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THE RESPONSE OF THE UPPER ATMOSPHERIC TEMPERATURE TO CHANGES IN SOLAR EUV RADIATION AND GEOMAGNETIC ACTIVITY

by

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ABSTRACT

The upper atmospheric neutral temperature derived from satellite drag is analyzed with a view to determine the relative importance of solar EUV and magnetic activity on heating of the upper atmosphere.

As the indices of solar EUV radiation, the radio fluxes obtained from the ground based observations in the frequency range of 200-9400 Mc/s are used. Also for the period March 7 - May 15, 1962, a direct comparison is made with the EUV flux obtained from the OSO 1 Satellite. As the index of magnetic activity the planetary magnetic index K_p is used.

The data have been analyzed by separating the long period components of 27 days and above from the short term components by using a 5 day running mean filter. A cross correlation study between the various parameters shows that the long term variations in temperature are strongly correlated with the similar variations in the radio flux in the frequency range of 1000-3750 Mc/s, the correlation being maximum at 1000 Mc/s. The short term variations in temperature, on the other hand are strongly correlated with those in ΣK_p, the daily sum of K_p indices and not with the radio flux at any of the frequencies considered. The correlation between temperature and EUV flux in the short term components is somewhat better though not as striking as the long term components.

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An empirical relation between temperature and the changes in radio fluxes and ΣK_p based on the above correlation study shows that

$$T_N = 524 + 2.73\ \overline{S}_{10.7} + 1.77\ (\Sigma K_p - \overline{\Sigma K}_p)$$

or $$T_N = 470 + 6.53\ \overline{S}_{30} + 1.77\ (\Sigma K_p - \overline{\Sigma K}_p)$$

where T_N is the nighttime minimum temperature; $\overline{S}_{10.7}$, $\overline{S}_{30}$ and $\overline{\Sigma K}_p$ are the 5 day running means of 2800 Mc/s radio flux, 1000 Mc/s radio flux and ΣK_p respectively.

The present investigation leads to the conclusion that short term variations in temperature are closely associated with the changes in magnetic activity represented by K_p and all the systematic variations in temperature including the so called semi-annual variation can be fully accounted for in terms of the similar variations in solar flux.

INTRODUCTION

In recent years, the vast amount of observational data obtained from the drag analysis of a number of satellites have proved to be a very valuable source of information in studying the thermal properties of the upper atmosphere [for detailed references see Jacchia, 1964a; Evans, 1966; Priester et al, 1967]. Although the physical processes governing the temperature of the neutral component and in particular, the heating associated with geomagnetic activity, are not fully understood, the empirical relationships between solar decimeter flux and geomagnetic indices, and exospheric temperature derived from satellite drag observations have been remarkably successful in describing the thermal response of the atmosphere to changes in solar activity.

Questions have occasionally been raised, however, about the suitability of a particular frequency in the radio region of the solar spectrum as an appropriate index of EUV radiation [Nicolet, 1963, Anderson, 1965]. This is because of the fact that the characteristics of the radio fluxes emitted from the sun show a marked dependence on the frequency of emission. For example, the amplitude of the 27 day variation is maximum at 2800 Mc/s whereas the corresponding variation at 200 Mc/s is almost negligible [Smerd, 1964]. The maximum variation over a solar cycle in the basic component is centered around 1000 Mc/s and falls off on either side of this frequency [Basu, 1966]. Unfortunately, the EUV data is available only for a limited period of a little over two months (March-May, 1962) and also for a limited range of the EUV spectrum (170A-370A) [Bourdeau et al, 1964] and it is not possible to make a general prediction for the entire solar cycle based on the data of such a short duration. But it is clear that even if the EUV data were available for a much longer period, it would not be possible to identify a single frequency in the radio region which would follow the EUV variation in every detail. It is, nevertheless, appropriate to ask, which frequency or range of frequencies in the solar radio spectrum can best represent the changes in exospheric temperature. What is the origin of the small day to day fluctuations in temperature which are superposed on the 27 day and longer term variations? What causes the so called semi-annual variation in atmospheric temperature and density? To what extent can the changes in solar activity account for these observations? This paper is an attempt to seek answers to some of these questions.

SOURCE OF OBSERVATIONAL DATA

The temperature in the present analysis is the global minimum temperature (T_N) derived from the precisely reduced drag data of Explorer IX [Roemer, 1966] and based on Jacchia's (1964b) atmospheric model. These data which approximately cover the period from 1961 to 1963, reflect the period of moderate solar activity and are particularly suited for studying the day-to-day variation in view of the good time resolution. Included in the present study are also Explorer I (1958α) data from 1958-1963, which have been used only for the study of the long-term variation. The poor resolution of this data does not permit the study of the small day-to-day variation in a meaningful way.

The temperature T_N, has been computed from the perigee temperature by using the diurnal model of Jacchia (1964b). This model is based on the symmetry of the diurnal bulge with respect to the latitude of subsolar point. There have been some discussions [Bourdeau et al, 1964; Jacchia and Slowey, 1966,1967] about the amplitude, phase and symmetry of the diurnal bulge and it should be admitted that there is no unique way of defining all these parameters with certainty. However, an uncertainty in the diurnal model is not likely to cause any appreciable change in the Explorer IX data since for the entire observation period of this satellite, the perigee angle with respect to the position of the diurnal bulge does not exceed 90°. Thus T_N is essentially independent of diurnal and spatial variation and any changes associated with it should be mainly due to changes in solar activity.

As the indices of solar EUV radiation, the radio fluxes in the frequency range 200-9400 Mc/s obtained from a number of ground based stations and given in the following table are used.

TABLE 1

Frequency of the radio flux	Station	Geographic Latitude	Geographic Longitude
200 Mc/sec	Nera	52.2°N	5.1°E
600 Mc/sec	Humain	50.2°N	5.3°E
1000 Mc/sec	Toyokawa	34.8°N	137.4°E
2000 Mc/sec	Toyokawa	34.8°N	137.4°E
2800 Mc/sec	Ottawa	45.4°N	75.6°W
3750 Mc/sec	Toyokawa	34.8°N	137.4°E
9400 Mc/sec	Toyokawa	34.8°N	137.4°E

Also for the period March 7 - May 15, 1962, a direct comparison is made with the EUV flux obtained from OSO 1 satellite [Bourdeau et al, 1964]. The corpuscular effects are assumed to be indicated by the changes in geomagnetic activities given by the planetary magnetic index K_p.

NEUTRAL TEMPERATURE IN RELATION TO SOLAR EUV FLUX AND MAGNETIC ACTIVITY

The changes in temperature related to EUV and magnetic activities are studied by separating the components of 27 days and above from the short term fluctuations by taking five day running means of all the data. This method of analysis is similar to the one described by the authors in a recent paper (1967).

Plotted in Fig. 1 are the five day running means of the flux at 1000 Mc/s, EUV flux, T_N and ΣK_p (the daily sum of K_p).

The figure shows that the 27 day variation in T_N, follows closely the corresponding variation in EUV and 1000 Mc/s as expected whereas ΣK_p does not follow similar variation. What is not quite expected are features of Fig. 2 which shows the difference series of the unsmoothed and smoothed (five day running mean) data of the various parameters. These difference series essentially represent the short term variations of periods of about 5 days. It is seen from this figure that the fluctuations in temperature follow very closely with those in ΣK_p and also to some extent with EUV flux, with the time lag of about 1 day. The 1000 Mc/s flux in general does not appear to follow similar fluctuations.

It should be pointed out that the EUV flux used in the present analysis is only a fraction of the entire EUV spectrum responsible for the upper atmospheric heating. This may partly be the reason for the comparatively less striking similarity between T_N and EUV than between T_N and ΣK_p. The close association between short term fluctuations of T_N, EUV and ΣK_p raises an interesting question. What causes the small day-to-day fluctuations in the exospheric temperature? It may seem reasonable to assume that the small day to day fluctuations in EUV should be reflected in the temperature. On the other hand, it appears from Fig. 2 that changes in the temperature associated with ΣK_p and EUV are indistinguishable. If ΣK_p is an index of solar wind velocity [Snyder et al, 1963] the relationship between ΣK_p and EUV if any, should reveal a time lag of about 2 days or more. Such a time difference is not always apparent from Fig. 2. Could it be then that some of the small day-to-day fluctuations in ΣK_p are partly the result of the atmospheric circulation in the lower atmosphere due to changes in temperature which in turn are caused by changes in EUV flux. This possibility was suggested by Newell (1966). It would be difficult to arrive at any definite conclusion about this hypothesis from the present analysis in view of the limited amount of data and the difficulty of separating the contributions from terrestrial and extraterrestrial causes. It nevertheless is reasonable to conclude that EUV plays an important role in affecting the upper atmospheric temperature both for short and long term variations and not withstanding the lack of full interpretation of K_p, it is a good index of short term variations in temperature.

CORRELATION BETWEEN T_N, ΣK_p AND SOLAR FLUXES AT DIFFERENT FREQUENCIES

In spite of the close association between temperature and EUV as revealed from the preceding analysis, an empirical relation cannot be established between the two parameters in view of the limited amount of data available for EUV. Instead, it is possible to investigate the relationship between temperature and solar radio fluxes at different frequencies since continuous data are available for both radio fluxes and temperature.

Using the Explorer IX neutral temperature data from the period Nov. 1961 to May 1963, correlations between temperature and radio fluxes at different frequencies are obtained giving a time difference of -5 to +5 days between the parameters in steps of one day after smoothing the data by taking five day running means. The maximum correlation which shows a time lag of one day between T_N and the fluxes is plotted as a function of frequency in Fig. 3. It is seen from this figure that the correlation rapidly increases with frequency and attains a maximum value at about 1000 Mc/sec. Afterwards it gradually falls off at higher frequencies. Since the correlation at 2800 Mc/sec is only slightly less than at 1000 Mc/sec, it seems both these fluxes can be used for obtaining an empirical relation between temperature and the fluxes. In fact, any frequency in the range 1000-3750 Mc/s may be used without an appreciable error. The correlation between the short term fluctuations (differences between unsmoothed and 5 day running mean series) in T_N and any of the radio fluxes is negligibly small. On the other hand, the correlation between the short term fluctuations in T_N and ΣK_p is very high as was shown in an earlier paper [Chandra and Krishnamurthy, 1967]. Based on the short and long term correlations between the various parameters, the following empirical relations are obtained (using the linear regression formula).

$$T_N' = 524 + 2.73\ \overline{S}_{10.7} + 1.77\ (\Sigma K_p - \overline{\Sigma K}_p) \qquad (1)$$

or

$$T_N' = 470 + 6.53\ \overline{S}_{30} + 1.77\ (\Sigma K_p - \overline{\Sigma K}_p) \qquad (2)$$

where $\overline{S}_{30}$, $\overline{S}_{10.7}$, and $\overline{\Sigma K}_p$ are 5 day running means of 2800 and 1000 Mc/sec flux and ΣK_p respectively. In view of the one day time difference between T_N and the various parameters the T_N' calculated by using the above relations, should be assigned to the next day. We wish to emphasize here that ΣK_p is being used only as an index to represent the short term variations in T_N whatever be its real physical significance.

COMPARISON BETWEEN TEMPERATURES OBTAINED FROM THE EMPIRICAL RELATION AND FROM SATELLITE DRAG DATA

The temperatures calculated from the empirical relations given in the preceding section are now compared with the Explorer IX temperature data for the period November 1961 to May 1963. Although the same Explorer IX data has been used to obtain the empirical relations, the comparison would still be meaningful as the correlation coefficients from which the empirical relations are obtained, are less than unity.

Plotted in Fig. 4 are the differences $T_N - T_N'$ where T_N are the Explorer IX temperature and T_N' are those obtained from equations (1 and 2). It can be seen from this figure that the residual $T_N - T_N'$, in general, varies between -50^o to $+50^o$K and does not show any systematic variation. This places a fair amount of confidence in equs. (1 and 2) in their ability to represent all the systematic variations.

As an additional test of equs. (1) and (2), comparison is also made between the temperature computed from these equations and Explorer IX temperature data for the period Feb. 1961 to Oct. 1961 which were not included in formulating the empirical relations. This period is particularly interesting for comparison because of the large changes in temperature associated with geomagnetic activities. It was found that the comparison is extremely good even to the finer details. This is illustrated in Fig. 5 which shows the plot of T_N' computed from 1000 Mc/s flux and the Explorer IX temperature data as given by Jacchia and Slowey (1965). Because of the difference of model, a correction of 5% is applied to this data to make it compatible with the Jacchia's atmospheric model (1964b) which was used in obtaining Explorer IX temperature for the period Nov. 1961-May 1963. An examination of Fig. 5 clearly shows the remarkable similarity between the two temperatures. Even during the periods of high magnetic activity, the fluctuations in both T_N and T_N', in general, follow each other very closely. Thus the variations in temperature associated with magnetic activity are well represented by the K_p index both during the quiet and disturbed periods.

From the comparisons made in this section it is evident that the empirical relations presented in the previous section are quite adequate to represent the global minimum temperature of the neutral atmosphere above thermopause.

SEMI-ANNUAL VARIATION IN TEMPERATURE

It was shown in the previous section that the empirical relation based on solar flux and K_p represents all the short and long term variations in temperature and the residual T_N-T_N' does not show any systematic variation. It has been reported by a number of workers [Paetzold and Zschorner, 1961, Jacchia 1965, King-Hele, 1966, Cook and Scott, 1966; Cook, 1967] that the atmospheric density and temperature after correcting to a standard solar activity show a semi-annual variation. The physical explanation for this effect has hitherto remained a mystery though a number of mechanism have been proposed [Paetzold and Zschörner 1961, Priester and Cattani 1962, Jacchia 1965, Anderson 1966, Cook 1967]. Since the residual T_N-T_N' in Fig. 4 does not show any systematic semi-annual variation, it appears that the so called semi-annual variation could be accounted for in terms of the solar flux variations. This point is investigated in further detail in the following.

Using again the Explorer IX T_N data, the solar fluxes at 2800Mc/s and 1000Mc/s and ΣK_p for the period November 1961 to May 1963, the 27-day and shorter components are smoothed out by taking 27-day running means. The resulting smoothed data essentially contain components of periodicities above 4 months. Plotted in Fig. 6 are the 27 day running means of all the four parameters. It can be seen from this figure that there is a remarkable similarity between the variations of T_N and those of S_{30} and $S_{10.7}$. All these three parameters show broad peaks around the months of March and October. The variations in ΣK_p do not follow those in T_N, or S_{30} or $S_{10.7}$. Quantitative estimates of the degree of association between the long term variations in the various parameters under consideration are obtained by evaluating the correlation coefficients, shown in Table 2.

TABLE 2

Parameters	Correlation Coefficient
T_N vs S_{30}	0.79
T_N vs $S_{10.7}$	0.76
T_N vs ΣK_p	0.16

It can be seen from Table 2 that T_N shows a high degree of correlation with both S_{30} and $S_{10.7}$ whereas the correlation with ΣK_p is poor. To investigate these long term variations over a longer period data from 1958α satellite which are available from 1958 to 1963, are analyzed along with the 2800 Mc/sec solar flux data from the same period. Components of 27 days and shorter periodicities are eliminated again by taking 27 days running means of the data. The resulting smoothed data of T_N and $S_{10.7}$ are plotted for each year separately as shown in Fig. 7. Also shown in the same figure are the smoothed data of the Zurich sunspot number (R_z) for each year separately.

Fig. 7 reveals a remarkable similarity between the variations in T_N, $S_{10.7}$ and R_z. It is interesting to note that the semi-annual variation in T_N, $S_{10.7}$, and R_z is not a persistent feature throughout the period from 1958 to 1963. Marked semi-annual variation is shown only during the years 1958 and 1962 and indicated in 1963. During the period 1959-1961, all the three parameters show oscillatory behavior and there is no clear trend of semi-annual variation though occasionally peaks around April and October could be detected among other peaks. In making the comparison between temperature and 10.7 cm flux, it should be remembered that the former is derived from the perigee temperature using an empirical diurnal model. Some of the phase differences between the corresponding peaks may be attributed to the uncertainties in the diurnal model.

The similarity between the long term variations in T_N, $S_{10.7}$, and R_z strengthens the view that they are not spurious. It is evident from the present analysis that the long-term variations in temperature can be fully accounted for by the similar variations present in the solar flux and it is not necessary to invoke any other mechanism to explain the long-term variations in temperature. The physical mechanism giving rise to these fluctuations in solar fluxes is not within the scope of this paper and will be discussed elsewhere. From the aeronomical point of view there appears to be no difficulty in understanding the so called semi-annual variation.

SUMMARY AND CONCLUSIONS

The present investigation of the variations in neutral temperature above thermopause in relation to solar and geomagnetic activities has led to the following conclusions.

1. The short-term fluctuations in temperature are associated with similar fluctuations in both EUV and ΣK_p. The correlation between temperature and ΣK_p is however greater than that between temperature and EUV.

2. The variation in temperature on a long-term (27 days and above) basis shows a good correlation with the similar variations in solar flux in the frequency range of 1000-3750 Mc/s, with maximum correlation at 1000 Mc/s.

3. The following empirical relations seem to account for all the systematic variations in temperature both during quiet and disturbed conditions.

$$T_N = 524 + 2.73\,\overline{S}_{10.7} + 1.77\,(\Sigma K_p - \overline{\Sigma K}_p)$$

or

$$T_N = 470 + 6.53\,\overline{S}_{30} + 1.77\,(\Sigma K_p - \overline{\Sigma K}_p)$$

4. The so-called semi annual variation in the upper atmospheric temperature and density is not a persistent feature throughout the solar cycle and may be accounted for in terms of similar variations in solar activities without the necessity of invoking any other involved mechanism.

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FIGURE CAPTIONS

1. Daily plots of 5 day running means of ΣK_p, T_N, EUV and S_{30}.

2. Daily plots of the differences between original and 5 day running mean data of ΣK_p, T_N, EUV and S_{30}.

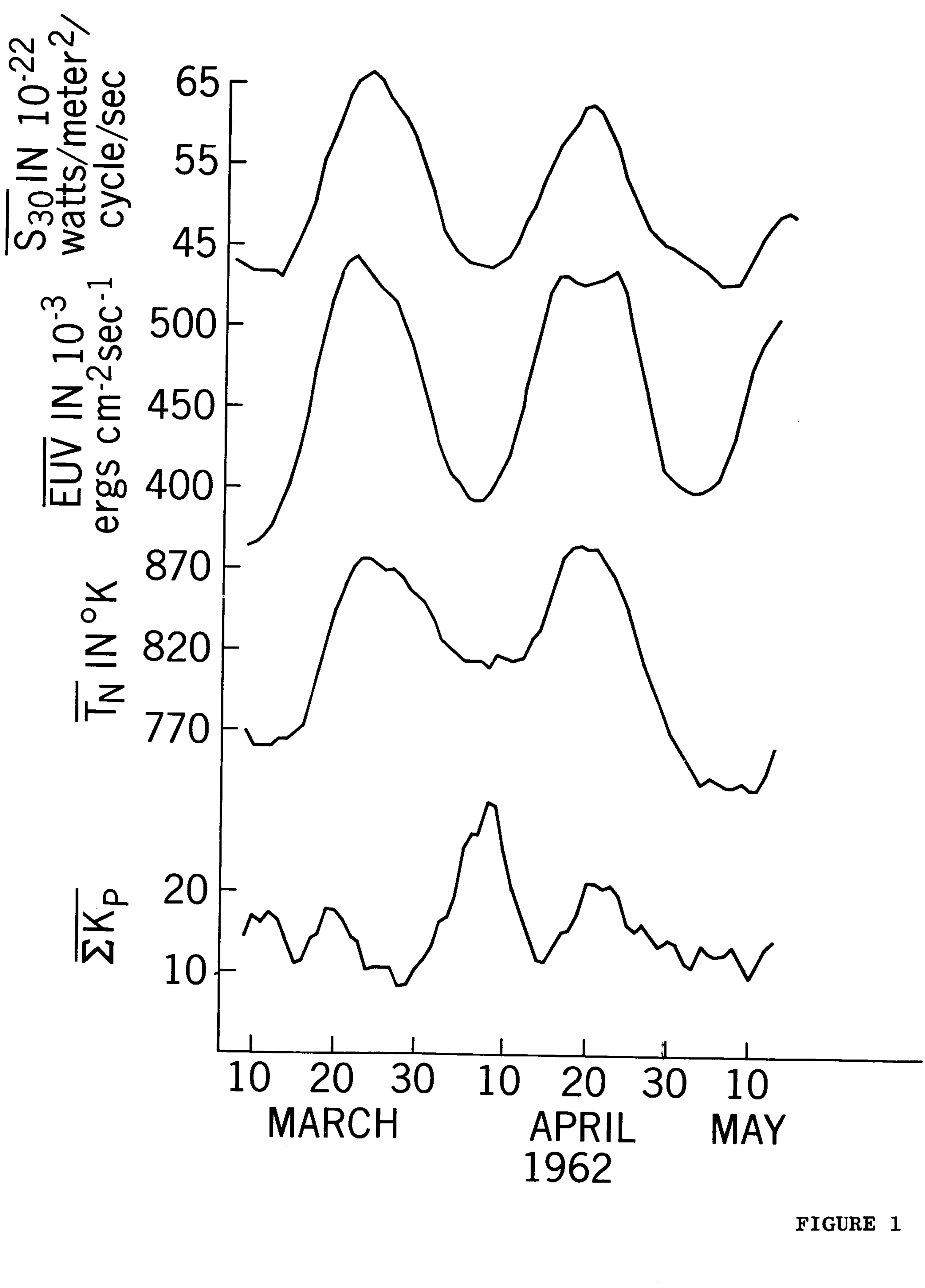
3. Correlation of temperature with radio fluxes at different frequencies.

4. Plots of the residual $T_N - T_N'$.

5. Comparison of T_N' computed from 30cm flux model with Explorer IX temperature T_N for the period February 1961 to October 1961.

6. Daily plot of 27 day running means of S_{30}, T_N, $S_{10.7}$ and ΣK_p.

7. Daily plot of 27 day running means of T_N, $S_{10.7}$ and R_z.



$\overline{S_{30}}$ IN 10^{-22} watts/meter^2/ cycle/sec
65
55
45
$\overline{EUV}$ IN 10^{-3} ergs cm^{-2}sec^{-1}
500
450
400
$\overline{T_N}$ IN °K
870
820
770
$\overline{\Sigma K_P}$
20
10
10
20
30
10
20
30
10
MARCH
APRIL
MAY
1962

FIGURE 1

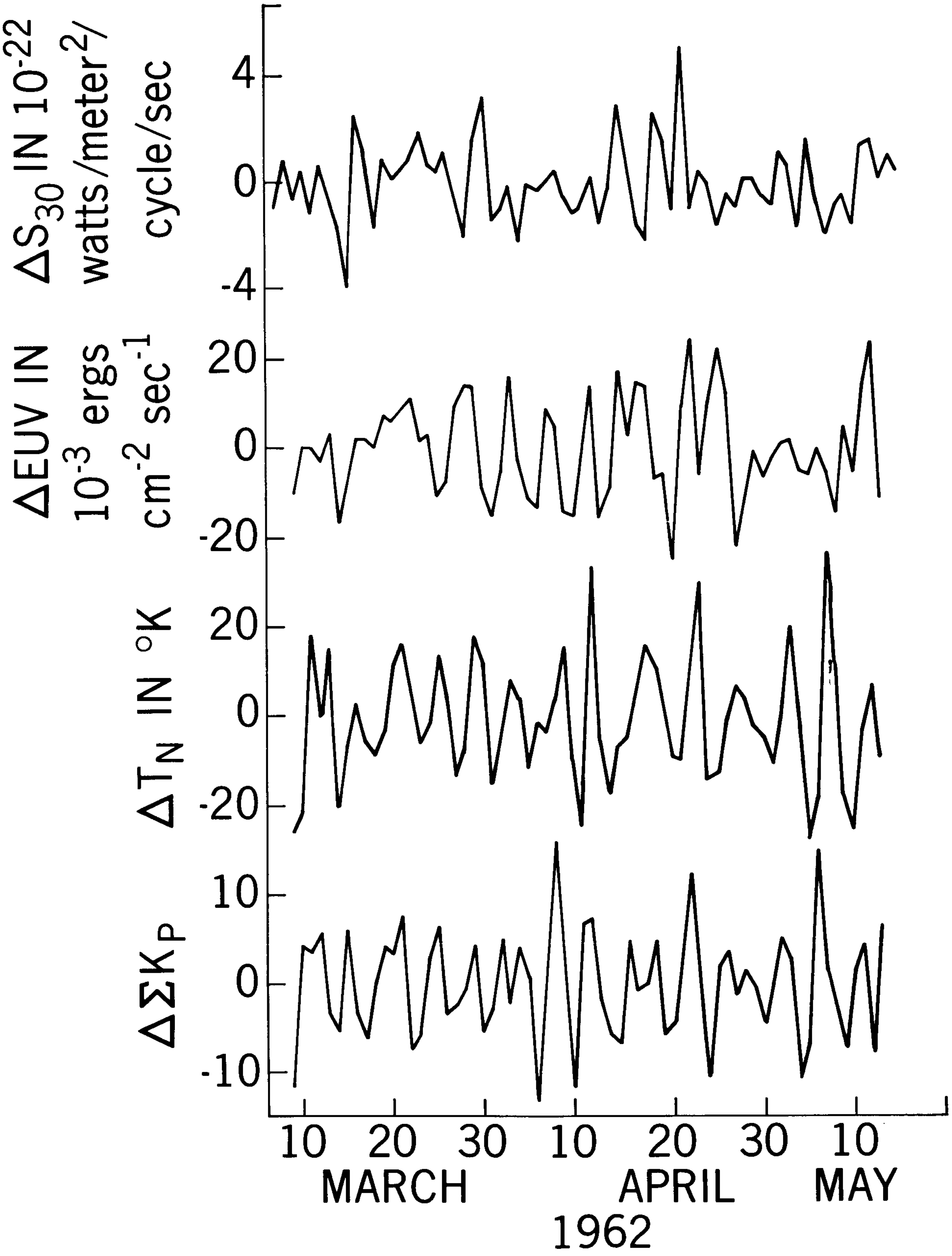

ΔS_{30} IN 10^{-22} watts/meter^2/cycle/sec
4
0
-4
ΔEUV IN 10^{-3} ergs cm^{-2} sec^{-1}
20
0
-20
ΔT_N IN °K
20
0
-20
$\Delta \Sigma K_P$
10
0
-10
10
20
30
10
20
30
10
MARCH
APRIL
MAY
1962

FIGURE 2

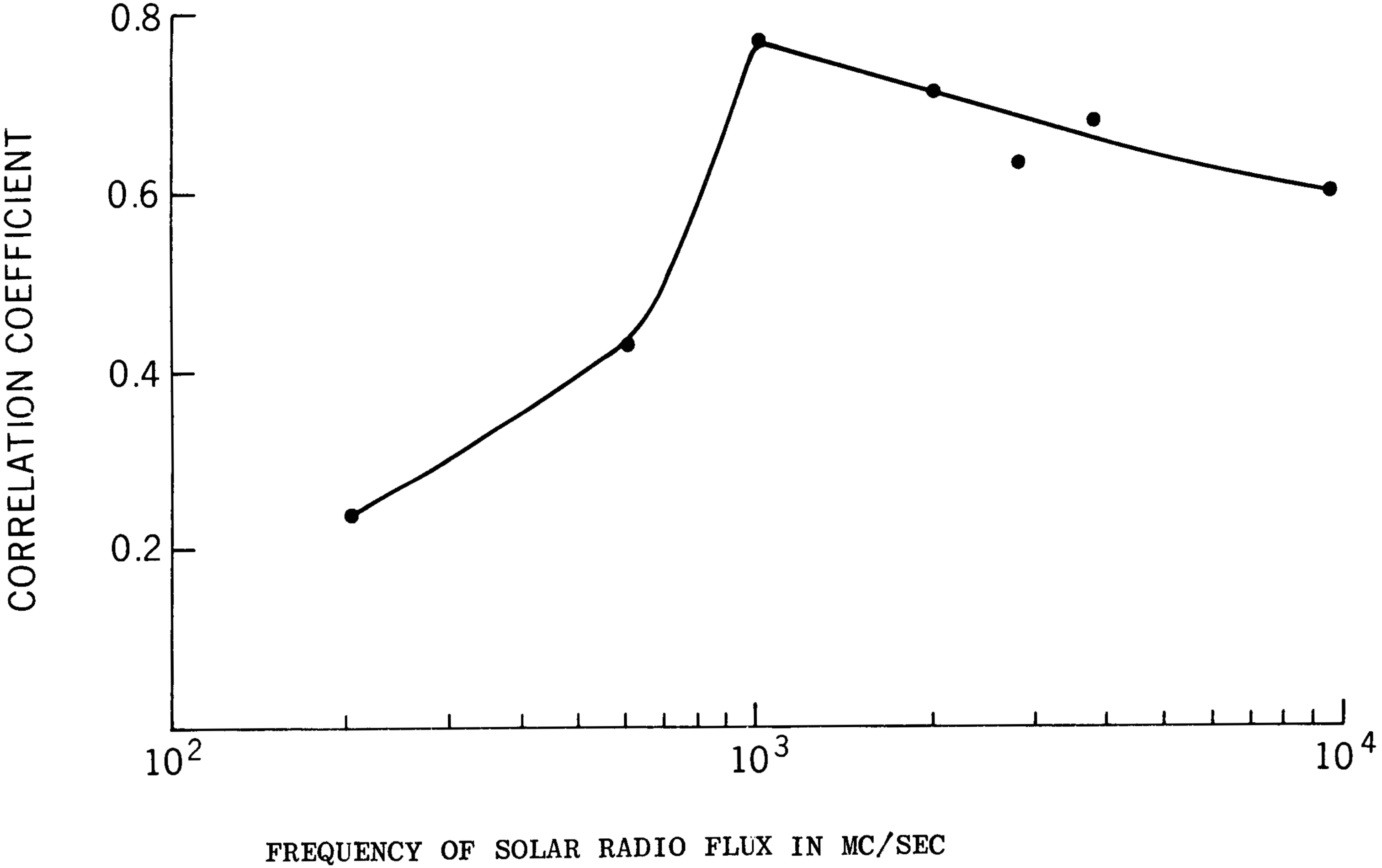
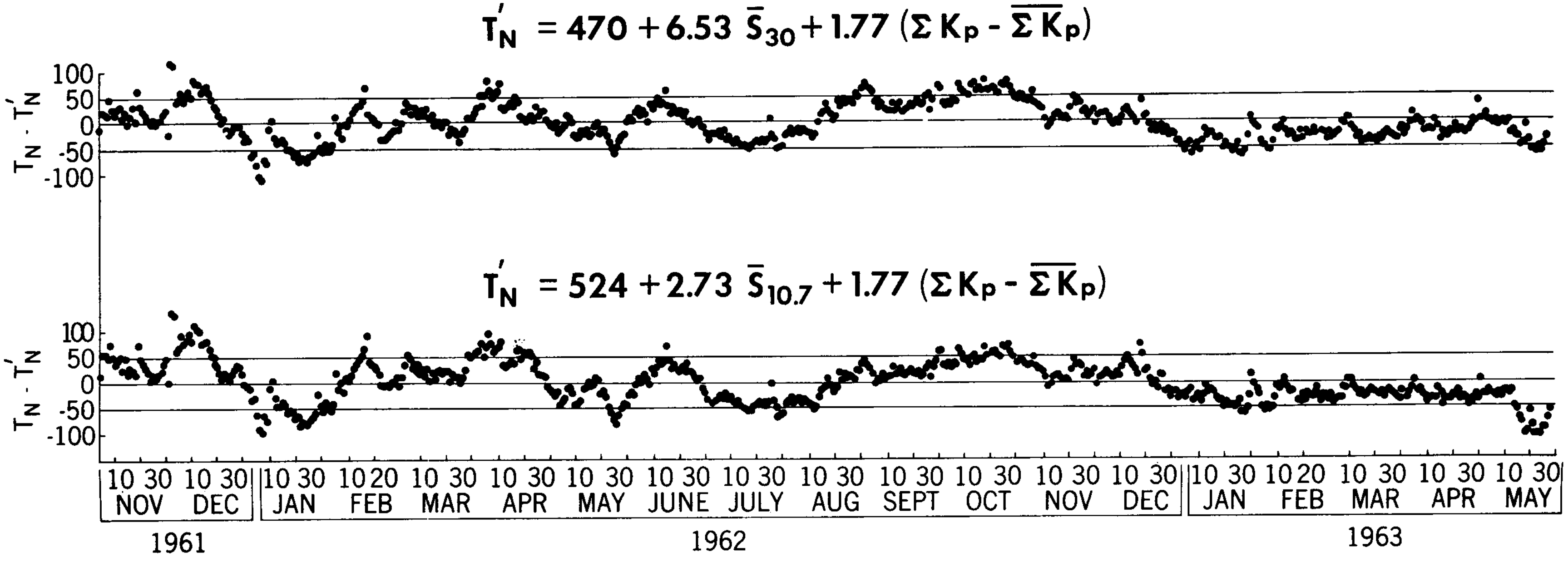

0.8
0.6
0.4
0.2
CORRELATION COEFFICIENT
10^2
10^3
10^4
FREQUENCY OF SOLAR RADIO FLUX IN MC/SEC

FIGURE 3



$$T'_N = 470 + 6.53\,\overline{S_{30}} + 1.77\,(\Sigma K_P - \overline{\Sigma K_P})$$

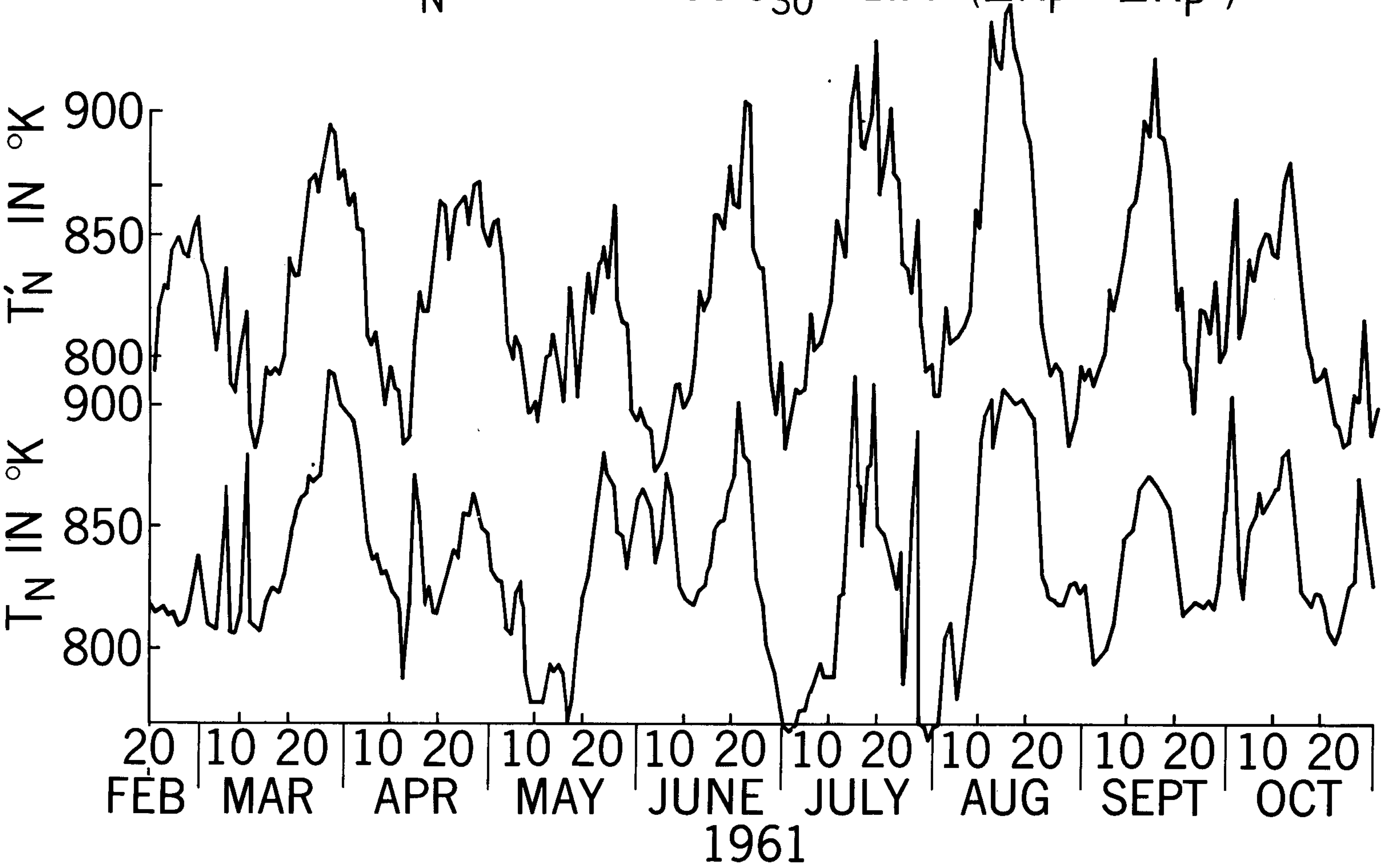
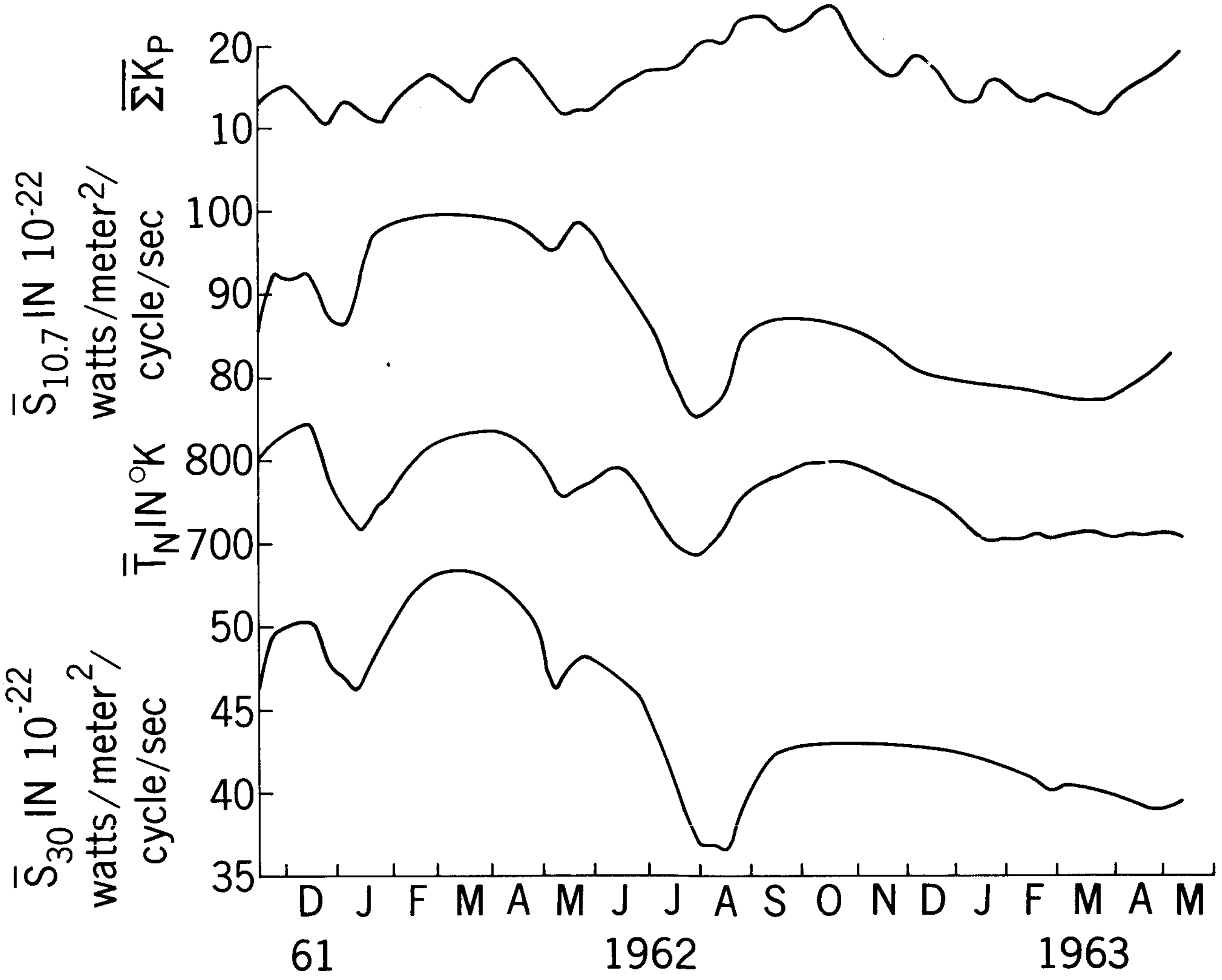


FIGURE 5



$\overline{\Sigma K_P}$
20
10
$\bar{S}_{10.7}$ IN 10^{-22} watts/meter^2/ cycle/sec
100
90
80
$\bar{T}_N$ IN °K
800
700
$\bar{S}_{30}$ IN 10^{-22} watts/meter^2/ cycle/sec
50
45
40
35
D J F M A M J J A S O N D J F M A M
61
1962
1963

FIGURE 6

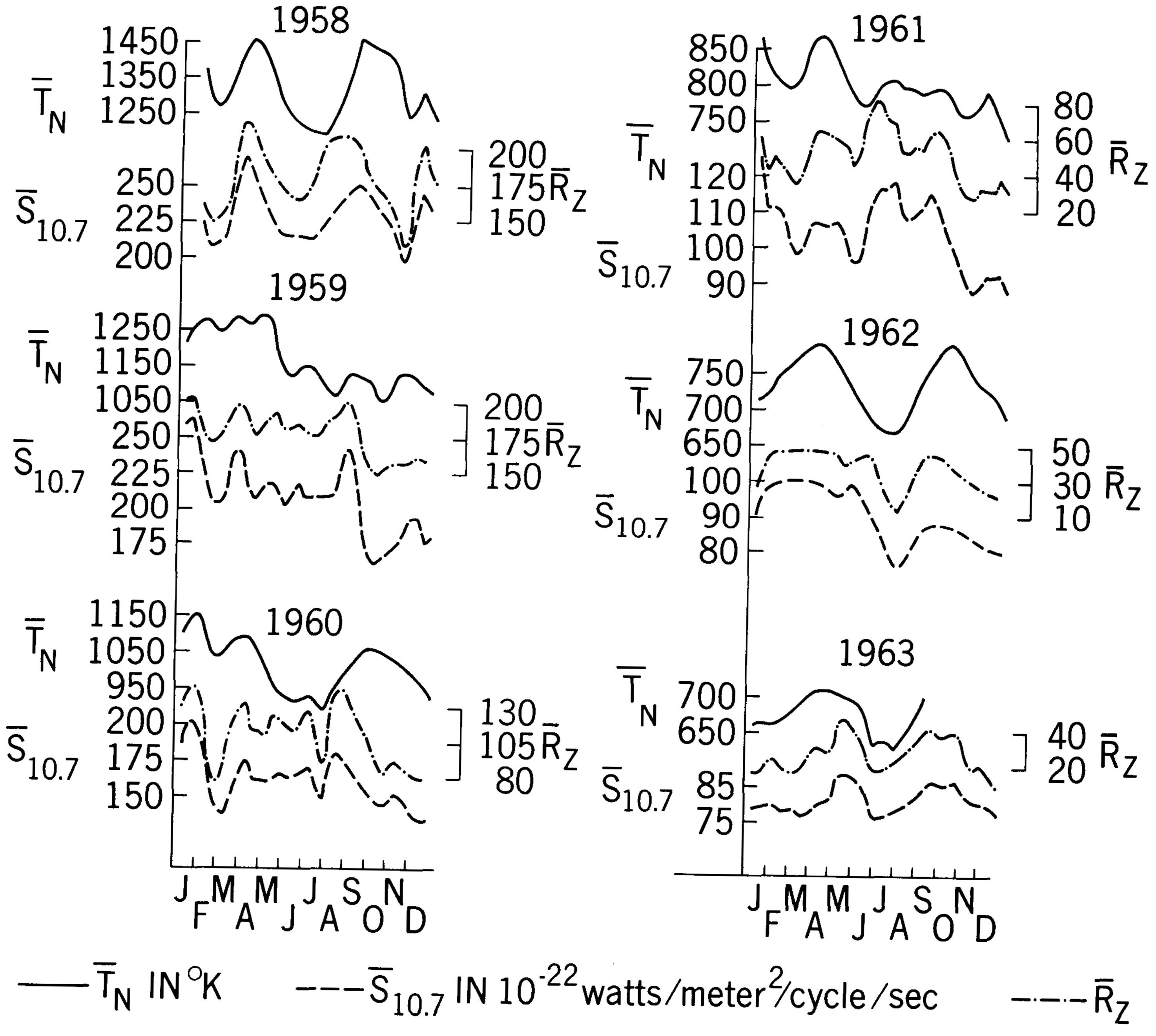

1958
1959
1960
1961
1962
1963
$\bar{T}_N$
$\bar{S}_{10.7}$
$\bar{R}_Z$
1450
1350
1250
250
225
200
200
175
150
1250
1150
1050
250
225
200
175
1150
1050
950
200
175
150
130
105
80
850
800
750
120
110
100
90
80
60
40
20
750
700
650
100
90
80
50
30
10
700
650
85
75
40
20
J F M A M J J A S O N D
—— $\bar{T}_N$ IN °K
- - - $\bar{S}_{10.7}$ IN 10^{-22} watts/meter^2/cycle/sec
—·—·— $\bar{R}_Z$

FIGURE 7