 months. The 12-monthly changes $\Delta°\bar{M}_A$, also shown in the figure, relate to the difference between the 12-monthly mean curves $°\bar{M}$ at epochs separated by one year. Thus the 12-monthly change from ${}_{51.\text{III}}°\bar{M}$ to ${}_{52.\text{III}}°\bar{M}$ is expressed by $\Delta°\bar{M}(52.\text{III}-51.\text{III})$.

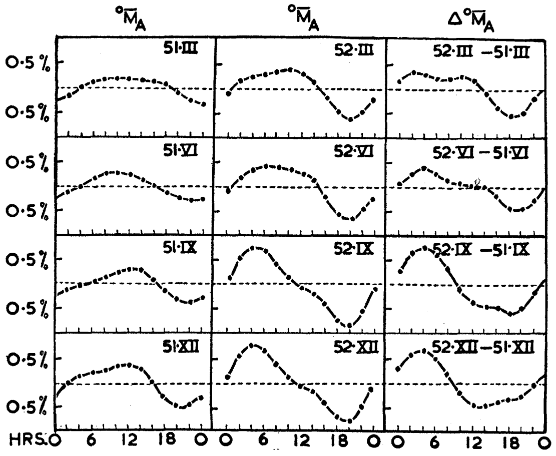


FIG. 5. The 12-monthly mean daily variation $°\bar{M}_A$ at Ahmedabad centered at successive epochs and the year-to-year differences $\Delta°\bar{M}_A$.

It is clearly seen that ${}_{51.\text{VI}}°\bar{M}_A$ is mainly diurnal with a maximum at about 1100 hours. However, a new diurnal contribution is added to it with a maximum near 0300 hours, so that about 8 to 9 months later we have a double-humped curve. During the subsequent 6 months, the day time diurnal contribution gets attenuated and $_{52.\text{XII}}{}^\circ\bar{M}_A$ has once again a mainly diurnal character but with a maximum in the early morning. From the curves for $\Delta^\circ\bar{M}_A$ shown alongside, it is seen that the radical changes taking place in $\Delta^\circ\bar{M}_A$ may be looked upon as caused by changes in the comparative magnitudes of two distinct contributions to the daily variation. These contributions are principally diurnal in character but each has a characteristic time of maximum which remains comparatively constant. The maximum of the first contribution occurs at about 0300 hours and of the second at about 1300 hours local time at Ahmedabad.

In Fig. 6 we show similarly the changes in $^\circ\bar{M}_K$ and $\Delta^\circ\bar{M}_K$ at Kodaikanal. During the period covered by Kodaikanal data, less violet changes have occurred than during the immediately preceding 18 months at Ahmedabad. In $^\circ\bar{M}_K$ for most of the period, only the maximum at about 0400 hours undergoes change of amplitude without an appreciable shift of the local time at which it occurs. In $\Delta^\circ\bar{M}_K$, we have evidence of an early morning diurnal contribution which has a maximum almost at midnight and a second much smaller diurnal contribution with a maximum near noon. Thus it appears that at Kodaikanal both contributions have maximum intensity at an earlier hour than at Ahmedabad.

VI. CHANGE IN THE 12-MONTHLY MEAN DAILY VARIATION OF MESON INTENSITY AT HUANCAYO AND CHELTENHAM

In order to confirm the view we have reached about the manner in which $^\circ\bar{M}$ changes at Ahmedabad and Kodaikanal, we can examine Carnegie Institution data from 1937 to 1952. The long term changes in $\bar{M}^D$ and $\bar{M}\phi^D$ have been described by us elsewhere.[23] Figure 7 shows the time series for $\bar{M}^S$ and $\bar{M}\phi^S$ at Huancayo and Cheltenham. The change of 12-monthly mean relative sunspot number R is also shown therein.

With ionization chambers the semidiurnal component of the daily variation of meson intensity, corrected for barometric pressure, is small and in general not much significance can be attached to small changes in it. While this is consistently so at Cheltenham and Christchurch, which are in middle latitudes, substantial changes in the semidiurnal component occur at the equatorial station of Huancayo, where the figure clearly reveals a continuous trend over the years. $\bar{M}_H{}^S$ is generally greater during sunspot maxima than during years of low activity, and it follows approximately the variation of the relative sunspot number R. However, correspondence with the eleven-year solar cycle of activity which is so clearly discernible in the time series for $\bar{M}\phi^D$, is not visible in changes in the time of maximum of the semidiurnal component of the daily variation. On the other hand, $\bar{M}\phi_H{}^S$ shifts steadily to later hours by as much as 5 hours in the period 1938 to 1950.

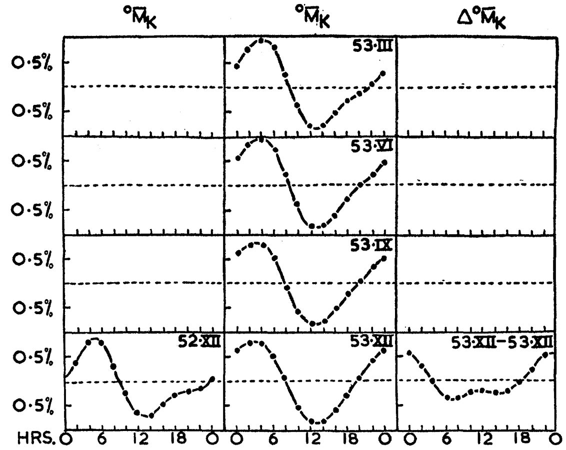


FIG. 6. The 12-monthly mean daily variation $^\circ\bar{M}_K$ at Kodaikanal centered at successive epochs and the year-to-year differences $\Delta^\circ\bar{M}_K$.

In view of significant changes in the semidiurnal component at Huancayo, it is interesting to look at changes of the total daily variation $^\circ\bar{M}$. Figure 8 relating to the equatorial station of Huancayo reveals the most striking changes that take place from year to year in the 12-monthly mean daily variation of meson intensity $^\circ\bar{M}$. The variation which is predominantly diurnal in character with a maximum around noon in the period 1939–1941, has progressively a new component added to it in the following six to seven years. This component may be considered to have a predominant diurnal character but with a maximum around 0100 hours. During 1946–1948, as a result of the day and the night components being both present to an almost equal degree, the daily variation $^\circ\bar{M}$ appears as a double-humped curve. In the following years, the day component gets progressively attenuated with the result that in 1952 we are left once again with $^\circ\bar{M}$ which has mainly a diurnal character. However, the essential difference between this and the earlier curve of 1940 is that the maximum now occurs in the night instead of during the day. The period separating these two types of daily variation curves is about 11 years, but undoubtedly the cycle of change is not complete and at first sight it would appear that in this period we are only going through half the cycle. While there is in the time series for $\bar{M}\phi^D$ a period corresponding to the normal solar cycle of activity, the daily variation as a whole might still undergo a 22-year cycle of change.

Another interesting feature revealed in Fig. 8 is that while the time of maximum of the day component remains almost stationary near 1300 hours from 1937 to 1944, it shifts significantly to later hours during the period 1944 to 1948. The night component also follows a similar shift to later hours during 1944 to 1948.

The changes in $^\circ\bar{M}$ at Cheltenham, representative of a

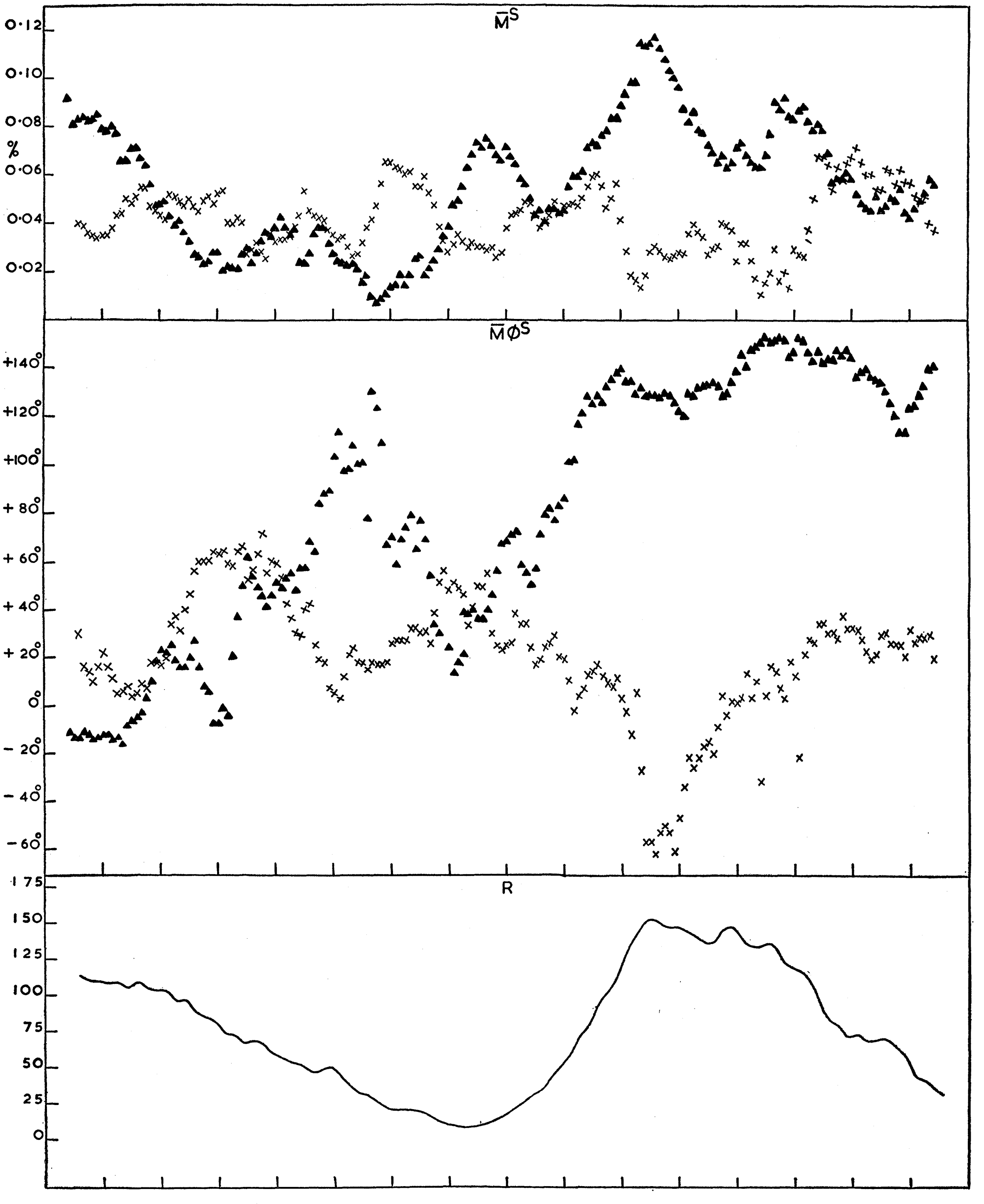


FIG. 7. Time series for the amplitude $\bar{M}^S$ and time of maximum $\bar{M}\phi^S$ of the semidiurnal component of 12-monthly mean daily variation $\bar{M}$, and of the Zurich relative sunspot number R. The results from Huancayo are indicated by ▲ and those from Cheltenham by ×.

station in middle latitudes are shown in Fig. 9. The changes are not as striking as at Huancayo. While $°\bar{M}_C$ never has a pronounced second maximum as is observed in $°\bar{M}_H$ during some years, noteworthy changes are seen to occur both in its magnitude and form. Since the semidiurnal component of the daily variation is small at

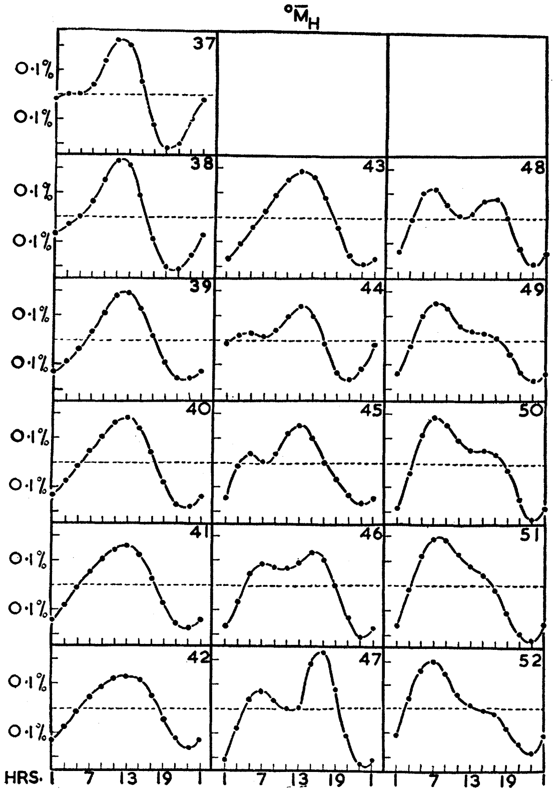


FIG. 8. The 12-monthly mean daily variations $^\circ\bar{M}_H$ at Huancayo centered on June of each year, from 1937 to 1952.

Cheltenham, it is of course to be expected that the observation of the changes in $^\circ\bar{M}$ cannot be much more revealing than study of the changes of the amplitude and the time of maximum of only the first harmonic component of the variation.

We can now examine the year to year difference curves $\Delta^\circ\bar{M}$ at Huancayo. These are shown in Fig. 10. We have seen earlier that there is reason to believe that the changes in $^\circ\bar{M}$, at least at low latitudes, take place due to additions or subtractions of two mainly diurnal contributions, one having a maximum in the daytime and the other at night. To study the form of these contributions we take the year to year difference by subtracting $^\circ\bar{M}$ for each year from the one for the preceding year. Normally therefore we have $\Delta^\circ\bar{M}((x+1).y-x.y)$. However, in periods where the contributions are getting attenuated, we get difference curves which are reversed in relation to the curves for the periods where the contributions are increasing from year to year. To facilitate visual comparison of the curves, we therefore take the differences $\Delta^\circ\bar{M}(x.y-(x+1).y)$ wherever there is an indication that attenuation of the contributions is taking place. Such difference curves are drawn with dotted lines.

Figure 10 shows that at Huancayo, $\Delta^\circ\bar{M}$ is composed of two contributions, one having a night and the other a daytime maximum, just as we have found at Ahmedabad and Kodaikanal. It may be argued that had we changed the sign of all our differences, we would conclude that the two contributions are at 0600 and at 1800 hours. Such a view can be legitimately taken if we look at only the difference curves $\Delta^\circ\bar{M}$. However, if we wish to have a simple explanation of the $^\circ\bar{M}$ curves also on the basis of similar contributions, we have clearly no choice but to reject this alternative manner of picturing the physical mechanism of the change of the daily variation of meson intensity.

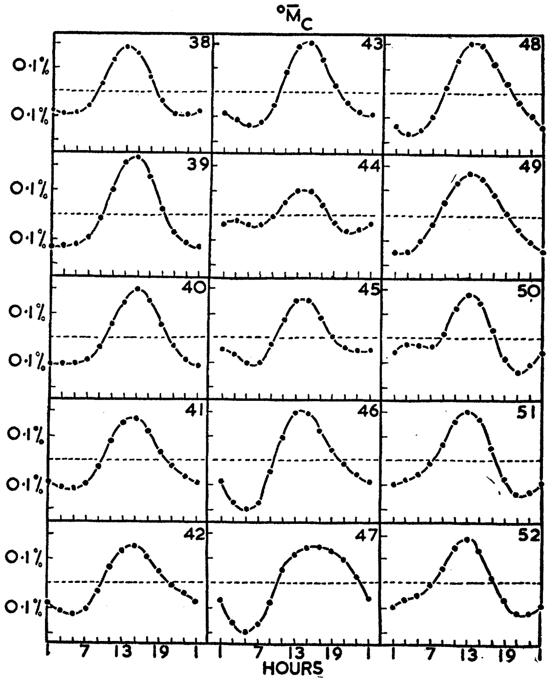


FIG. 9. The 12-monthly mean daily variations $^\circ\bar{M}_C$ at Cheltenham centered on June of each year, from 1938 to 1952.

VII. THE RELATIONSHIP OF CHANGE OF 12-MONTHLY MEAN DAILY VARIATION OF MESON INTENSITY WITH THE SOLAR CYCLE OF ACTIVITY

The year-to-year changes of $^\circ\bar{M}_H$ are generally small and it is therefore advantageous to group together several years where there is indication of similar changes having occurred. By examination of Fig. 8 relating to Huancayo, it is clear that the entire period from 1937 to 1952 may be divided into six groups. The first group extends from 1937 to 1942 during diminishing solar activity. The second and third groups relate to the period 1942 to 1944 near sunspot minimum when violent changes have occurred in $^\circ\bar{M}_H$. The fourth group extends from 1944 to 1947 during increasing solar activity and the fifth group to the period 1947 to 1951 when solar activity diminishes after reaching a maximum. The last group including the years 1951, 1952 represents the period just preceding sunspot minimum.

In Fig. 11(a) we show the difference curves representing the change of $^\circ\bar{M}_H$ for the pairs of years at the beginning and end of each group. The mean relative sunspot number R for the years comprising each group is also indicated. As before, we have shown the difference curves with dotted lines whenever there is an indication that the day and night contributions are being attenuated.

It is seen from the figure that for the solar cycle extending from the maximum in 1937 to the maximum in 1947, with the exception of the period near the sunspot minimum from 1942 to 1944, there is in groups one and four a continued attenuation of the day and the night contributions. However, after the sunspot maximum in 1947, there is in group five an addition of the two contributions up to the year 1951 preceding the next sunspot minimum. With approaching sunspot minimum, there is first a period with only the day contribution. While this contribution is added in group two, it is attenuated in group six during the next cycle. Thus the pattern of change appears to be reversed on the completion of the first eleven-year period from sunspot maximum in 1937 to the following maximum in 1947. There may here be an indication that the addition and attenuation of contributions alternates in successive solar cycles of eleven years. Further data from Carnegie Institution stations would enable a confirmation of the important feature that the complete cycle of changes takes place in 22 years.

The changes described above may be compared with corresponding ones at Cheltenham by examination of Fig. 11(b) relating to $\Delta{}^\circ\bar{M}_C$. There is same evidence of a night contribution at 0500 hours and a day contribution at 1500 hours. However, both contributions are more diffuse than at Huancayo and instead of characteristic double-humped curves, we observe distorted or broadened diurnal curves. The change of form of difference curves with solar cycle is broadly similar to what we observe at Huancayo.

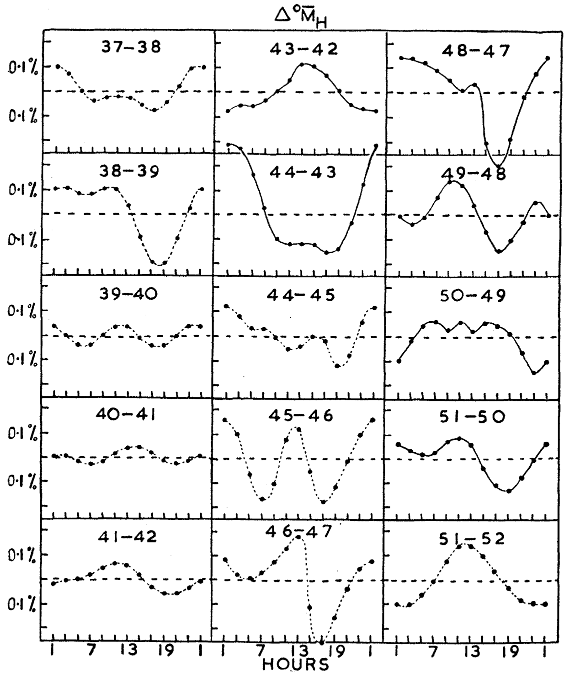
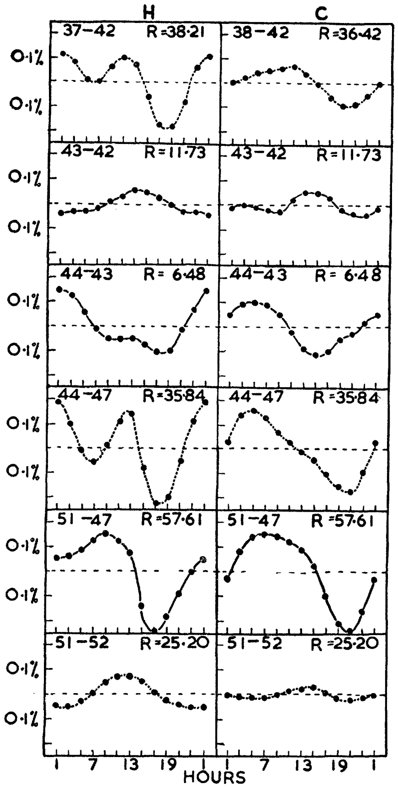


FIG. 10. The year to year difference curves $\Delta{}^\circ\bar{M}_H$ representing the change in ${}^\circ\bar{M}_H$ during successive years. Broken line curves indicate negative change with respect to those with full lines.



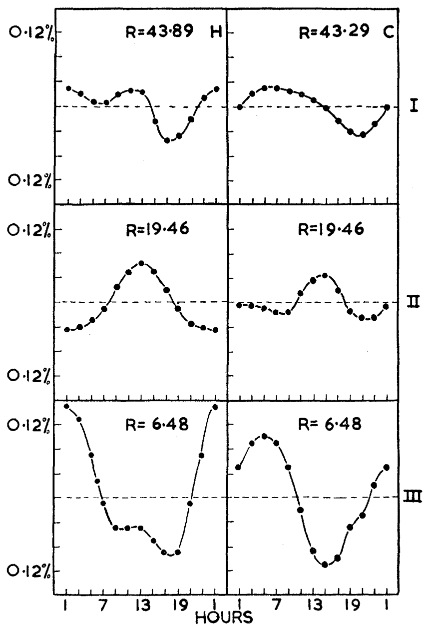
(a) (b)

FIG. 11. The difference curves $\Delta{}^\circ\bar{M}$ representing the change of ${}^\circ\bar{M}$ for the pairs of years at the beginning and end of groups of years arranged according to solar activity. R gives the mean relative sunspot number for the years comprising each group. Figure 11(a) refers to Huancayo, and Fig. 11(b) to Cheltenham. Broken line curves indicate negative change with respect to those with full lines.

We can see from the foregoing that there are three basic types of changes that take place in ${}^\circ\bar{M}$. In the first type both contributions are active. In the second the day contribution is individually active, while in the third only the night contribution is active. The six groups discussed earlier can therefore be reduced to three by combining groups one, four and five; two and six; leaving three as before. Since we are interested in the form of contributions in each type, we neglect the question of their addition or attenuation and algebraically superimpose the curves as shown in Figs. 11(a) and 11(b). The values so obtained in each type are then divided by the number of year to year changes that are involved in the period covered by the type. Thus we finally obtain the form of the mean year-to-year change for each type. These are shown for Huancayo and for Cheltenham in Figs. 12(a) and 12(b).

It will be realized that the mean year-to-year difference curve of type 1 is an abstraction of what may be supposed to take place repeatedly over a period of years. In fact, there is not a uniform change every year by an amount corresponding to the curve shown. Reference to Fig. 10 reveals that the magnitude of the change is much greater in some years than in others.

The position of the maxima in the type 2 and type 3 curves correspond almost exactly with the two maxima of the type 1 curve. The concept of the day and the night contributions being responsible for the change of $^{\circ}\bar{M}$ appears therefore to be well borne out. A further insight into the rapid and striking change from the activity of the day contribution to the activity of the night contribution approaching the year of minimum solar activity is obtained by following the changes in $^{\circ}\bar{M}_H$ at epochs separated by three months. These are shown in Fig. 13, where we can clearly follow in $\Delta^{\circ}\bar{M}_H$ the progressive attenuation of the day contribution and the addition of the night contribution over the period of 18 months. But this type of change occurs only near sunspot minimum, and for the rest of the solar cycle the two contributions are added or attenuated simultaneously. It is noteworthy that the amplitude of the mean year-to-year difference curve is greatest for type 3. There is great similarity of the difference curves at Huancayo and Cheltenham in types 2 and 3. However, the maxima in both types occur a little later by about 2 to 4 hours at Cheltenham than at Huancayo.



(a) (b)

FIG. 12. Mean year-to-year difference curves representing three types of changes. Figure 12(a) refers to Huancayo and Fig. 12(b) to Cheltenham.

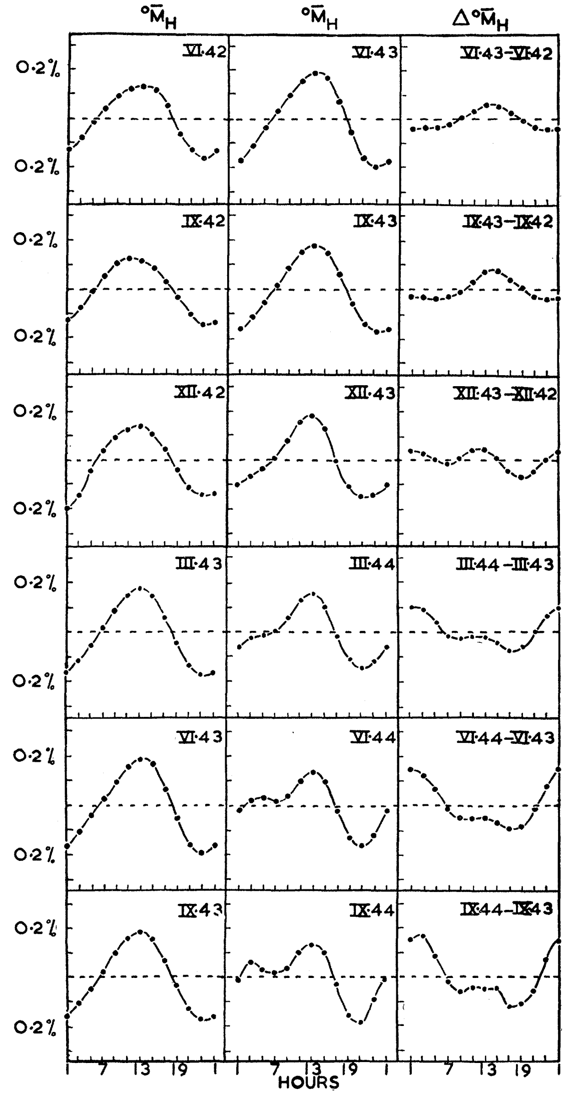


FIG. 13. Year-to-year difference curves $\Delta^{\circ}\bar{M}_H$ at epochs separated by 3 months during a period of rapid change in $^{\circ}\bar{M}_H$ at Huancayo.

VIII. CONCLUSIONS

The study of the daily variation of meson intensity with counter telescopes at low latitudes has revealed new and important features which have a bearing on its interpretation. These may be summarized as follows:

(1) The semidiurnal component of the daily variation of meson intensity is not only due to the semidiurnal variation of barometric pressure, but also arises from the anisotropy of the primary cosmic radiation. Instances[3,5] where the correlation between the semidiurnal components of $^{*}M$ and P is positive may therefore arise when the semidiurnal effect of the anisotropy is in opposition to and larger than the semidiurnal effect of the change of the barometric pressure.

(2) There is no satisfactory experimental determination at the present moment of β, the barometric

coefficient that should be applied to the daily variation of meson intensity. However there is good reason to use a barometric coefficient of about -2.2% per cm of Hg in order to correct atmospheric influences. The daily variation so corrected can be ascribed to an anisotropy of the primary radiation.

(3) The semidiurnal component of $\bar{M}$, the 12-monthly mean daily variation of meson intensity after correcting for barometric pressure, undergoes significant long-term changes, particularly at low latitudes. It was shown earlier that the diurnal component of $\bar{M}$ also undergoes significant long-term changes.

(4) The examination of long-term changes of the amplitude and the time of maximum of only the first harmonic component does not reveal the true nature of the physical process which is operating. Similar is the handicap in looking separately at the changes of the amplitude and time of the maximum of the second harmonic component.

(5) It is important to consider changes of the daily variation $\bar{M}$ rather than of its harmonic components. However, in so far as $\bar{M}$ has generally only the first two harmonic components with significant amplitudes, it is convenient to deal with a smoothed $^\circ\bar{M}$ which is built by superposition of the first two components.

(6) Changes of $^\circ\bar{M}$ at Ahmedabad and Kodaikanal are suggestive of a mechanism which involves the addition or attenuation of two distinct daily contributions. Each is principally diurnal in character and while one of them has a maximum near midnight, the other has a maximum near noon.

(7) Changes of $^\circ\bar{M}_H$ at Huancayo, calculated from Carnegie Institution data from 1937 to 1952, reveal similarly the operation of day and night contributions. At Cheltenham also, there is some evidence of the two contributions, although the simultaneous action of both contributions is not as clearly seen as at stations in low latitudes.

(8) The activity of the two contributions is closely related to the solar cycle of activity. In general, the day and the night contributions are simultaneously added or attenuated. However, just preceding sunspot minimum there is a brief period when only the day contribution is active. This is immediately followed by a short period when only the night contribution is active. The pattern of addition and attenuation of the contributions appears to get reversed after 11 years.

(9) The amplitude of the semidiurnal component of $^\circ\bar{M}_H$ changes in a general way like the changes in the relative sunspot number R. Thus at low latitudes $^\circ\bar{M}^S$ and $^\circ\bar{M}\phi^D$ exhibit an eleven year cycle of change.

(10) The changes of $^\circ\bar{M}\phi^S$ and of $^\circ\bar{M}$ indicate that in eleven years perhaps only half the cycle of change is completed and the complete period may extend to 22 years.

(11) The changes of $\bar{M}\phi^D$ recorded by a counter telescope of moderate aperture are much greater than what are revealed by an omnidirectional instrument such as an ionization chamber. Thus in regard to both the magnitude of the daily variation as well as to its changes, an instrument with directional sensitivity offers advantages over one with omnidirectional characteristics.

The phenomological study of long-term changes of the daily variation of meson intensity has prompted a quantitative evaluation of changes of the day and the night contributions and their relationship with solar activity. The results of this analysis will be presented in a later communication.

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