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GODDARD SPACE FLIGHT CENTER
GREENBELT, MARYLAND

QUASI-BIENNIAL VARIATIONS OF COSMIC-RAY INTENSITIES*

by

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* To be submitted to the Journal of Geophysical Research.

Quasi-Biennial Variations of Cosmic-Ray Intensities

30351

Abstract

Owing to the atmospheric temperature effect on cosmic-rays, the so-called quasi-biennial (or 26-month) oscillation in the stratosphere should be apparent in the hard component of cosmic-ray data at the ground. As it is estimated theoretically, the cosmic-ray muon data near the equator (Lae, $6^{\circ}44$ S) shows a significant biennial variation, the period of which seems longer than 26 months, but shorter than 30 months for 1954-1964. The previous power spectrum analysis of Huancayo (12° S) ion-chamber data (Maeda and Suda) is also elaborated by choosing the five highest counting days in each month, indicating a significant peak at the period of 24 months. A similar analysis made for the ion-chamber data from Godhavn ($69^{\circ}5$ N) shows a very weak peak at 24 months for 1947-1959. It is concluded from present analyses that biennial variations in cosmic-ray intensity are predominantly of terrestrial origin, i.e., if the days of large extraterrestrial modulation (such as geomagnetic disturbed days) are chosen no significant 26-month variation appears in cosmic-ray data.

Introduction

Since its discovery in the tropical stratospheric wind system (Reed, 1960; Veryard and Ebdon, 1961), features of the biennial variation, or the so-called 26-month oscillation in the earth's atmosphere have been revealed to a great extent in the past few years, except the theories to explain its origin and mechanisms (Reed, 1962, 1963, 1964 and 1965; Reed and Rogers, 1962; Staley, 1963; Belmont and Dartt, 1964; Dartt and Belmont, 1964; Newell, 1964; Kriester, 1964; Sparrow and Unthank, 1964; Wescott, 1964, etc.).

On the other hand, cosmic-ray intensities observed at the earth's surface are continuously modulated not only by the astrophysical variations in outer space (particularly the magnetic field) but also by the atmospheric variations. Due to the decay processes of unstable components such as pions and muons, produced by incoming primary cosmic-ray particles in the upper atmosphere, intensities of cosmic-radiation at the ground change with variations of barometric pressure and of the atmospheric temperatures (Jánnosy, 1950; Dauvillier, 1954; Heisenberg, 1963; Dorman, 1957). Therefore, the cosmic-ray muon data, which are more commonly called cosmic-ray meson data, or the hard component intensities measured at the ground and corrected for barametric effect, are very good indicators of continuous atmospheric temperature variations, provided that information about geomagnetic variations is available. For this reason, we can expect the 26-month variations occurring in the upper atmosphere should be found also in the pressure-corrected cosmic-ray muon data. This is already shown by means of power spectrum analysis of ion-chamber data from Huancayo (geographic lat. 12° S). Since this station is not close enough to the equator, the result is hardly significant (as shown in Fig. 4, Maeda and Suda, 1965). The purpose of the present paper is to report another more significant detection of quasi-biennial variations in cosmic-ray data from the near-equator station (Lae, $6^{\circ}44'$ S) which was suggested in the previous paper, but not available at that time.

Meteorological Effects on Cosmic-Ray Intensities

The variation of cosmic-ray intensity at the ground due to the atmospheric temperature variation is an accumulated effect of the differential contribution from each layer in the atmosphere, which is not only a function of the altitude of each layer in the atmosphere, but also a function of the cut-off energy of observed cosmic rays. The latter depends on the geomagnetic and geographic location of the observing station and on the geometric condition of the measuring instrument, such as the thickness of shield and the type of cosmic-ray detector. These relations are well-known both experimentally and theoretically, and can be expressed by a simple formula:

$$\frac{\delta I}{I_o} = \int_o^{x_o} \gamma(E_o,x)\ \delta T\ (x)\ dx$$

$$\cong \sum_{i=0}^{n} \gamma(E_o,x_i)\ \delta T\ (x_i)\ \Delta x_i$$

and $$\gamma(E_o,x) = \alpha(E_o,x) + \beta(E_o,x)$$

where I_o, δI are the mean and the deviation of cosmic-ray intensity at the atmospheric depth x_o due to the temperature variation δT at the depth x, respectively.

$\gamma(E_o,x)$ is called the partial temperature coefficient, which indicates the relative variation of cosmic-ray muon intensity with cut-off energy E_o at the depth x_o, due to 1^o C increase in the layer δx at x. The details of these coefficients as the function of E_0 and x, as well as comparisons with the experimental data have been discussed by many workers (Maeda and Wada, 1954; Trefall, 1955; Wada and Kudo, 1956; Dorman, 1957; French and Chasson, 1956; Matthews, 1959; Wada, 1961; Carmichael et al., 1963; etc.). It should be noted that the atmospheric temperature effect on the cosmic-ray intensity consists essentially of two parts; one is positive and due to the change in production rate of cosmic-ray muons with temperature variations in the upper atmosphere, $\alpha(E_0,x)$, and the other is negative, corresponding to the change of decay-rate of muons in the atmosphere, $\beta(E_0,x)$. These are shown in Fig. 1, where $\alpha(E_0,x)$ and $-\beta(E_0,x)$ are plotted against x, for E_0 = 0.3, 10 and 40 GeV. Corresponding $\gamma(E_0,x)$'s are also shown in Fig. 2 against x. As can be seen from these figures, the temperature coefficient is mostly negative for usual cosmic-ray data, the cut-off energies of which are less than the order of 0.5 Gev. On the other hand, the positive effect dominates at high energies (particularly above the ground production level of cosmic-ray mesons, i.e., above 200 mb level), because decay-rates of muons produced with energies higher than several Gev in the atmosphere are practically negligible.

It is known that the phase of 26-month oscillation in the upper atmosphere differs with height, shifting from higher altitude downwards with a rate roughly of the order of 1 km/month. This is shown in the upper curves in Figure 3, in which variations of the stratospheric temperature differences between 3° S and 28° N are plotted from data obtained during the period from 1951 to 1961 at four different levels above 100 mb (full lines), and zonal winds at Balboa, Panama (8° N) are also shown by a dashed line, whose scale is indicated on the right side with units m/sec (Reed, 1965).

Since the phase of 26-month oscillation and the effect of temperature variation of cosmic-ray intensity are different with height, this kind of information is most suitable to see the corresponding variations in cosmic-ray intensities at the ground.

By using the above-mentioned formula, we can see the amplitude and phase of 26-month cosmic-ray variation for the corresponding periods of years. The calculations are made for three different cut-off energies, $E_0 = 0.3$, 10 and 40 Gev, using $\gamma(E_0,x)$'s, as shown in Fig. 3 (Maeda and Suda, 1965).

It is found from previous calculations that the phase relation between 26-month oscillation in the upper atmospheric temperature and that of cosmic-ray intensity at the ground is not simple, but rather reversed at low energies ($E_0 < 0.5$ Gev) and at high energies ($E_0 \gg 1$ Gev). This results from the different temperature effects at low energies (negative) and at high energies (positive). The former corresponds to the usual hard component data such as those observed by an ion-chamber or by the so-called cubical meson telescope, while the latter corresponds to the underground cosmic-ray intensities. These are shown by two dash-dot lines in the bottom of Fig. 3 for E_o = 0.3 Gev (heavy line) and 10 Gev (thin line), respectively. It should be noted that although the positive temperature effect increases with increasing cut-off energy, there is an upper limit (Maeda, 1960) and that because of its energy spectrum, cosmic-ray intensity decreases rapidly with increasing cut-off energy, i.e., with depth underground.*

At any rate, it is concluded that if continuous measurements of cosmic-ray intensity had been made at the geographic equator for more than one decade, the 26-month variation with amplitude of the order of 0.03% or the maximum deviation of the order of 0.1% can be detected even by ion-chamber data. If the underground cosmic-ray measurements had been made continuously for more than several years near the geographic equator, the 26-month variation with amplitude of more than 0.2% (which is the order of magnitude observed in the diurnal variations of cosmic-ray intensity) can also be found in these data with an anti-phase to those of low energies (Maeda and Suda, 1965).

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* For example, relative intensities with cut-off energies E_o = 0.3, 10 and 40 Gev are roughly 1 : 0.1 : 0.005, respectively.

Quasi-Biennial Variations of Cosmic-Ray Intensities

By means of the power spectrum analysis applied for the ion-chamber data from Huancayo, Peru (12° S, geographic) and from Cheltenham, Maryland (39° N, geographic) for the period of more than 20 years since 1937, the 26-month variations of cosmic-ray intensities have been hardly shown, if only geomagnetically quiet days (5-Q days in each month) are used (Maeda and Suda, 1965). This result is somewhat elaborated by choosing 5-H days in each month as shown in Fig. 4, where 5-H days means the five highest cosmic-ray intensity (counting) days in each month. When the galactic cosmic rays are modulated by the change in solar emissions, their intensities in general decrease. In other words, the highest counting days correspond to the period when the effects of solar disturbances, such as the Forbush effect, are eliminated, or at least minimum. A similar analysis is also applied for the identical ion-chamber data from Godhavn, Greenland ($69^{\circ}23'$ N geographic) for the period extending from January 1947 to July 1959. The results are shown in Fig. 5, where the scale of the ordinate is taken arbitrarily, but is identical for all three curves. 5-Q and 5-H mean five quiet days and five highest counting days in each month, respectively. Comparing Figs. 4 and 5, one can see that the biennial variation of cosmic-ray intensity at high latitude is very small as compared with those near the equator.

and zonal wind analysis (shown in the upper portion of Fig. 3), are shown by a full line in the bottom of Fig. 3, where a heavy dashed line and dots represent the first and the second harmonics of this curve.

Discussion

The results shown in the previous section, particularly those shown in Figures 3, 4, 5 and 6, indicate consistently that the 26-month variations in cosmic ray intensities are predominantly of atmospheric origin. In other words, 26-month periodicity is clearer in the geomagnetically quiet period than in geomagnetically disturbed days. According to the latest investigation (Reed, 1965), the amplitude of the 26-month variation in the stratospheric temperature field is largest at the geographic equator above the 100 mb level, which is of the order of 2° C, and decreases with latitude, but increases again slightly beyond 20 degrees of latitude, indicating a minimum around 17 degrees in each hemisphere. It is also indicated that the phase of 26-month oscillation is reversed between these two regions, i.e., tropics and subtropics.

From the viewpoint of this present status of 26-month oscillations, the location of Huancayo is rather close to the region of minimum

As it was suggested in the previous paper (Maeda and Suda, 1965), the cosmic-ray data from Lae, New Guinea ($6^{o}44'$ S) is most promising to see the 26-month variation, because this is the data from the stations closest to the geographic equator, where the variation is known to be maximum.

The analysis is made as follows: (i) all available data, being corrected by a coefficient -0.14%/mb obtained by the standard statistical method, are folded by different lengths of month extending from 20 to 30 months. (ii) The folded sum of the data is then divided by the number of folding, where the total available data consist of two periods, one from July 1957 to October 1960, and the other from September 1962 to December 1964. The result is shown in Fig. 6, where 5-Q and 5-H correspond to the data chosen from five quiet (geomagnetically) days and five high counting days in each month, respectively. The bottom lines stand for normalization into the same scale, taking the average value as 100%. From these curves, one can see that the period of biennial variation appearing in the cosmic-ray data from Lae is somewhat longer than 26 months, but less than 30 months, for 1960-1964. It should be noted that the standard deviations (dispersions of each point in vertical scale) are of the order of 0.1%.

Finally, the results of 26-month folding of the 5-H cosmic-ray data from Huancayo, corresponding to Reed's stratospheric temperature

temperature variation, but within the region of tropic oscillation (not in the subtropic). In this respect, cosmic-ray data from Makerere in Kampala, East Africa (0.33° N geographic, near sea level) are more useful for the present analysis, though the data from Lae have shown already a significant quasi-biennial variation as shown in Fig. 6. The difference between the theoretically estimated cosmic-ray intensity variation and those obtained from data, as shown at the bottom of Fig. 3, is possibly due to the following two reasons: (i) Though the period of analysis is the same for both Reed's and the present analysis, cosmic ray data are taken far from Reed's analysis. (ii) Huancayo is rather close to the subtropic boundary, while theoretical estimations are made for near-equator. In this respect, further analysis of cosmic-ray data near the equator is desirable.

As indicated by recent aerological observations, the quasi-biennial variations are persistent even in the high latitudes, especially in the southern hemisphere, including the Antarctic (Funk and Garnham, 1962; Angell and Korshover, 1964; Sparrow and Unthank, 1964; Reed, 1965). Since high energy cosmic-ray data, particularly those measured underground, should be available at several places in the world, quasi-biennial variations in cosmic-ray phenomena still seem worthy of investigation.

Finally, it should be emphasized that since the sources of cosmic-ray variations are terrestrial as well as extraterrestrial, they are separable, as shown in Figures 5 and 6. Investigations of the present analysis show, however, the quasi-biennial variations in cosmic-ray data are predominantly of terrestrial origin. This conclusion seems to be consistent with the results of spectrum analysis of the quiet day geomagnetic variations at Huancayo (12° S geographic), Alibag (19° N geographic) and Apia (14° S geographic) given by Stacey and Wescott (1962). Further analysis seems necessary, however, to check the consistency with other phenomena which have been discussed recently by many authors (Shapiro and Ward, 1962; Hope, 1963; Wescott, 1964; Newell, 1964 a.b; Linden, 1964; Reed, 1965, etc.).

Acknowledgement

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Figure Captions

Figure 1 Coefficients of the partial temperature effect (in %/g cm^{-2} ^{o}C) for cosmic-ray intensity at sea level with cut-off energies, E_o = 0.3, 10 and 40 Gev, plotted against atmospheric depth x (in g cm^{-2}). Full lines and dashed lines stand for positive (production) effect, $\alpha(E_o,x)$ and negative (decay) effect, $-\beta(E_o,x)$, respectively.

Figure 2 Composite coefficient of the partial temperature effects in linear scale, $\gamma(E_o,x)$ in %/g cm^{-2} ^{o}C, derived from Fig. 1.

Figure 3 The 26-month variations of tropical stratospheric temperatures (ΔT)* at Canton Island (3^{o} S) and zonal wind at Balboa (8^{o} N) given by Reed (1965) for the period from 1951 to 1961. The full line

* The temperature difference between Canton Island and five subtropical stations (average latitude 27^{o} N). Since the variation at the latter is very small as compared to the one at the equator, ΔT can be regarded as the variation at Canton Island.

in the lower portion is a similar expression of the ion-chamber data from Huancayo (12^o S) based on 5-Q days in each month. Dashed line and dots are the first and the second harmonics of the full-line.

Dashed lines are theoretical estimations corresponding to ΔT-curves in the upper portion of the figure computed by coefficients shown in Fig. 2, where heavy dash-dot and thin dash-dot lines correspond to the cut-off energies, E_o = 0.3 Gev and 10 Gev, respectively.

Figure 4 Power spectrum (Periodogram) of Huancayo (12^o S) ion-chamber data based on 5-H days in each month for the period from 1937 to 1961. The vertical scale is arbitrary and τ in the horizontal scale is in months.

Figure 5 Power spectrum of Godhavn ($69^o23'$ N) ion-chamber data for the period from 1947 to 1959. 5-Q and 5-H stand for the data of five quiet days and five high counting days in each month.

Figure 6 The folded-average curves of cosmic-ray muon data from Lae ($6^{\circ}44'$ S), where horizontal scale indicates the length of folding and vertical scale is relative cosmic-ray intensity corrected for barametric effect. The meaning of 5-Q and 5-H are the same as Fig. 5. The bottom curves correspond to the relative variation with a mean value normalized to 100%.

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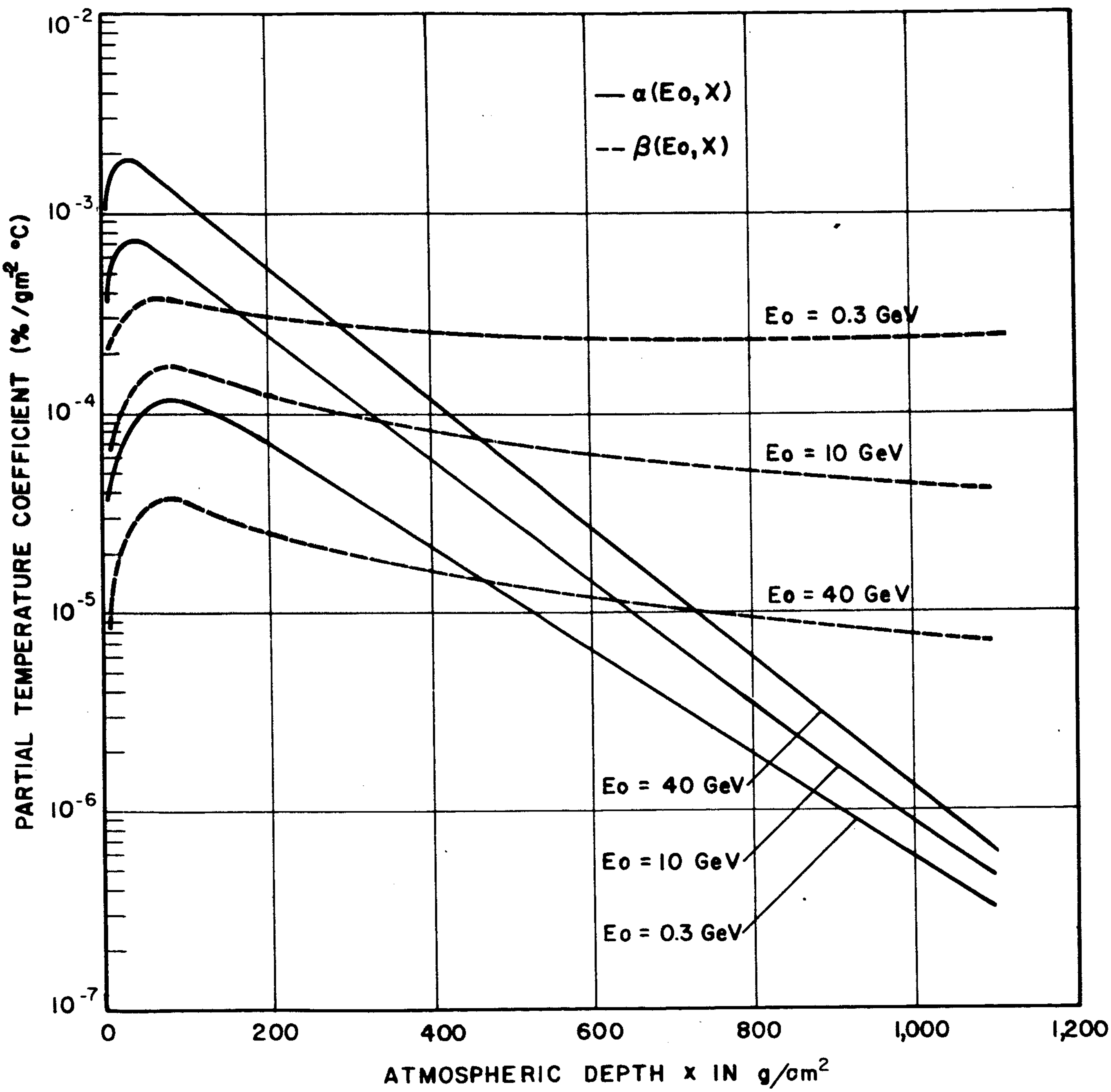
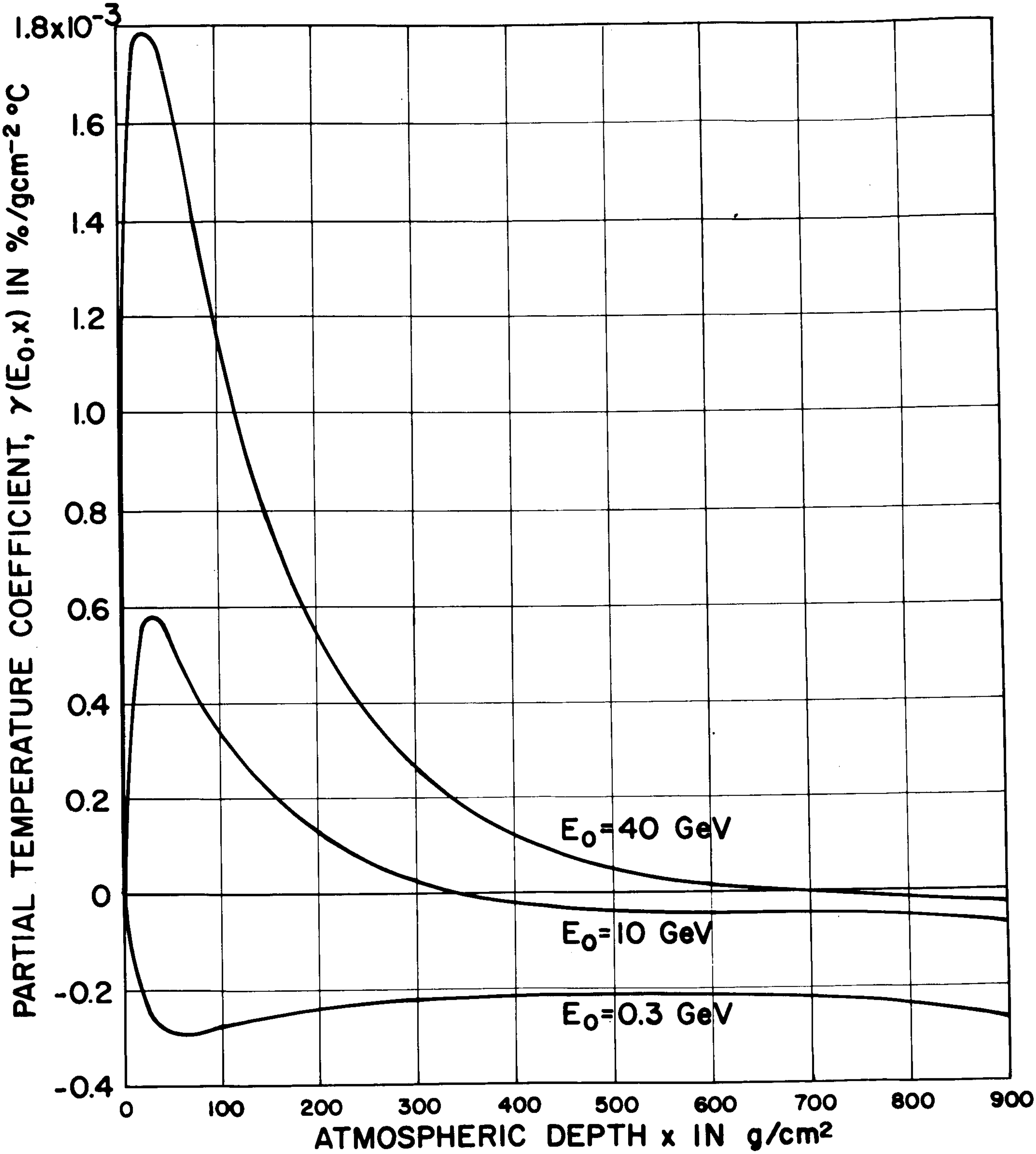


PARTIAL TEMPERATURE COEFFICIENT (% /gm^{-2} °C)
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
— α(Eo, X)
-- β(Eo, X)
Eo = 0.3 GeV
Eo = 10 GeV
Eo = 40 GeV
Eo = 40 GeV
Eo = 10 GeV
Eo = 0.3 GeV
0
200
400
600
800
1,000
1,200
ATMOSPHERIC DEPTH x IN g/cm^2

FIG Fig. 1.



1.8x10⁻³
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0
-0.2
-0.4
PARTIAL TEMPERATURE COEFFICIENT, $\gamma(E_o,x)$ IN %/gcm^{-2} °C
E_o=40 GeV
E_o=10 GeV
E_o=0.3 GeV
0
100
200
300
400
500
600
700
800
900
ATMOSPHERIC DEPTH x IN g/cm^2

Fig. 2

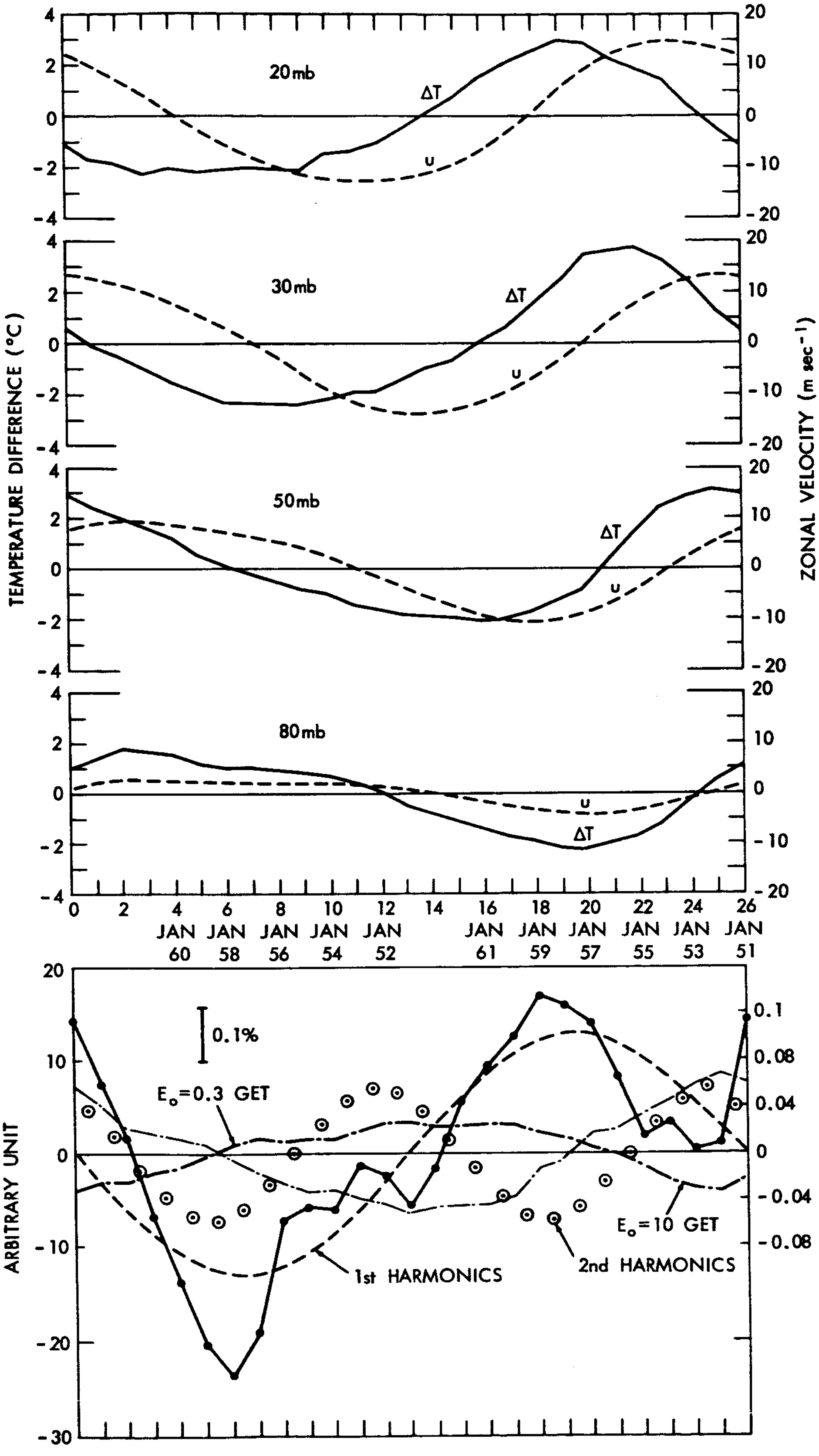

20mb
ΔT
u
30mb
ΔT
u
50mb
ΔT
u
80mb
u
ΔT
TEMPERATURE DIFFERENCE (°C)
ZONAL VELOCITY (m sec^{-1})
JAN 60
JAN 58
JAN 56
JAN 54
JAN 52
JAN 61
JAN 59
JAN 57
JAN 55
JAN 53
JAN 51
0.1%
E_o=0.3 GET
E_o=10 GET
1st HARMONICS
2nd HARMONICS
ARBITRARY UNIT
PERCENT

Figure 3

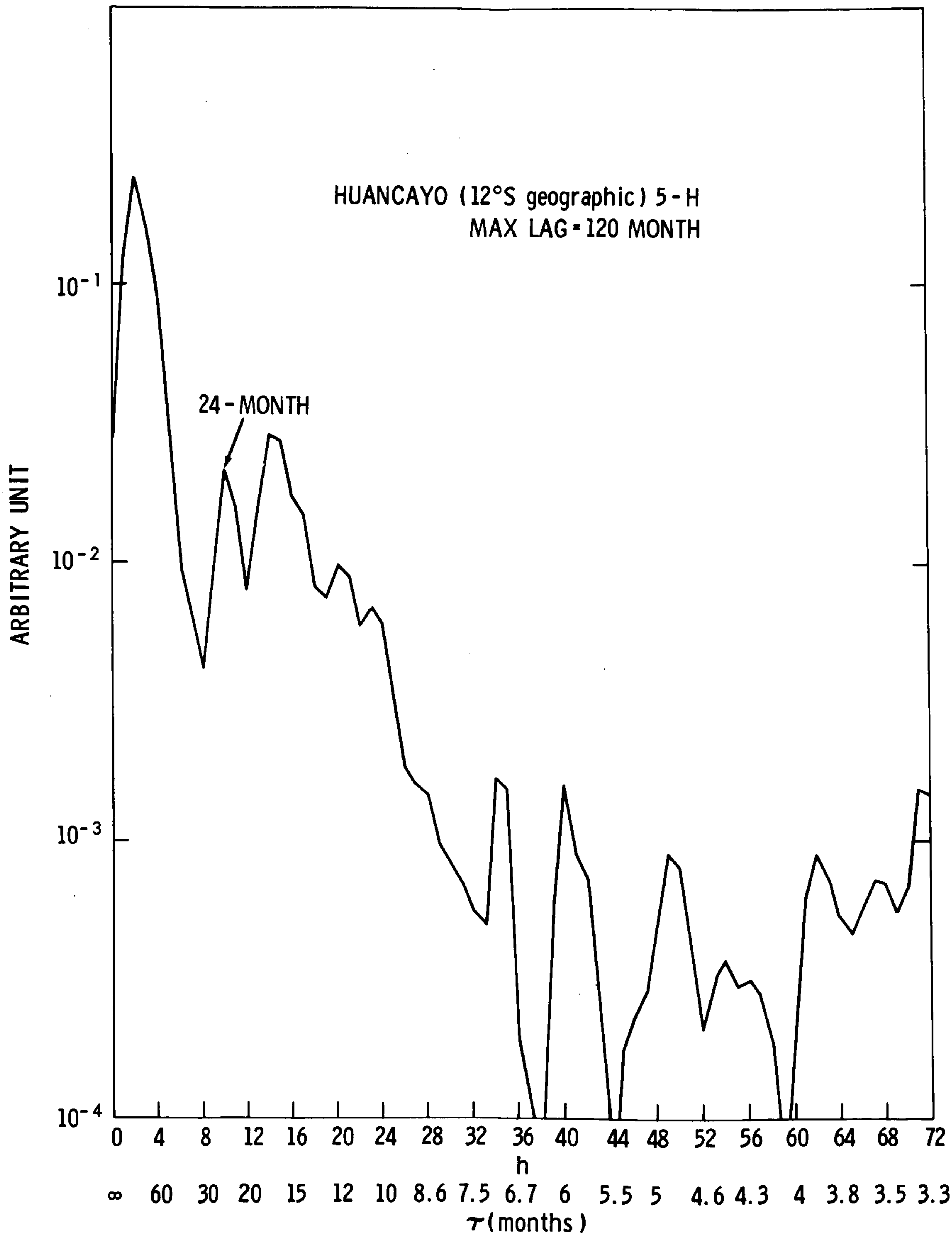

HUANCAYO (12°S geographic) 5-H
MAX LAG = 120 MONTH
24-MONTH
ARBITRARY UNIT
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60 64 68 72
h
∞ 60 30 20 15 12 10 8.6 7.5 6.7 6 5.5 5 4.6 4.3 4 3.8 3.5 3.3
τ (months)

Figure 4

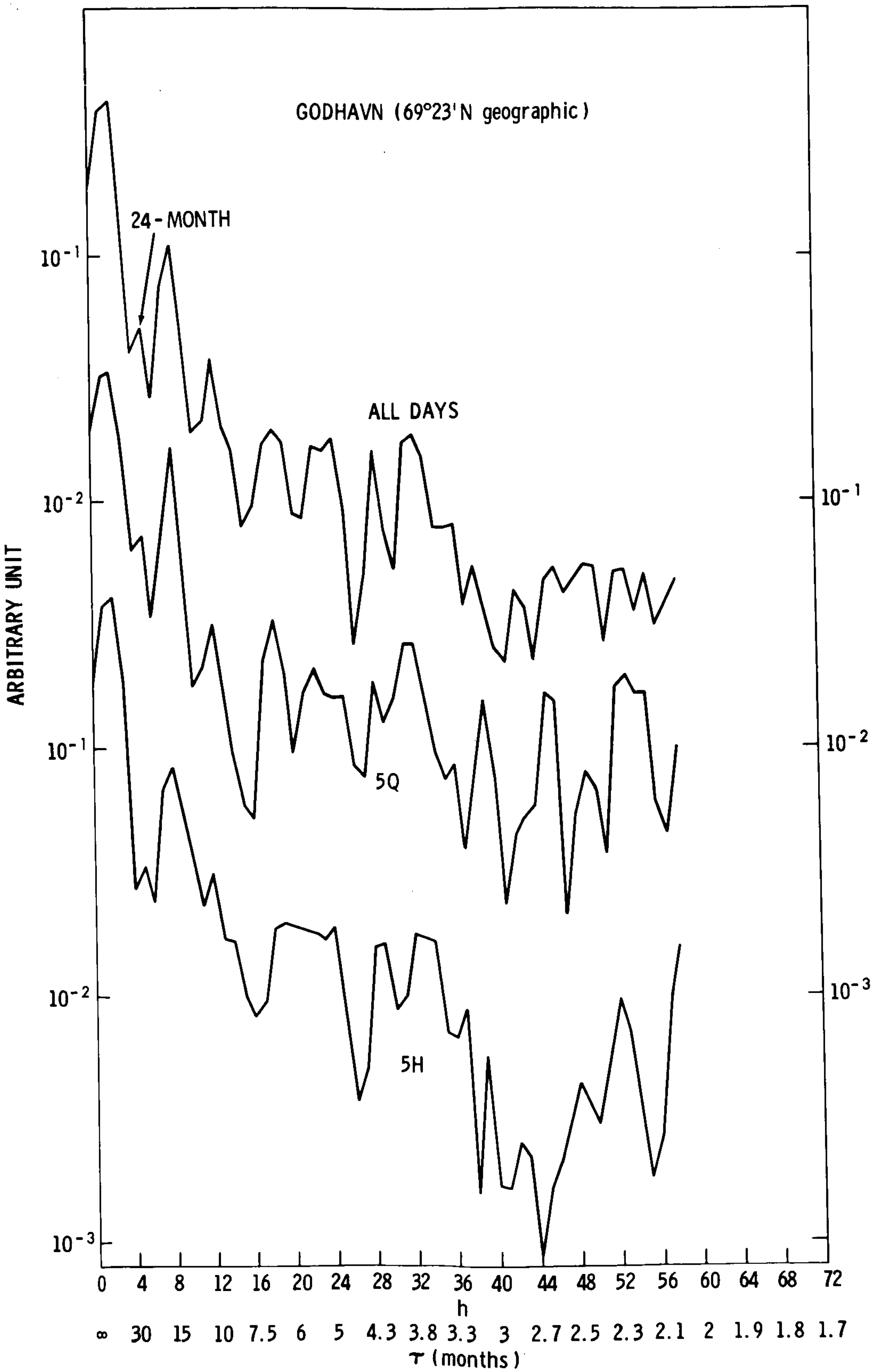

GODHAVN (69°23'N geographic)
24-MONTH
ALL DAYS
5Q
5H
ARBITRARY UNIT
10⁻¹
10⁻²
10⁻¹
10⁻²
10⁻³
10⁻¹
10⁻²
10⁻³
0 4 8 12 16 20 24 28 32 36 40 44 48 52 56 60 64 68 72
h
∞ 30 15 10 7.5 6 5 4.3 3.8 3.3 3 2.7 2.5 2.3 2.1 2 1.9 1.8 1.7
τ (months)

Figure 5

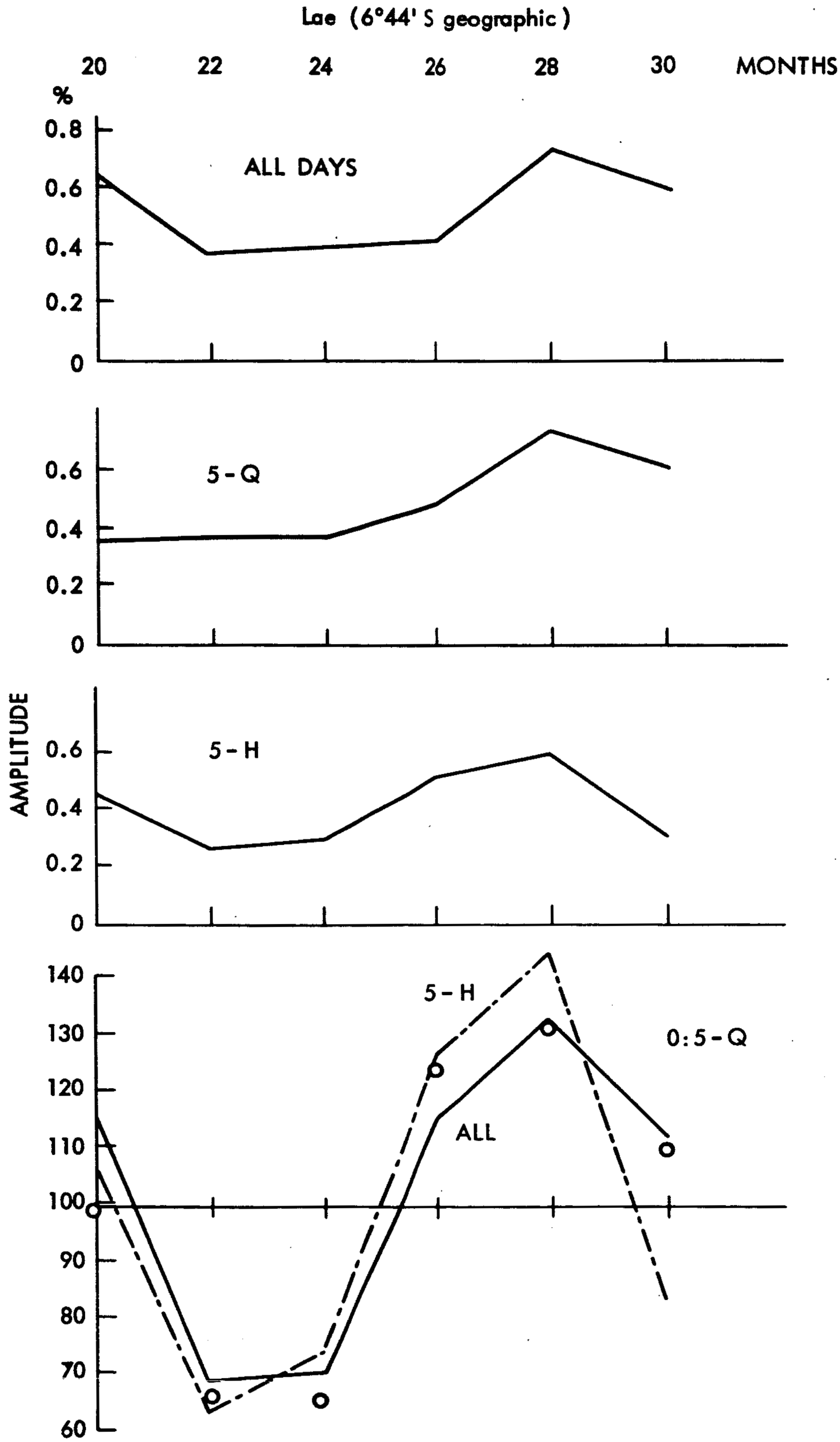

Lae (6°44' S geographic)
20
22
24
26
28
30
MONTHS
%
0.8
0.6
0.4
0.2
0
ALL DAYS
5 - Q
5 - H
AMPLITUDE
140
130
120
110
100
90
80
70
60
5 - H
0:5 - Q
ALL

Figure 6