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2/01/69

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AERONOMICA ACTA

A - N° 21 - 1963

Solar radioflux and upper atmosphere temperatures

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FOREWORD

"Solar Radioflux and Upper-Atmosphere Temperature" is a paper presented at the COSPAR symposium in Warsaw (June 1963) and will be published in Journal of Geophysical Research, USA.

AVANT-PROPOS

"Solar Radioflux and Upper-Atmosphere Temperature" a été présenté au Symposium de COSPAR à Varsovie, juin 1963 et sera publié dans Journal of Geophysical Research, USA.

VOORWOORD

"Solar Radioflux and Upper-Atmosphere Temperature", werd in juni 1963 voorgesteld op het symposium van COSPAR te Warschau en zal gepubliceerd worden in de Journal of Geophysical Research, USA.

VORWORT

"Solar Radioflux and Upper-Atmosphere Temperature" wurde während des COSPAR Symposium in Warschau (Juli 1963) vorgestellt und wird im Journal of Geophysical Research herausgegeben werden.

Solar Radioflux and Upper-Atmosphere Temperature

by

Marcel NICOLET.

Résumé.

Afin de déterminer la variation de la température de la haute atmosphère, au niveau de la thermopause, en fonction des conditions solaires, on a effectué une analyse générale des flux radio-électriques solaires dans le domaine spectral de 10.000 Mc/s (3cm) à 1000 Mc/s (30cm).

La relation essentielle permettant de tenir compte du chauffage ultraviolet solaire peut être trouvée dans le domaine spectral décimétrique en introduisant comme composante fondamentale du flux radioélectrique, une valeur moyenne couvrant une période de 27 jours. La comparaison effectuée entre les énergies émises à 8 cm et à 10 cm démontre qu'une relation linéaire existe au cours de tout le cycle solaire pour le flux émis à 8 cm tandis qu'une variation différente se présente pour le flux émis à 10 cm pour les conditions de faible activité solaire.

Les valeurs journalières du flux radio-électrique représentant ses fluctuations au cours d'une période de 27 jours interviennent dans la variation de la température à la thermopause avec un poids moindre que le flux moyen. L'ensemble des deux effets montre que la radiation ultraviolette solaire fournit le chauffage adéquat de la thermosphère et aucun effet corpusculaire n'est requis.

L'établissement des formules suivant le procédé utilisé par Jacchia permet de fournir à priori le tableau des températures et des flux solaires. Finalement, les températures moyennes en même temps que les températures maximales et minimales possibles ont été déterminées pour les conditions de jour et de nuit de 1952 à 1962.

1.- Introduction.

The correlation between the orbital deceleration of an artificial satellite and the solar radioflux in the decimeter range has led to relationships between the atmospheric density at various heights and the 10.7 and 20 cm radiofluxes. Considering that the density variation is due to a temperature variation, it may be concluded that the solar ultraviolet radiation is responsible for the heating of the upper atmosphere and heat conduction is responsible for its cooling. A change in the ultraviolet radiation can be correlated with a change in the radioflux just as with the sunspot number, which is a well known index of solar activity.

Since all solar ultraviolet radiations do not vary with the same amplitude during a complete solar cycle, it appears logical to consider that a specific radiation in the radio range cannot be a perfectly reliable index.[1] Furthermore, various spurious correlations, or lack of correlations, may occur if the published values of the radiofluxes are subject to drifts of instrumental origin[2]. There is no way to account for a special behavior, for example at 5000 Mc/s, when the entire spectrum between 1000 Mc/s and 10,000 Mc/s varies in exactly the same manner. Consequently, before carrying out an analysis of the various causes of the temperature variations of the thermopause, it is desirable to obtain reliable data on the variations of the solar radiofluxes.

2.- Variations of Solar Radiations.

Extensive solar observations have been conducted at a wavelength of 10.7 cm (2800 Mc/s) (Covington [3]) at Ottawa by the Radio and Electrical Engineering Division of the National Research Council of Canada. The series of observations began in 1947, and the errors, which have been discussed by Medd and Covington [4] and Covington [5], should be of the order of ± 2 percent, or not more ± 3 percent in the monthly measurements. Intensive calibration measurements have been made at Ottawa with two radiometers calibrated from two fixed points, one for the ambient temperature, and the other at the temperature of the sky; taken to be 8°K. A possible systematic error may be introduced, therefore, with an assumed constant sky temperature apparently leading to a seasonal periodic variation proportional to the solar flux.

The routine observations at 8 cm have been carried out at Nagoya by the Institute of Atmospherics since November 1951 (Tanaka and Kakimuna[7]) with also an estimated accuracy of the order of ± 2 percent. A comparison of the 10.7 cm and 8 cm fluxes made by Tanaka [8] during the period of sunspot minimum shows that the ratio is almost constant within ± 3 percent. The ratio 10.7 cm/8 cm, which has a minimum in July and a maximum in January, indicates, however, the possibility of a periodic variation in the monthly average values which is dependent on the calibration. Other observations have also been conducted at Nagoya (Tanaka and Kakimuna [9]) at 3.2 cm since May 1956 and at 15 cm and 30 cm since the beginning of the International Geophysical Year (Tanaka and Kakimuna[10]). On that an attenuation due to the lower atmosphere may occur in the radiofluxes, particularly for the shortest wavelengths, systematic errors may be introduced in the published data since the transmission through unit atmosphere is subject to various variations. Such variations, generally proportional to the solar fluxes, may introduce periodic oscillations in the basic correlations between radiofluxes and upper-atmospheric parameters. These in addition to sporadic fluctuations which are not related to the solar emission.

The significance of radio observations for studying the physical conditions in the upper atmospheres of planets is well established since such observations provide indices of solar activity in addition to the Zürich sunspot number (see for example, Kundu [11]). It is clear that a solar activity index can be chosen in the 1,000 - 10,000 Mc/s spectral range, but it appears that the spectral variation must be considered in the study of correlations with atmospheric phenomena. Since the radioflux is composed, without considering the burst emissions, of a quiet component (basic radio flux) and a slowly varying component, the variation of ultraviolet radiations which heat and ionize the planetary atmospheres must be compared along with that of the X-ray radiations. Friedman[12] has clearly shown that the X-ray spectrum between 40 and 60 A varies by a factor of approximately 7 during a solar cycle while the variation in the range 8 - 20A attains a value of about 50 and is several hundred in the 2 to 8A wavelength range. Consequently the behavior in the 3-30 cm interval cannot be taken as representative of the solar X-ray flux or of the integral of the ultra-violet flux. The radioflux in the neighbourhood of 10 cm may be compared during a certain period of the solar cycle with an ionospheric index, such as the ionization of the E region, but cannot be expected to fit all such observations during an entire solar cycle. There is always a relationship between solar radio emissions in the 3-30 cm interval, X-ray and UV emission and atmospheric parameters but the correlations vary during the solar cycle.

Allen [13] and Covington and Harvey [14] have found that the quiet sun radioflux should have a significant variation with solar activity, which can reach a factor of about 2, for the minimum-to-maximum variation in the 10 cm flux. The slowly varying component, which is associated with disturbed regions on the solar disk and is closely correlated with sunspot numbers, leads, in the same spectral region, to a minimum-to-maximum variation of at least a factor of 4. A recent analysis by Das Gupta and Basu [15] shows that, during the International Geophysical Year (July 1957 to December 1958, maximum of solar activity), there is a close correlation between the sunspot number and daily flux between 3 and 30 cm, and furthermore, that the maximum variation occurs near 8-10 cm.

3.- Solar Cycle Variations.

Since the solar radio-emissions in the range of wavelengths from 3 cm to 30 cm show similar variations with a so-called 27 day cycle, it is of interest to plot the 27-day average value of the Zurich relative sunspot number and of the solar radio flux at 10 cm from 1957 till 1962. The plot (Fig. 1) of the Wolf number (*) $\bar{R}_{27}$ with the radioflux (**) $\bar{S}_{27}$(10.7 cm)

(*) 27-day geomagnetic period (Bartels) deduced from Zurich Observatory data.

(**) deduced from Ottawa data in units of 10^{-22} watts/m^2/cycle/sec.

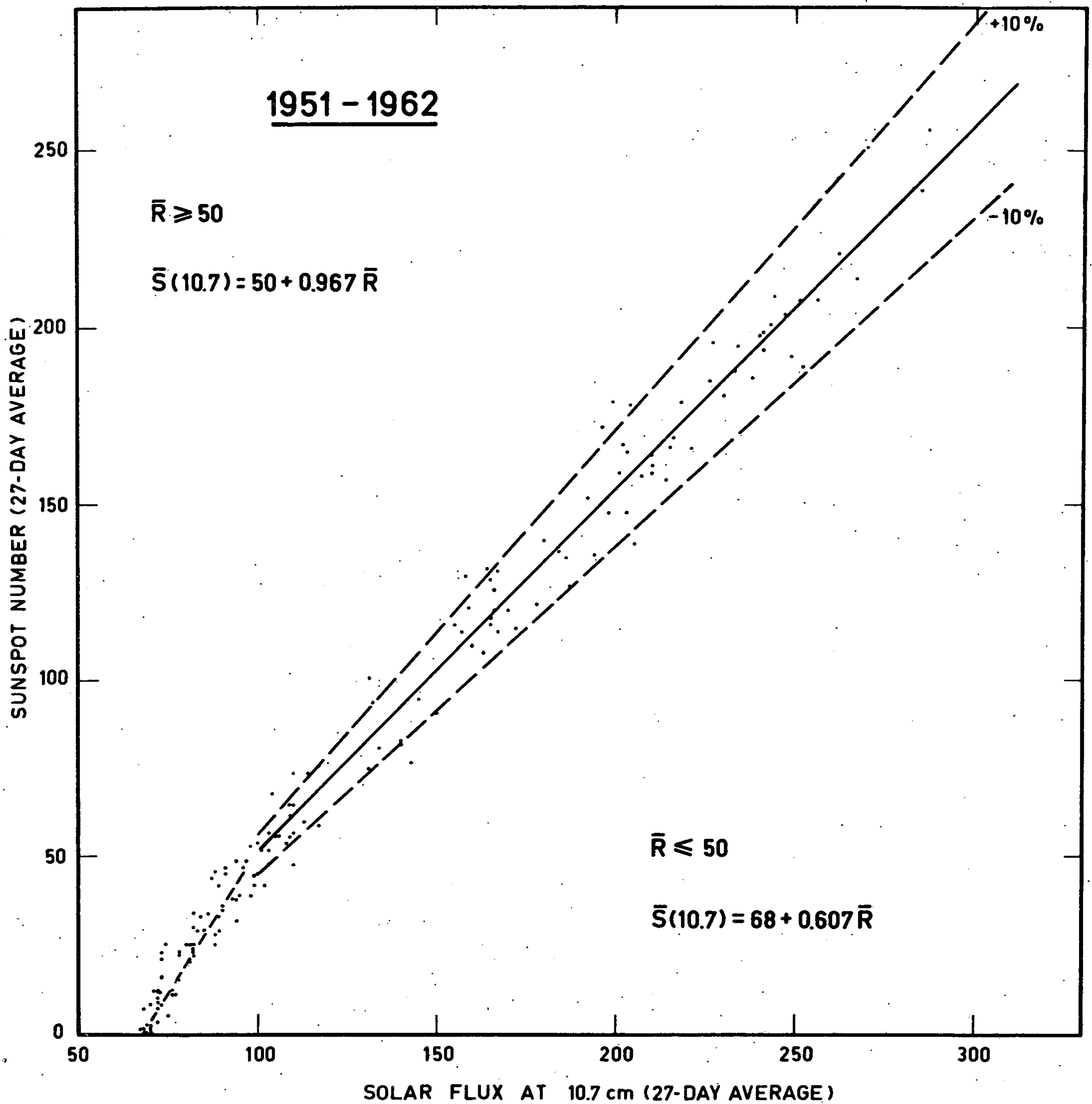


Fig. 1.- Solar radioflux at 10.7 cm versus relative sunspot number between 1951 and 1962 when 27-day mean values are used.

shows that, for $\bar{R} \geqq 50$, there is a linear relationship between these quantities which, with an error of $\pm$ 10 °/∘, takes into account the variations of the radioflux for values greater than S = 100 units, i.e.

$$\bar{S}_{27}(10.7\ \mathrm{cm}) = 50 + 0.967\ \bar{R}_{27}$$

But for $\bar{S} < 100$ or $\bar{R} < 50$, a linear variation would be :

$$\bar{S}_{27}(10.7\ \mathrm{cm}) = 68 + 0.607\ \bar{R}_{27}$$

Thus, the close association of the 10 cm radiation with sunspots cannot be expressed during a whole cycle with the same linear relationship. Furthermore, the dispersion of the daily values is larger than the 27-day mean values. Fig. 2, which shows a plot of daily values with a variation reaching $\pm$ 20 percent, indicates how such a solar index may lead to important errors in deducing any empirical correlation with atmospheric parameters.

To determine the differences between two radio emissions we can compare, first, the 27-day mean values at two wavelengths, such as 8 cm and 10.7 cm for which data are available since 1952. Even if the absolute measurements of radiofluxes are estimated with an error of $\pm$ 7 percent, and can deviate by such a percentage from a ratio of unity after normalisation, the general variation during a whole solar cycle should be significant [16]. Fig. 3 shows the gradual difference in the ratio of the 27-day mean values of solar fluxes at 10.7 cm and 8 cm. Near 200 units, both fluxes are identical, i.e. $\bar{S}_{27}(10.7) = \bar{S}_{27}(8)$. For the lower values $\bar{S}_{27}(8) > \bar{S}_{27}(10.7)$ while the ratio is reversed, $\bar{S}_{27}(10.7) > \bar{S}_{27}(8)$ for the higher values, it is clear that the ratio $\bar{S}_{27}\ (10.7)/\bar{S}_{27}(8)$ varies during a solar cycle, even if the emissions at these two wavelengths originate from almost identical levels in the solar atmosphere.

If we compare the variation of fluxes for two years of high and low solar activity (Fig. 4 and 5, 1958 and 1961), the annual mean values are :

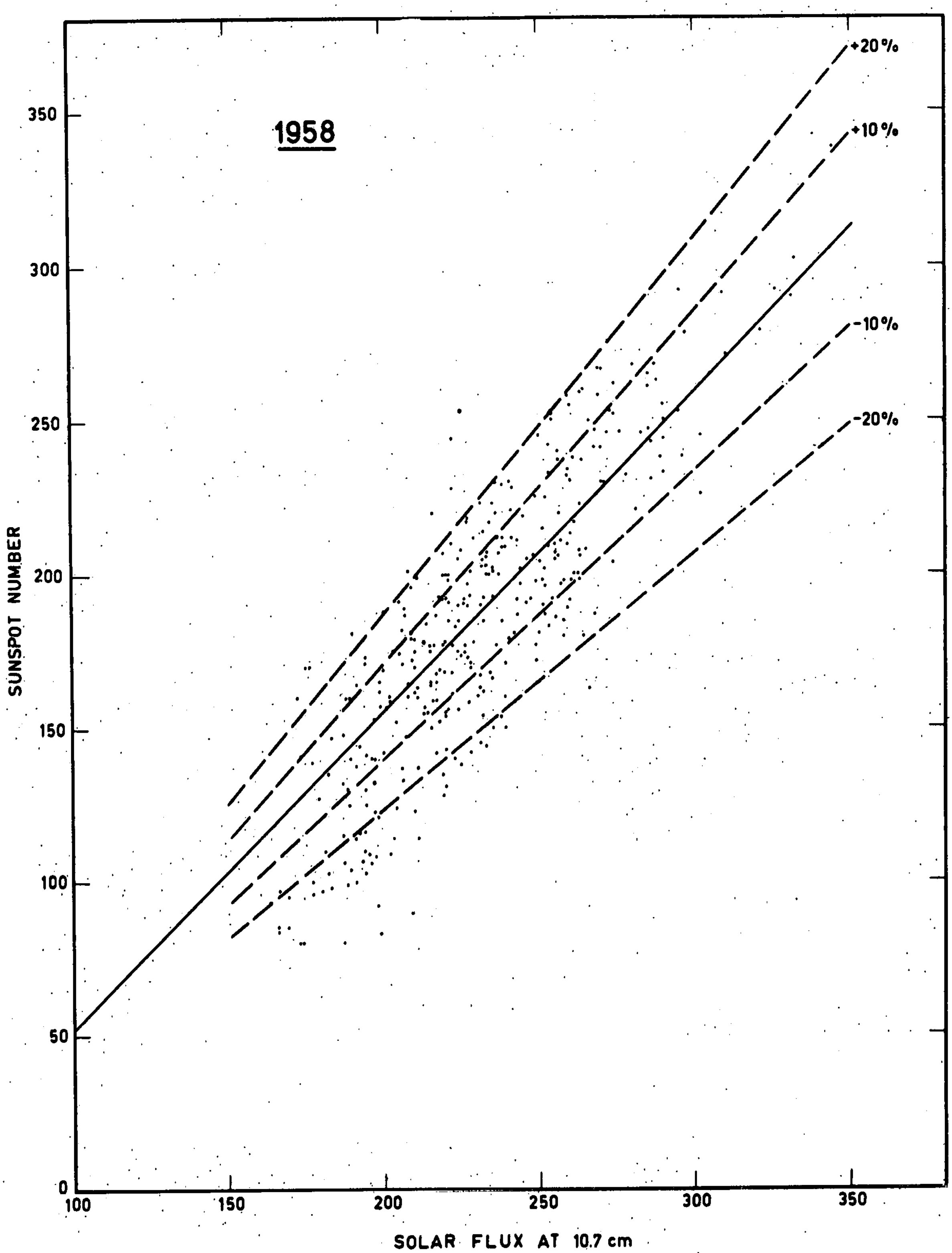


Fig. 2.- Solar radioflux at 10.7 cm versus relative sunspot number for daily values in 1958 near sunspot maximum.

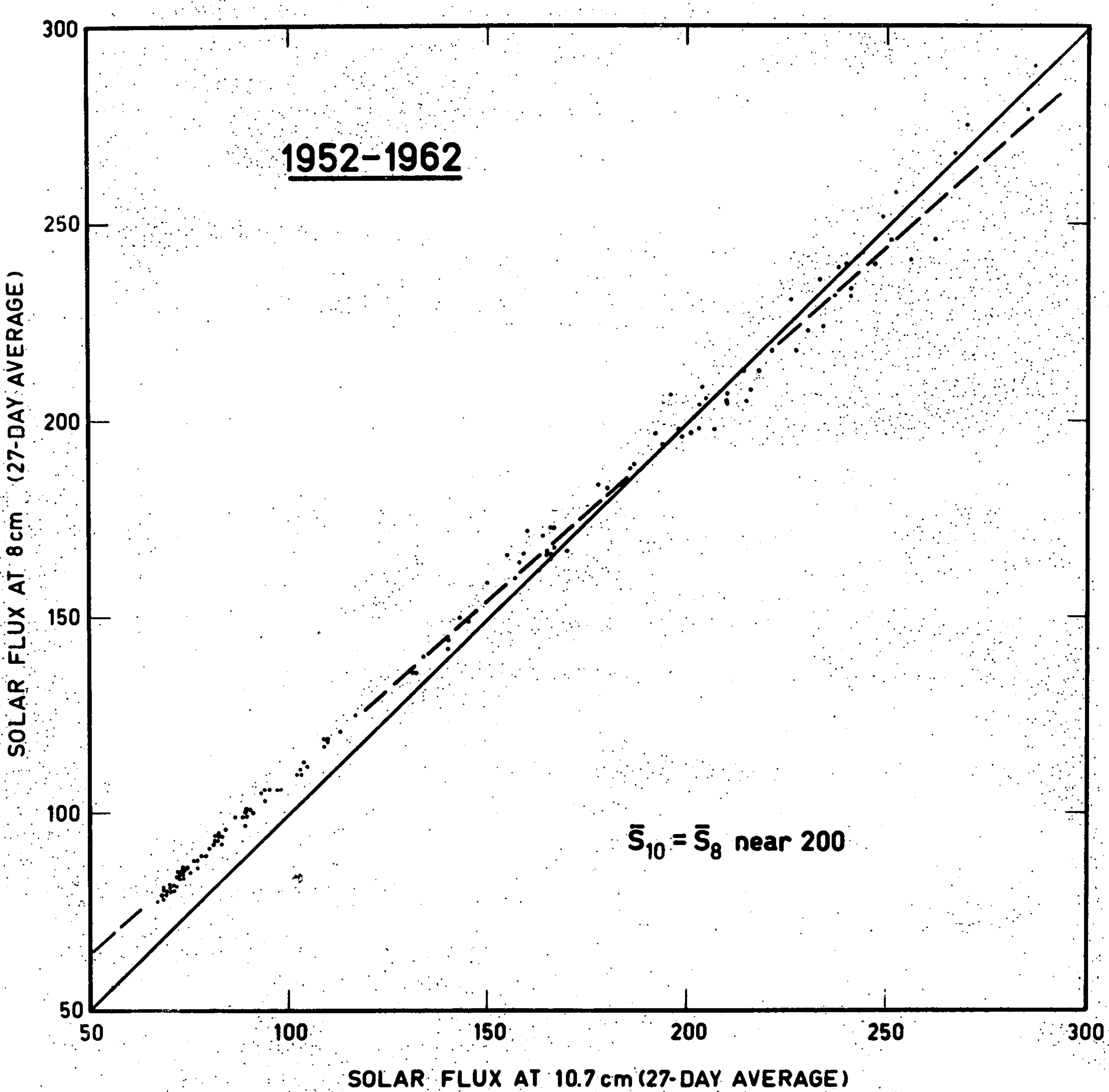


Fig. 3.- Solar radiofluxes at 10.7 cm and 8 cm. 27-day mean values between 1952 and 1962.

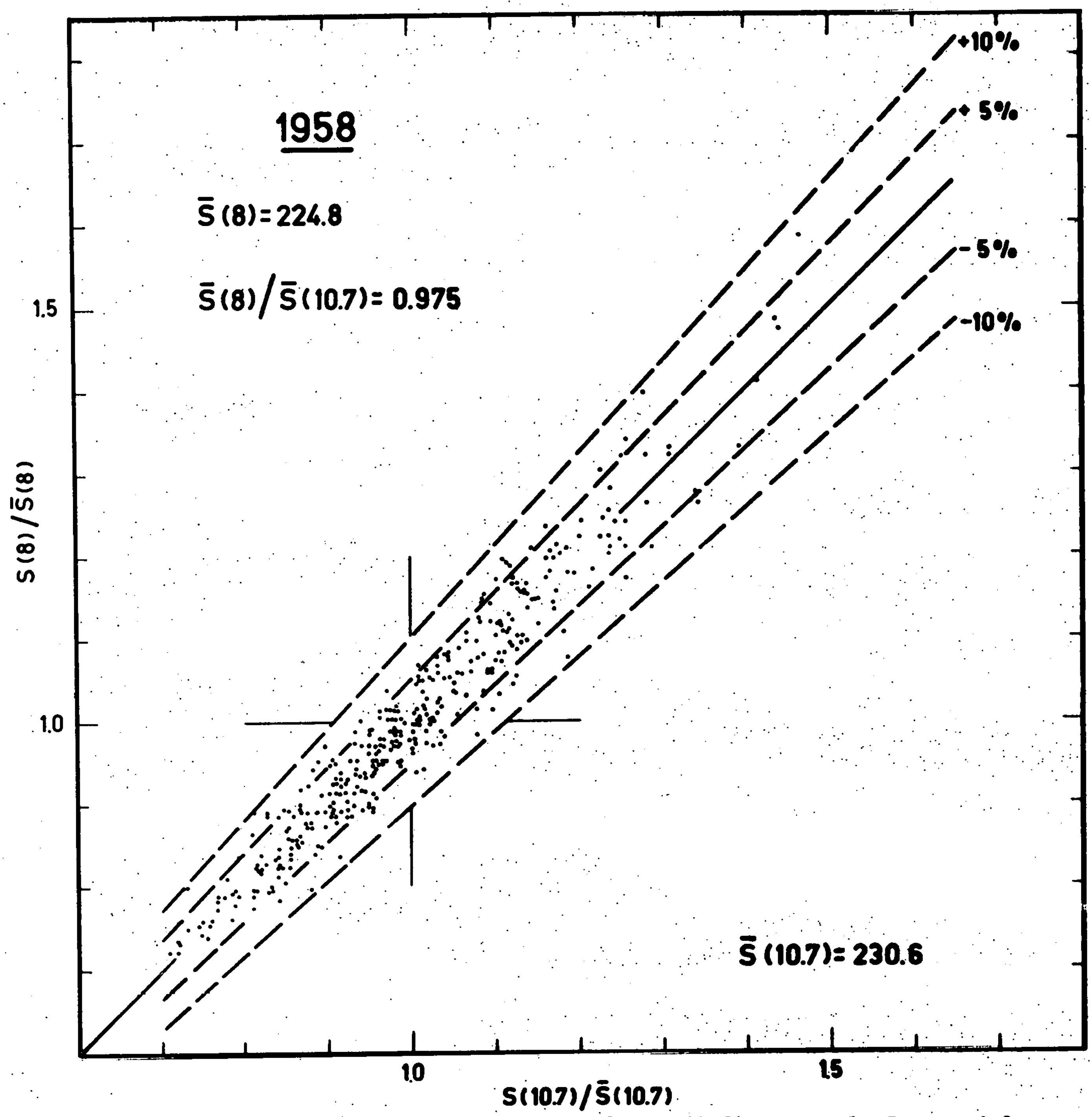
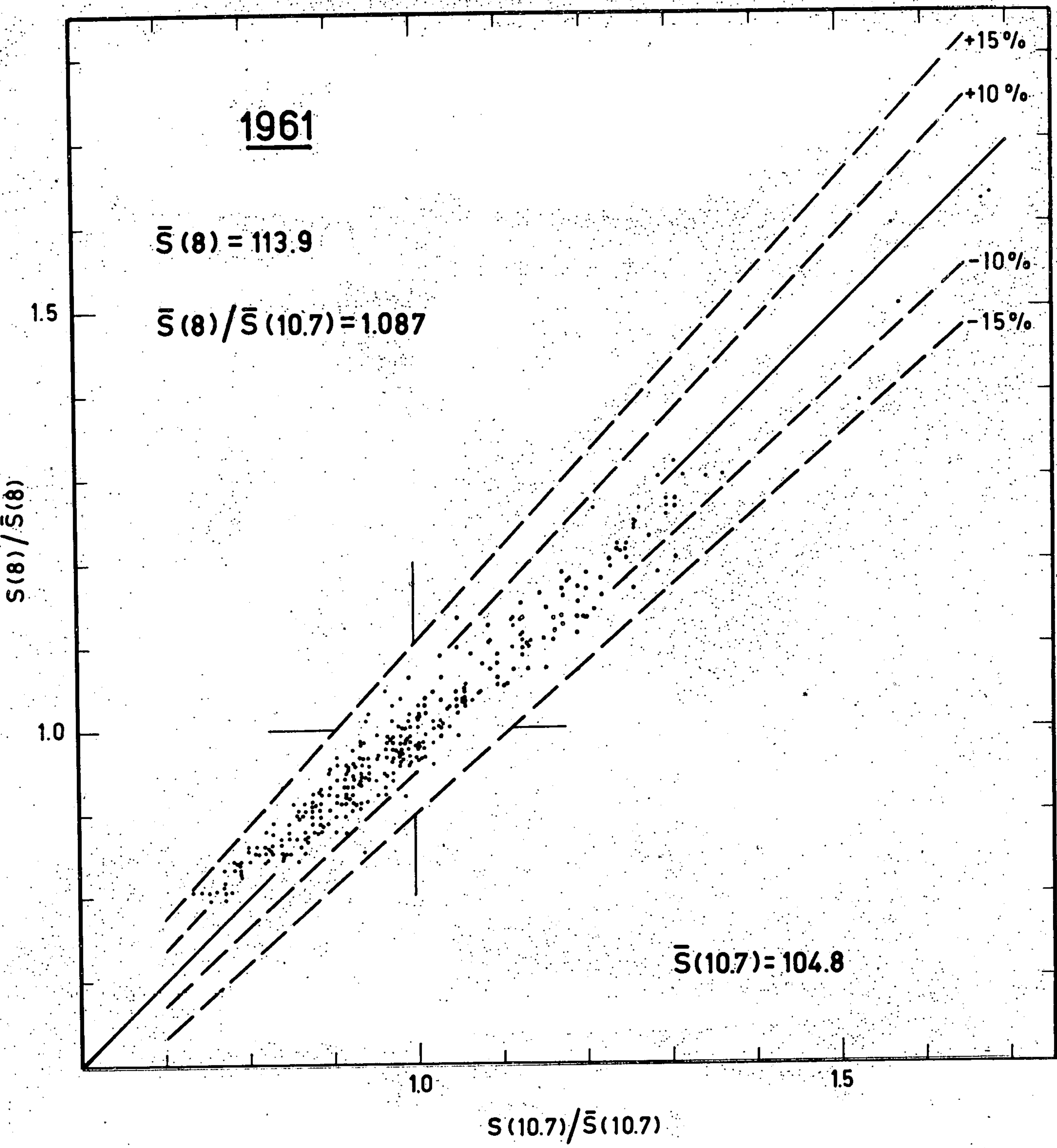


Fig. 4.- Distribution of daily values of solar radiofluxes at 10.7 cm and 8 cm in 1958 near sunspot maximum.


1961
$\bar{S}(8) = 113.9$
$\bar{S}(8)/\bar{S}(10.7) = 1.087$
$\bar{S}(10.7) = 104.8$
+15%
+10%
-10%
-15%
1.5
1.0
1.0
1.5
$S(8)/\bar{S}(8)$
$S(10.7)/\bar{S}(10.7)$

$$\frac{\bar{S}_{1958}(8)}{\bar{S}_{1958}(10.7)} = \frac{224.8}{230.6} = 0.975$$

and

$$\frac{\bar{S}_{1961}(8)}{\bar{S}_{1961}(10.7)} = \frac{114.9}{113.9} = 1.09$$

There is, therefore, a reversal in the ratio of the 8 cm and 10.7 cm radiofluxes when there is a variation of a factor of about two in the absolute values of the fluxes. Furthermore, the maximum amplitude of the variation of daily fluxes, compared with the annual mean value, is, in both cases, of the order of $\pm$ 30 °/₀. At sunspot maximum (1958, Fig. 4) the fluctuations of the ratio $[S(8)/\bar{S}_{1958}(8)]/[S(10.7)/\bar{S}_{1958}(10.7)]$ are generally less than $\pm$ 5 percent and always less than $\pm$ 10 percent. However, the same ratio in 1961 (Fig. 5)is represented by scattered values reaching $\pm$ 15 °/₀ but with systematic differences when the ratio is greater than or less than unity. In fact, the amplitude of the variation at 8 cm appears to be less than that at 10 cm. Thus, it can be concluded that the systematic differences occuring in the annual average, 27-day average and daily values of fluxes measured at 10.7 cm (Ottawa) and at 8 cm (Nagoya) are a clear indication of real variations in the spectrum of the solar radiofluxes between 2800 Mc/s and 3750 Mc/s.

4.- Spectrum from 1,000 Mc/s to 10,000 Mc/s.

A comparison between the fluxes at 15 cm and 30 cm, which are also measured at Nagoya, and the 10.7 cm flux does not show systematic differences such as those ~~which~~ are noted between 8 cm and 10.7 cm. From Fig. 6, it appears that the ratios have the following median values :

$$\bar{S}_{27}(15) \;/\; \bar{S}_{27}(10.7) \;=\; 0.72 \pm 0.08$$

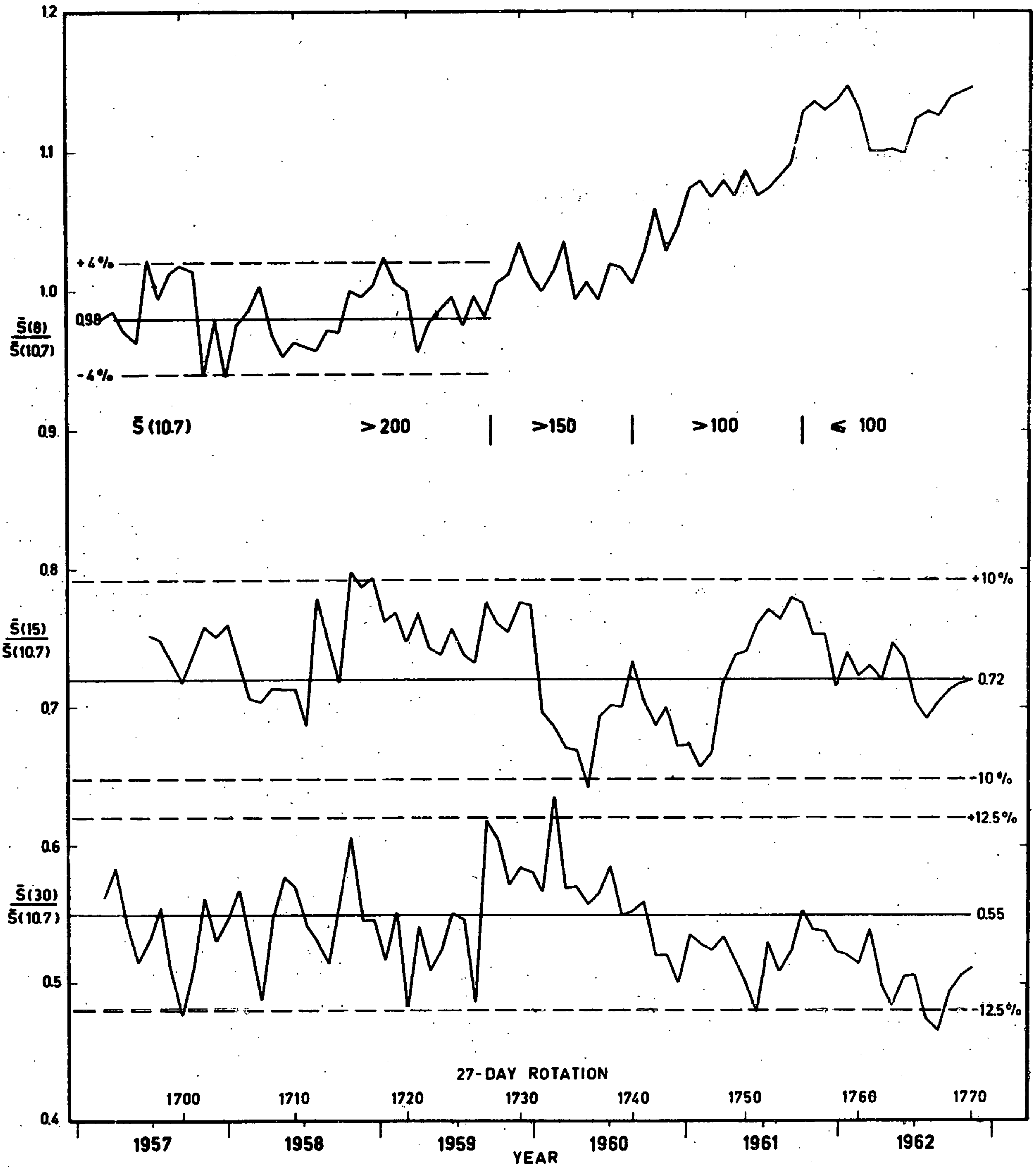


Fig. 6.- Variation of ratios of 27-day mean values of solar radio fluxes at 8 cm, 15 cm and 30 cm and radioflux at 10.7 cm.

and

$$\bar{S}_{27}(30) \ / \ \bar{S}_{27}(10.7) = 0.55 \pm 0.07$$

In other words, the fluctuations, of the order of $\pm$ 10 percent, are of sufficiently small magnitude to be explained by experimental errors without showing real spectral differences. In any event, such a variation of the ratios cannot be indicative of a systematic difference associated with the solar cycle as has been found for 8 cm. In fact, the ratio of two radio-fluxes really becomes sensitive to the solar cycle when the radiation is at a wavelength shorter than 10 cm.

The ratios $\bar{S}_{27}(3.2) \ / \ \bar{S}_{27}(8)$ and $\bar{S}_{27}(3.2) \ / \ \bar{S}_{27}(10.7)$ are considered in Fig. 7. The two curves lead to the median value of $\bar{S}_{3.2}/\bar{S}_{10.7} = 1.5$ for $\bar{S}_{27}(10.7) > 200$ with a maximum fluctuation of $\pm$ 10 percent. The ratio increases with a decrease a solar activity.
It is so sensitive to solar activity that its fluctuations follow the variations of the solar flux. Peaks in the ratio correspond to decreasing fluxes, and the minimum value of the ratio, namely 1.3, is real and is associated with the highest activity of the sun in 1957. Thus, the variation of radiofluxes with solar activity in the spectral range 1,000 Mc/s - 10,000 Mc/s is always expressed as follows :

$$\frac{\bar{S} \ < \ 10 \text{ cm}}{\bar{S} \ \geq \ 10 \text{ cm}} \quad \text{decreases when S increases.}$$

It is evident that an adequate solar radio index may be chosen at 10 cm or at shorter wavelengths. However, a more complete analysis must be made before adopting a general law for the entire solar cycle. Fig. 8 shows how the ratio $\bar{S}_{27}(8)/\bar{S}_{27}(10.7)$ varies between 1952 and 1962. The ratio reaches a maximum at the minimum of the solar cycle with a median value of 1.15 $\pm$ 5 percent and decreasing to a median value of 0.98 $\pm$ 5 percent at the maximum of the solar cycle, i.e. a difference

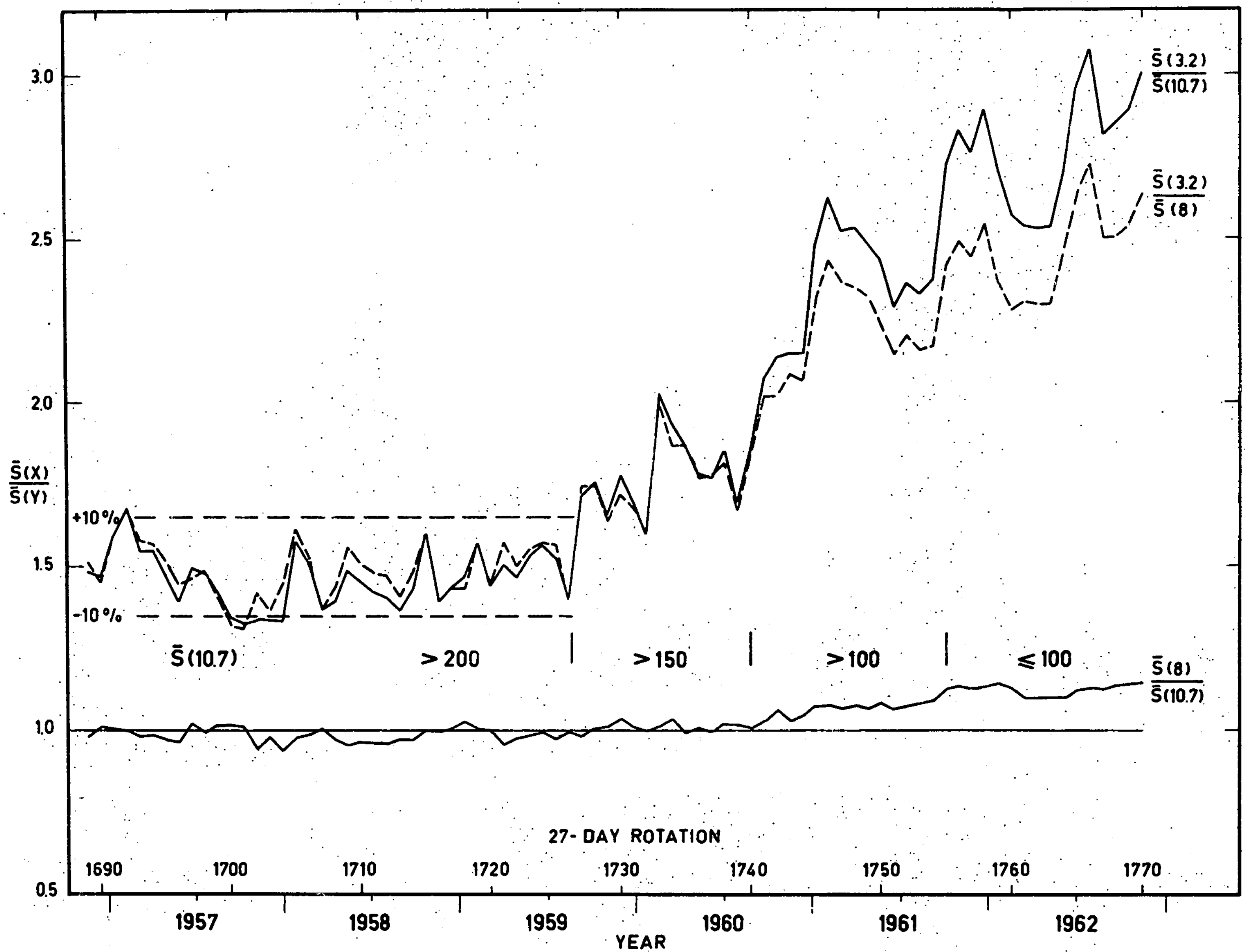


Fig. 7.- Effect of solar activity on the spectral variation between 10 cm and 3 cm.

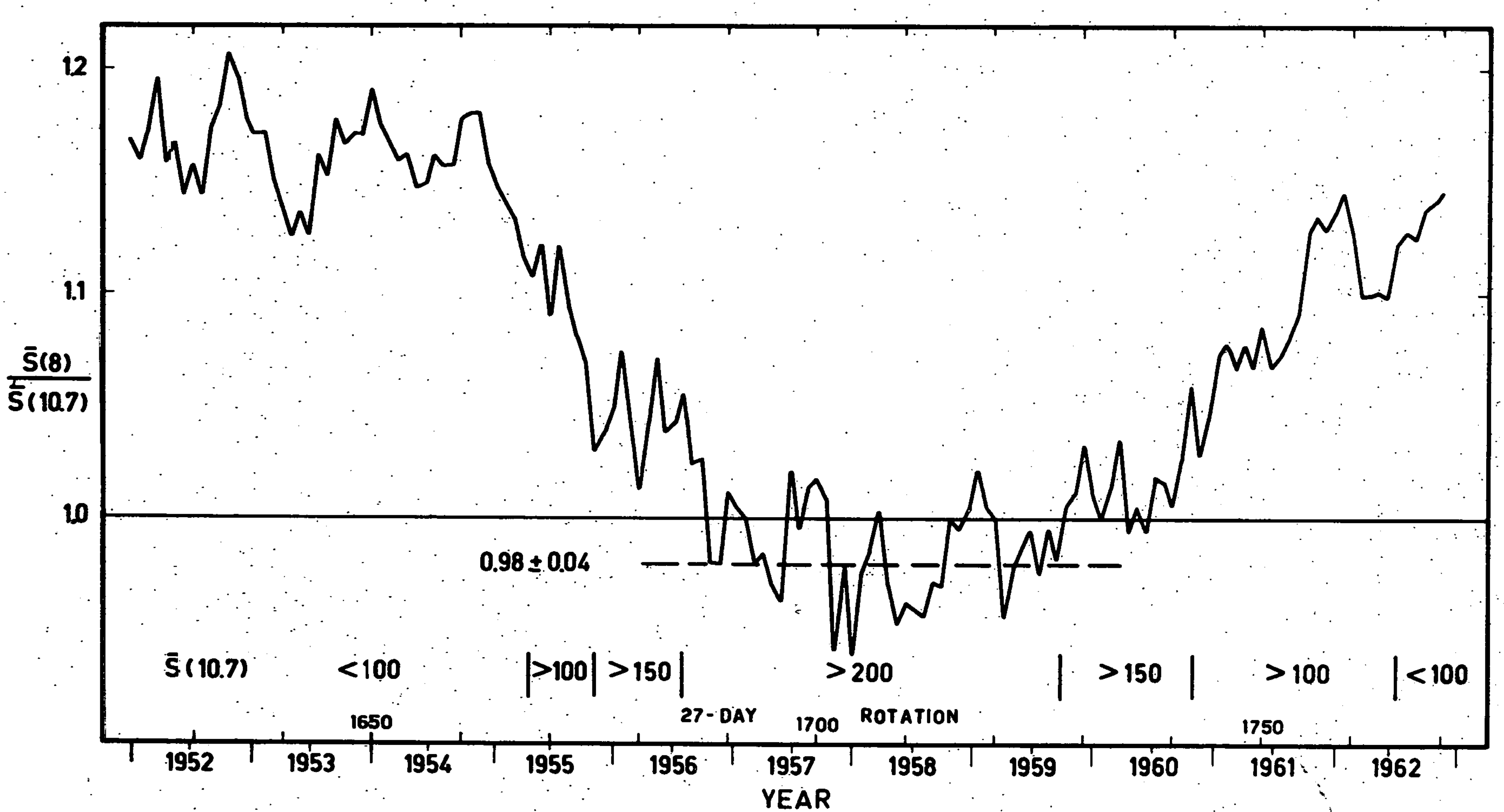


Fig. 8.- Variation of the ratio of 27-day mean values of solar radiofluxes at 8 cm and 10.7 cm from 1952 to 1962.

reaching 20 percent for the minimum-to-maximum variation of a solar cycle. It is clear, therefore, that the absolute fluxes must change as indicated by this ratio.

To give an idea of the amplitude of the 27-day variation of the slowly varying component, Figs 9 and 10 show the ratio S_{Max}/S_{27} and S_{Min}/S_{27}, representing the highest and lowest values of the daily fluxes for each 27-day period. No systematic difference can be immediately detected with the solar cycle for 10 cm and 8 cm. It is clear that the amplitude of the 27-day cycle at 3 cm is always less than that at 8 cm. As far as 15 cm is concerned, it appears that for $S(8) \geqq 200$ units, i.e. for high solar activity, $\Delta S(15\text{ cm}) \leqq \Delta S\ (8\text{ cm})$ while $\Delta S\ (15\text{ cm}) > \Delta S\ (8\text{ cm})$ at low solar activity, i.e. when $S(8) < 120$. The same law seems also to be adequate for 30 cm, since $\Delta S(30\text{ cm}) < \Delta S(8\text{ cm})$ when $S(8) \succ 150$ and $\Delta S(30\text{ cm}) \geqq \Delta S(8\text{ cm})$ when $S(8) < 120$. Such striking features exhibited by the 27-day cycle between 8 cm and 30 cm indicate that its maximum-to-minimum amplitude as detected by the daily mean fluxes, cannot be subject to simple laws related to the frequency. A systematic variation is found at high solar activity during the International Geophysical Year period (for example Das Gupta and Basu [15]), but is completely different in 1961 and 1962 as shown in Fig. 9.

Thus, a complete analysis of the solar radiofluxes should be made at wavelengths shorter than 10 cm since no clear conclusion (systematic errors or spectral differences) can be reached for the spectral range of wavelengths greater than 10 cm.

5.- Atmospheric Temperatures and Solar Fluxes.

Since the increase of the atmospheric scale height with altitude is due to a normal decrease of the molecular mass and not to an increase of the temperature [1], and the thermopause temperature is related to the ultraviolet heating and conduction cooling, a relationship can be found between the solar radioflux and the thermopause temperature. Jacchia [17],

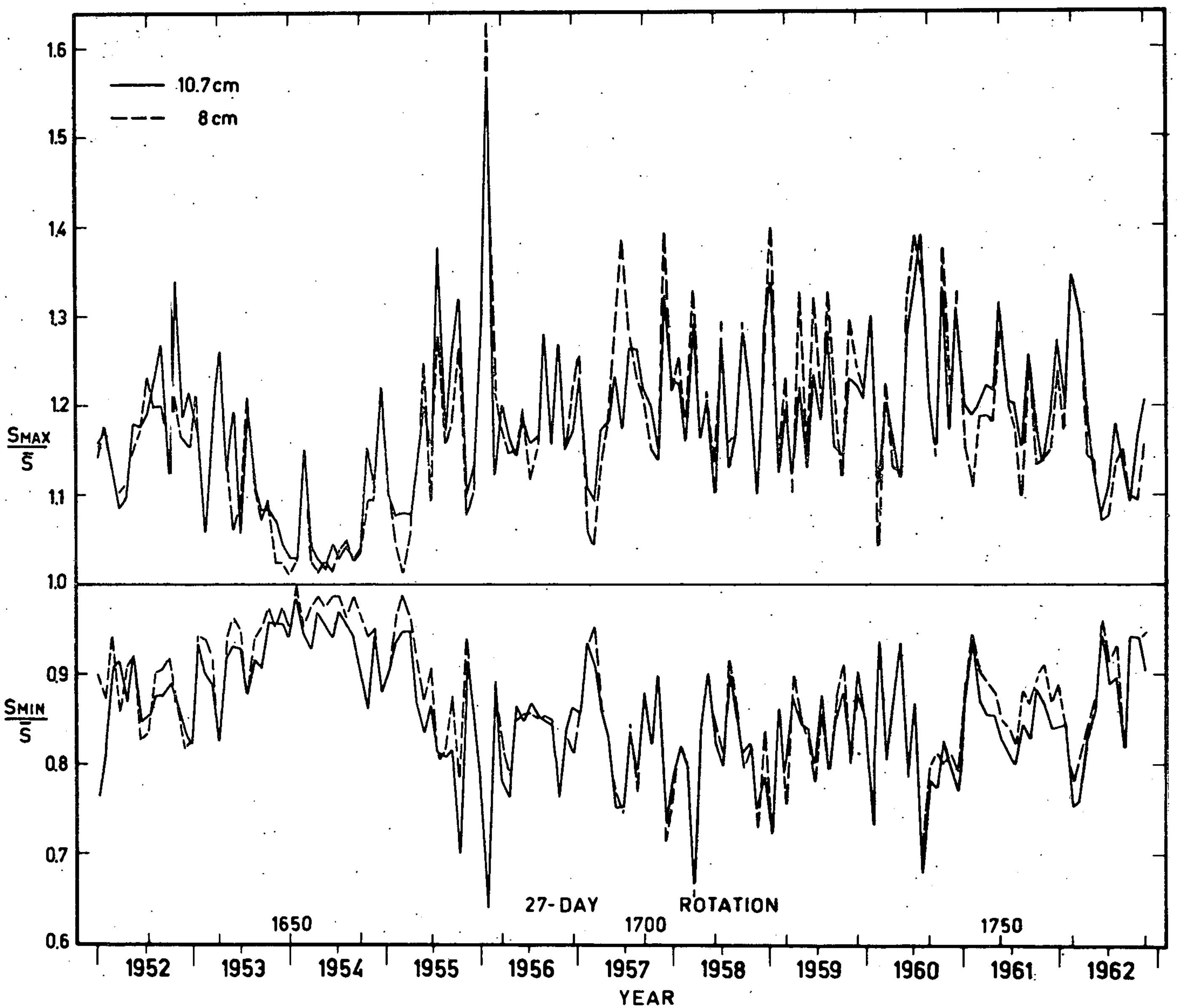


Fig. 9.- Minimum-to-maximum variations of solar radiofluxes at 8 cm and 10.7 cm for a 27-day period between 1952 and 1962.

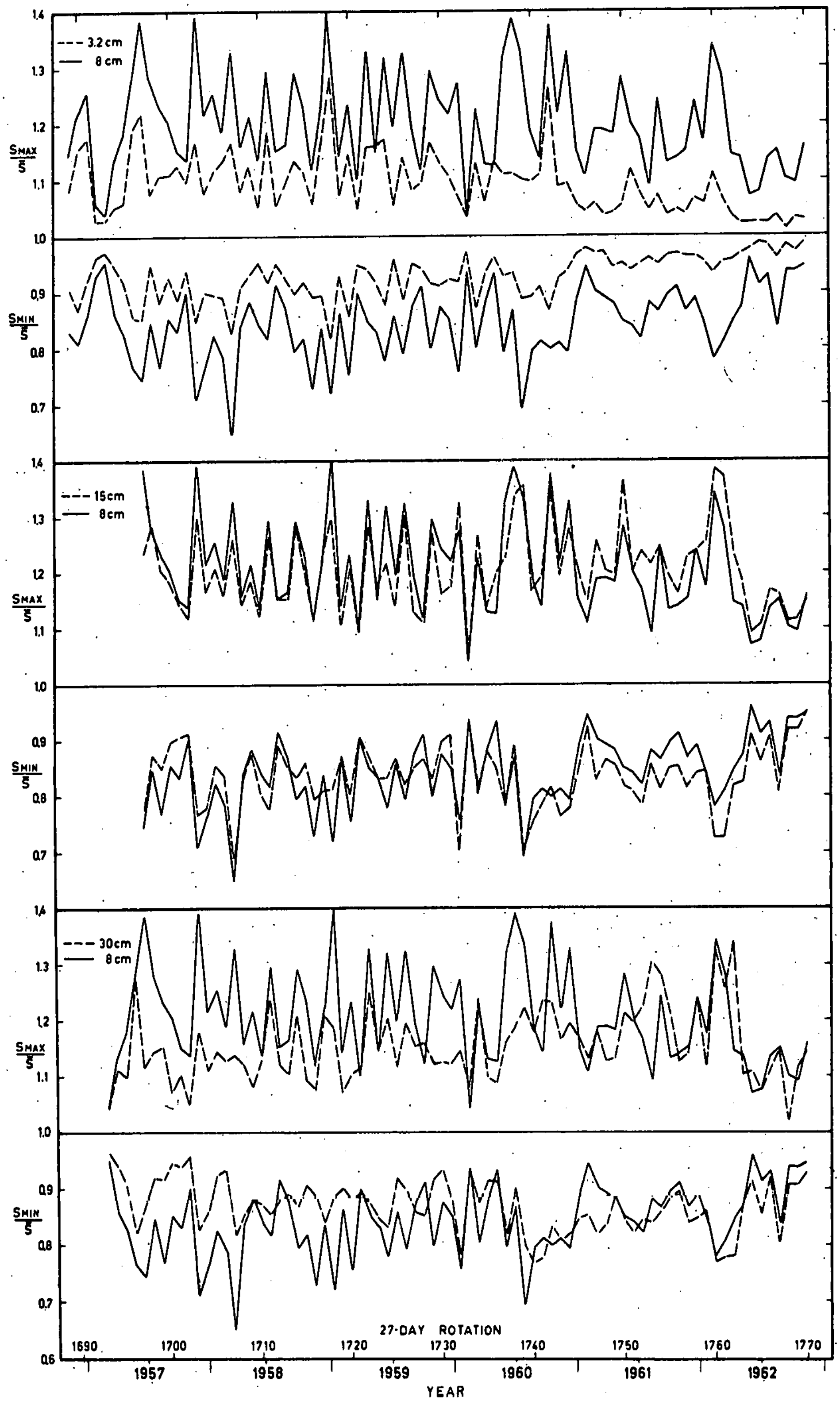


Fig. 10.- Minimum-to-maximum variations at 3.2 cm, 15 cm, 30 cm and 8 cm between 1957 and 1962.

after adopting Nicolet's atmospheric model [18], deduced an equation having the following form :

$$T = T_o + aS \tag{1}$$

in which the temperature of the thermopause, T, is related to the solar flux, S, with dT/dS = a and T_o a constant. Linear relationships such as (1) have also been adopted by Harris and Priester [19] and Paetzold [20].

From the preceding discussion it is clear that the adoption of a radio index at different wavelengths will modify the value of the coefficient a in equation (1). Further, these different coefficients will be obtained depending on the wavelength chosen.

Let us again consider the 5 monochromatic radiofluxes at 3.2 cm, 8 cm, 10.7 cm, 15 cm and 30 cm for which the analyses made in the preceding paragraphs have shown the general behavior for a complete solar cycle. The following ratios were determined :

(i) Ratio of the maximum 27-day mean value reached in 1957 (period n° 1701 or 1703) and the minimum 27-day mean value reached in 1954 (periods near n° 1655) or, when no continuous observations are available, individual values during n° 1766 in August 1962.

(ii) Ratio of the minimum daily fluxes reached in 1957 (periods between n° 1695 and n° 1715) and the minimum 27-day mean value.

(iii) Ratio of the maximum of maximum daily fluxes reached in 1957 (period n° 1703) and the minimum 27-day mean value.

The first ratio, R_i, will give the maximum amplitude during a solar cycle of the 27-day mean value of the radioflux. The second ratio, R_{ii}, corresponds to the maximum possible variation of the quiet sun during a solar cycle and the third ratio, R_{iii}, corresponds to the minimum-to-maximum variation which can be reached. The various ratios are shown in Table I. A factor of about 6, which represents the minimum-to-maximum variation R_{iii} near 2000 Mc/s, corresponds to an extreme case. It is still,

TABLE I.- Ratios of various maxima of solar fluxes to the minimum values for a quiet sun at minimum solar activity.

Mc/s	9400	3750	2800	2000	1000
λ(cm)	3.2	8	10.7	15	30
R_i	1.6	3.7	4.2	4.5	4.5
R_{ii}	1.2	2.2	2.5	2.8	3.0
R_{iii}	2.0	5	5.5	5.9	5.4

however, less than the variation of the X-ray flux (Friedman [12]), absorbed in the ionospheric E layer. In fact, a factor of 7 in the X-ray emission must be compared with the maximum ratio R_i of 4.5 representing the 27-day meam ratio. The ratio R_{ii}, which varies from 1.2 at 3.2 cm to 3 at 30 cm, shows how difficult it is to determine the amplitude of the quiet sun variation which should be related, first of all, to the ultraviolet flux associated with the solar heating of the upper atmosphere.

Nevertheless, since the ratio R_{iii}/R_i is of the order of 1.3 and the ratio R_{ii}/R_i is of the order of 0.6 between 8 cm and 15 cm, equation (1) is used in a different form in which a basic component corresponds to the mean value $\bar{S}_{27}$ for a 27-day period and a varying component ΔS represents the oscillation during such a period :

$$T = T_o + a\,\bar{S}_{27} + b\,\Delta S \qquad (2)$$

where

$$\Delta S = S - \bar{S}_{27} \qquad (3)$$

or

$$T = T_o + (a - b)\,\bar{S}_{27} + b\,S \qquad (4)$$

The coefficients a and b will have different values. a will be greater than b since it must take into account the basic component of the solar flux primarily associated with the ultraviolet flux. The factor b represents the 27-day oscillation of a radioflux which is less important for the ultraviolet variation. In other words, considering the ratios R_i and R_{iii}, the term a $\bar{S}_{27}$ in (4) is associated with the variation of R_i during a whole solar cycle and the term b Δ S corresponds to the fluctuations (R_{iii} - R_i) during a 27-day period.

In order to determine the variations for an entire solar cycle, one may compare the ratios of R_i for 3.2 cm, 8 cm and 10.7 cm since the variation for the ultraviolet heating must be associated with this spectral range. The variation of $\bar{S}_{27}$(10.7 cm) is plotted against the ratio $\bar{S}_{27}$(8)/$\bar{S}_{27}$(10.7) in Fig. 11 with the unit ratio at S(10.7 cm) = 250. A smoothed relation is drawn and indicates that the slope is steeper for lower activity. The correction factor reaches 20 percent at sunspot minimum and, it should be mentioned that, one would not expect a severe departure for the smooth curve since the individual ratios are affected with a maximum error of $\pm$ 5 percent, i.e. not more than the possible errors in the absolute values. Fig. 12 represents the characteristic difference in the 27-day mean fluxes of 3.2 cm and 10.7 cm. The normalisation of the ratio $\bar{S}_{27}$(3.2)/$\bar{S}_{27}$(10.7) is made for 250 < $\bar{S}_{27}$(10.7) < 300 units. There is a significant change with the solar cycle, reaching a factor of 2.6. The dashed-line curve corresponding to the ratio $\bar{S}_{27}$(8)/$\bar{S}_{27}$(10.7), compared with the 3.2 cm curve, shows how the spectrum varies with solar activity between 3,000Mc/s and 10,000 Mc/s. The conclusion arrived at from such an analysis is that the variations of the ultraviolet radiation can be correlated with a radioflux in the range 10 cm - 30 cm during the maximum of the solar cycle. However, the relative change of flux is systematically less for higher frequencies, and can be regarded as being more representative of the change of the ultraviolet spectrum related to the heating of an upper atmosphere. Since there are no measurements available between 10,000 Mc/s and 3,750 Mc/s, a complete analysis can only be made at 8 cm and 10.7 cm.

Jacchia [21], using a smoothed value $\bar{S}$(10.7 cm) such as :

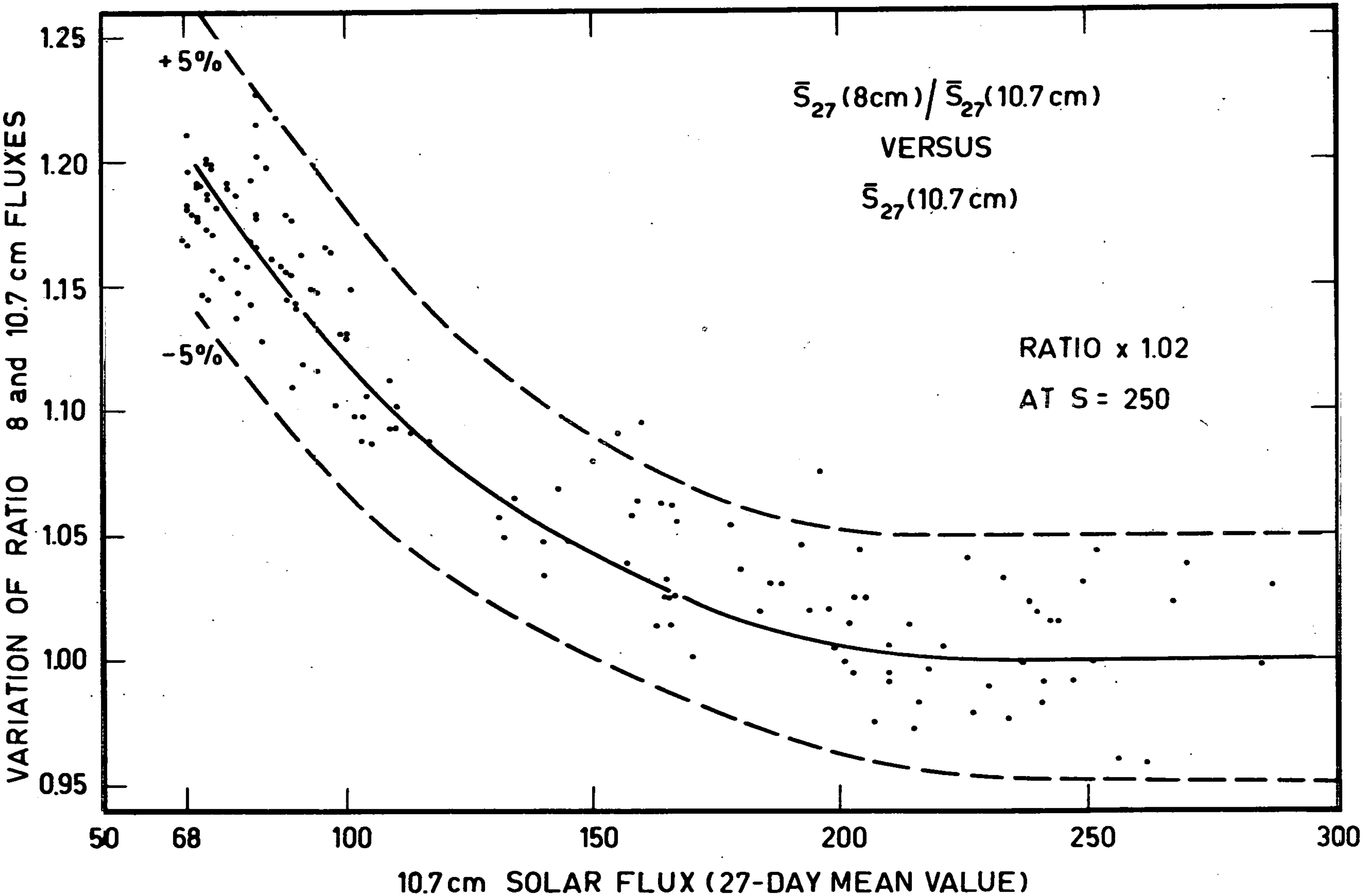


Fig. 11.- Ratio of solar radiofluxes at 8 cm and 10.7 cm.

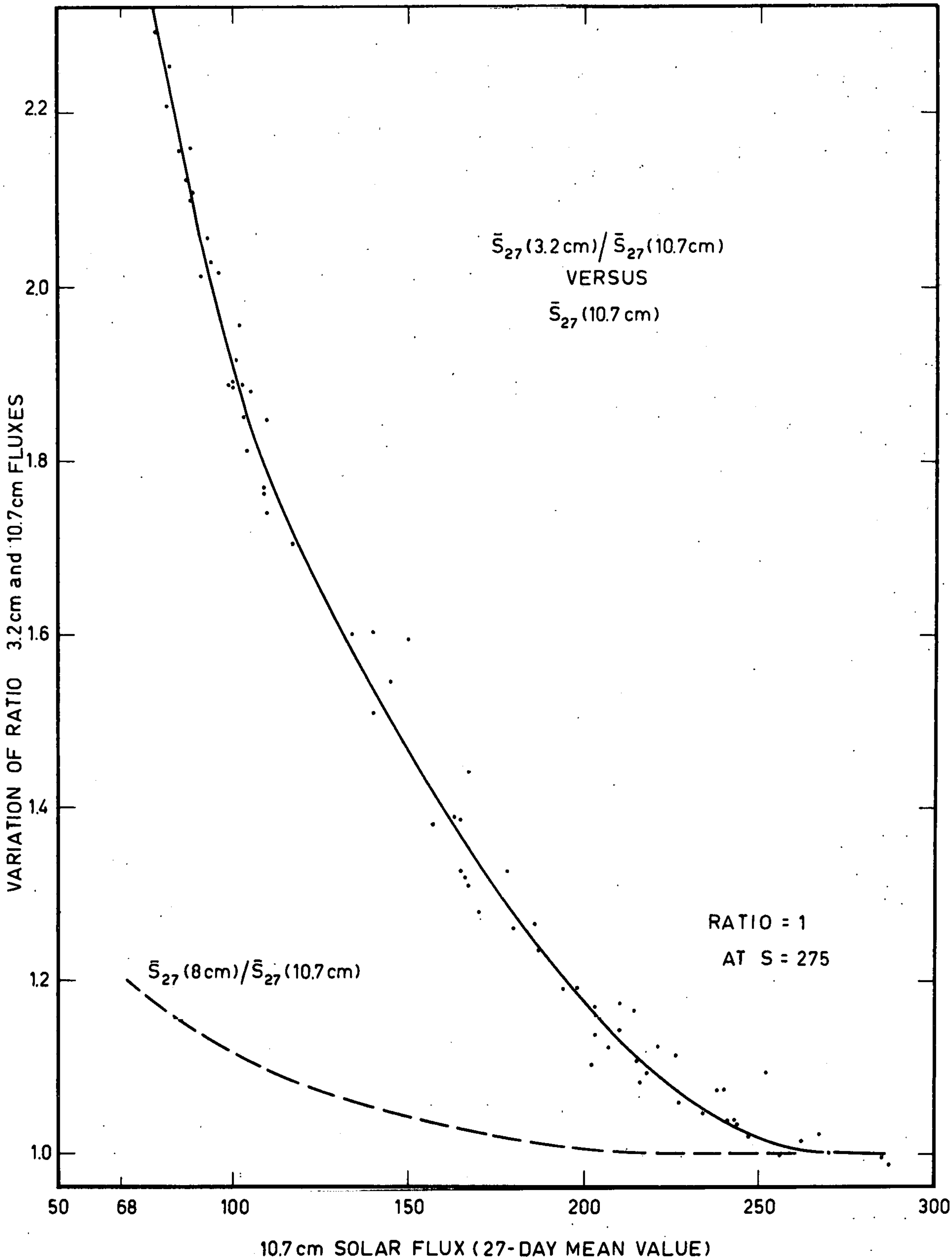


Fig. 12.- Comparison between solar radiofluxes at 3.2 cm and at 8 cm with 10.7 cm.

$$\bar{T} = T(S = 200) + 2°5\ \bar{S}(10.7\ \text{cm}), \tag{5}$$

has determined average night-time and day-time temperatures corresponding to an average value for the diurnal bulge. The result is that, except for the lowest values of $\bar{S}$, a linear correlation with an average slope of 4°5 between night-time temperatures and $\bar{S}$(10.7 cm) may be found. The same linear relationship is also used by Harris and Priester [19], i.e.

$$\bar{T}_{night} = 275°K + 4°5\ \bar{S}(10.7\ \text{cm}) \tag{6}$$

Adopting the same formula for 8 cm, we see (Fig. 11) that equation (8) below may be used if we adopt for the average slope of the variation of the night-time temperature :

$$\frac{d\bar{T}\ (\text{night})}{d\bar{S}_{27}(8\ \text{cm})} = 4°6 \tag{7}$$

The use of the 8 cm flux as a solar index leads to a basic correlation between the temperature and the flux at 10.7 cm which is no longer linear. Taking into account the differences of $\pm$ 5 percent occuring between 8 cm and 10 cm fluxes we use, instead of (6),

$$\bar{T}_{night} = 280°K + (4°6 \pm 0.25)\ \bar{S}_{27}(8\ \text{cm}) . \tag{8}$$

The variation of $\pm$ 5 percent in the second term of (8) shows that differences of at least $\pm$ 0.25 S should be expected in any determination of a correlation between the temperature and the 27-day mean value of any observed radioflux.

In order to fit the temperatures of the day-time bulge we use Jacchia's relation

$$\bar{T}_{day} = \bar{T}_{night} \times 1.33 \tag{9}$$

leading to $\bar{T}_{day} = 370°K + (6.1 \pm 0.3)\ \bar{S}_{27}(8)$ (10)

The maximum day-time temperature may require a factor a little greater than 1.33, but the following expression, equivalent to that used by Harris and Priester [19],

$$\bar{T}_{\text{day-time maximum}} = \bar{T}_{\text{night}} \times 1.35 + \bar{S}\ (10.7\ \text{cm}) \tag{11}$$

is not adequate since it leads to diurnal amplitudes which are too large and, furthermore, to systematic differences, depending on the level of solar activity, with temperatures which are too high.

Thus, equations (8) and (10) have been used to determine the diurnal oscillation with the variation of $\bar{S}_{27}(8\ \text{cm})$. In Fig. 13 the temperature variation is plotted against the usual 10.7 cm solar flux utilizing a re-conversion from 8 cm which shows the non-linearity of the relationships. The minimum-to-maximum variation of the average night-time temperature during a solar cycle is from about 650°K for the completely quiet sun to 1600°K for the highest solar activity. The same variation for day-time temperatures corresponds to the range of 850°K to 2100°K.

In order to use the 27-day mean values of the 10.7 cm radioflux at low solar activity the following formulas may be adopted instead of (8) and (10) :

$$\bar{T}_{night} = 380°K + (4° \pm 0.25)\ \bar{S}_{27}(10.7\ \text{cm}) \tag{8a}$$

and

$$\bar{T}_{day} = 500°K + (5°3 \pm 0.3)\ \bar{S}_{27}(10.7\ \text{cm}) \tag{10a}$$

if $S_{27}(10.7\ \text{cm}) < 200$ units.

Jacchia and Slowley [22] have made a precise analysis of the 27-day oscillation deduced from the drag of several satellites. The temperature variation may be expressed by a relation such as

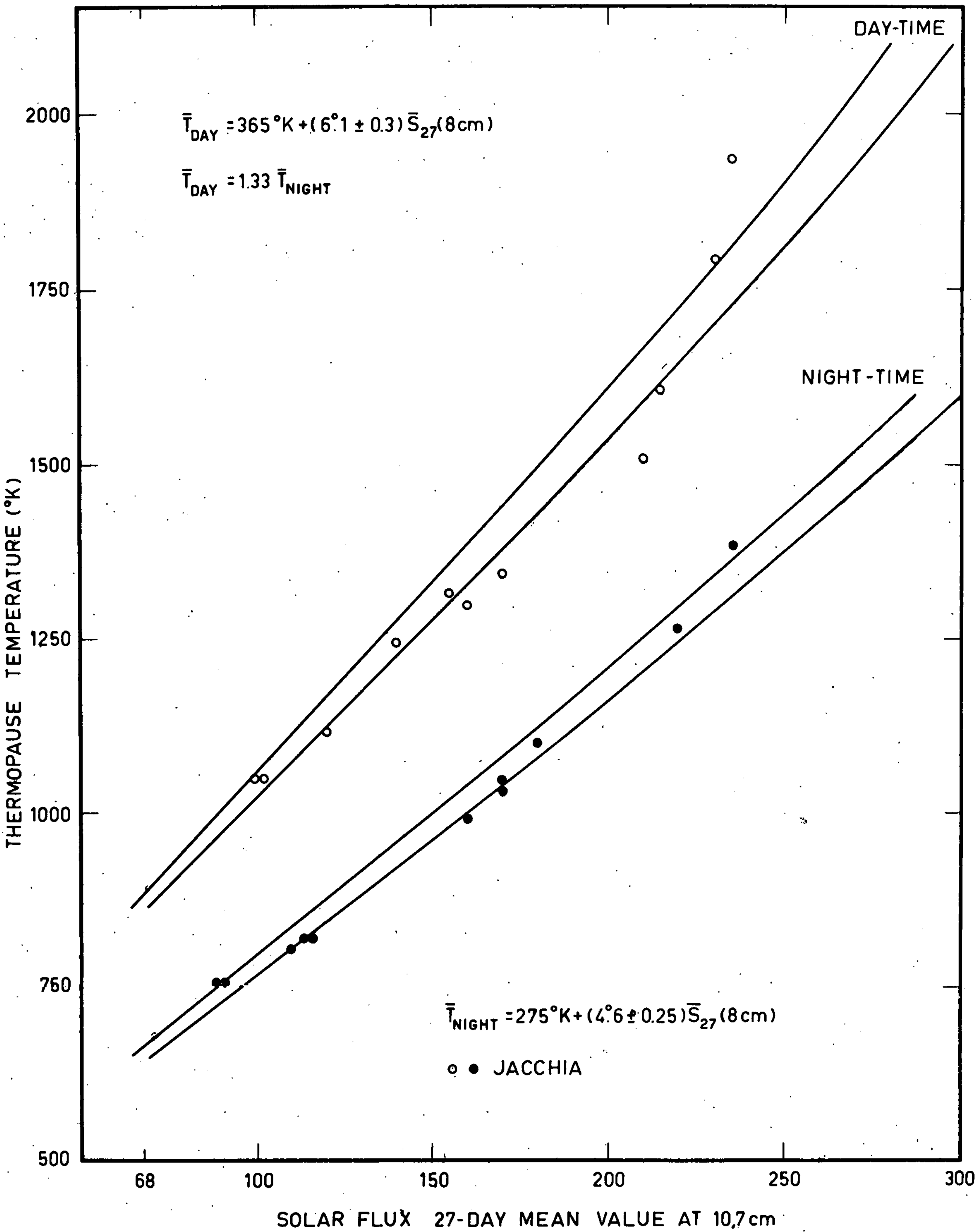


Fig. 13.- Average night-time and daytime temperatures of the thermopause for a complete solar cycle.

$$T = \bar{T} + b\,\Delta S \qquad (12)$$

with values of the coefficient b which may be of the order of 2.5 ; extreme values of the order of 2° and 3° could be used for night and day-time conditions. However, it is not yet certain that there is a real difference between dark and sunlit atmospheres since Jacchia and Slowley considered the possibility of a constant value of b = 2.2.

Thus the final formula may be written, according to (2), (4), (8) and (12), and neglecting the possible error of $\pm$ 5 percent,

$$T_{night} = 280°K + 4.^{\circ}6\ \bar{S}_{27}(8\ cm) + 2.^{\circ}5\ \Delta\ S \qquad (13)$$

or

$$T_{night} = 280°K + 2.^{\circ}1\ \bar{S}_{27}(8\ cm) + 2.^{\circ}5\ \Delta\ S\ (8\ cm) \qquad (14)$$

This relation holds, as a general relation, between the solar flux at 8 cm and atmospheric temperature over a complete solar cycle and including the 27-day oscillation. Consequently, there is no need for an explanation of atmospheric heating involving a solar wind or any other corpuscular effect. In fact, the term involving $\bar{S}_{27}$ is the basic component for the ultraviolet heating while the other term incorporating ΔS involves, with a smaller weight, the effect of the 27-day oscillation. However, when both S and $\bar{S}$ are used in the same formula the coefficients are of the same magnitude as deduced from the observations.

There are other effects which have also been introduced, such as the semiannual or annual variations detected by Paetzold [20], for which an origin has been suggested as an effect of a solar or an interstellar wind; respectively. The fact, however, that a solar index such as 8 cm instead of 10.7 cm flux has removed an essential difficulty, such as a lack of a linear correlation at low solar activity and also a systematic drift in the atmospheric temperature from 1958 to 1962, leads to other possible explanations for such effects which may be detected only after several reductions of observational data. Several factors must be kept in mind : (i) Any atmospheric model may lead to systematic differences in the temperature of the thermopause of at least $\pm$ 50°K. (ii) The boundary conditions in the thermosphere cannot be kept constant for an entire year. (iii) A steady state of diffusion conditions cannot be assumed in a detailed study of the diurnal variation. (iv) The absolute value of any solar radioflux may lead to an undetectable error of $\pm$ 5 percent. (v) Depending on the type of calibration, systematic drifts due to seasonal atmospheric effects can occur. Thus, fluctuations may occur which lead to possible singular behavior of certain parameters. In spite of these difficulties, the solar radioflux at 8 cm establishes a simple pattern which is suitable for representing the average temperature conditions of the earth's upper atmosphere at various stages of the solar cycle. This requires a heating by ultraviolet radiation and a cooling by heat conduction without postulating any essential corpuscular process. The later would lead to an absorbed energy of not less than 0.2 erg cm^{-2} sec^{-1} while the normal atmospheric conditions show that it cannot exceed 0.05 erg cm^{-2} sec^{-1}. These influences must be found in the auroral zone, and are important during magnetic storms through hydromagnetic heating.

6.- Temperature Variations during a Solar Cycle.

Since the ratio $\bar{S}_{27}(8)/\bar{S}_{27}(10.7)$ varies with solar activity and there is no general relation which is applicable, numerical values must be used. In order to show how the differences may be dealt with a calculation has been made for average night-time and day-time temperatures corresponding to the 27-day mean values of solar radiofluxes at 8 cm and 10.7 cm by using formulas (6) and (8). Fig. 14 shows how the night-time temperatures deduced from the 10.7 cm radioflux would be systematically too low when the temperature is less than 1250°K, the difference increases with the decrease of the solar activity. Fig. 15 gives the day-time temperatures from 850°K to 2100°K with a systematic difference below 1750°K. It should be remarked that the scatter of the various points represents differences in the measured solar

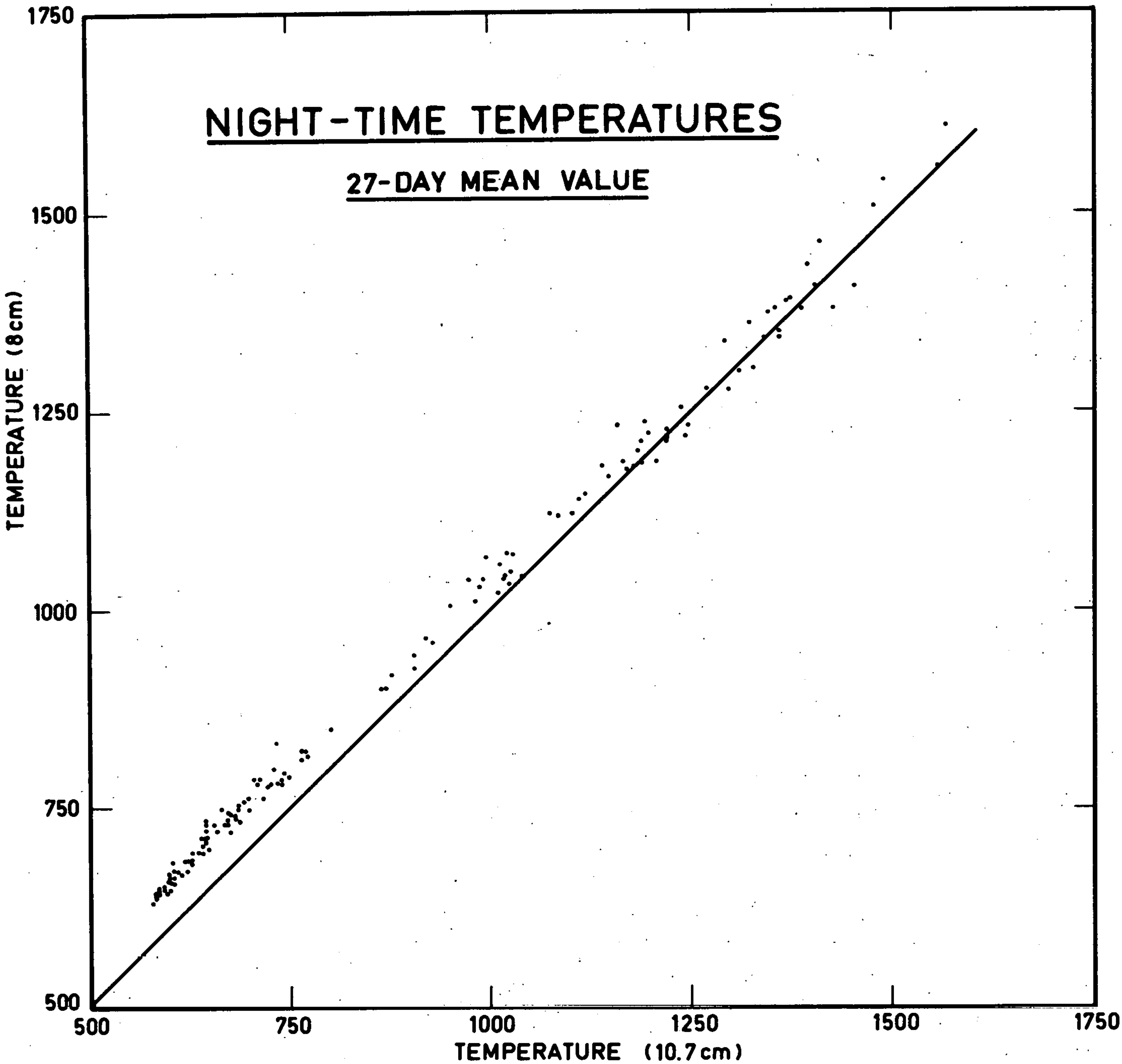


Fig. 14.- Differences in the determination of the thermopause temperatures
——— according to ratio $S_{27}(8cm)/S_{27}(10.7\ cm)$ used as found in Fig. 11.

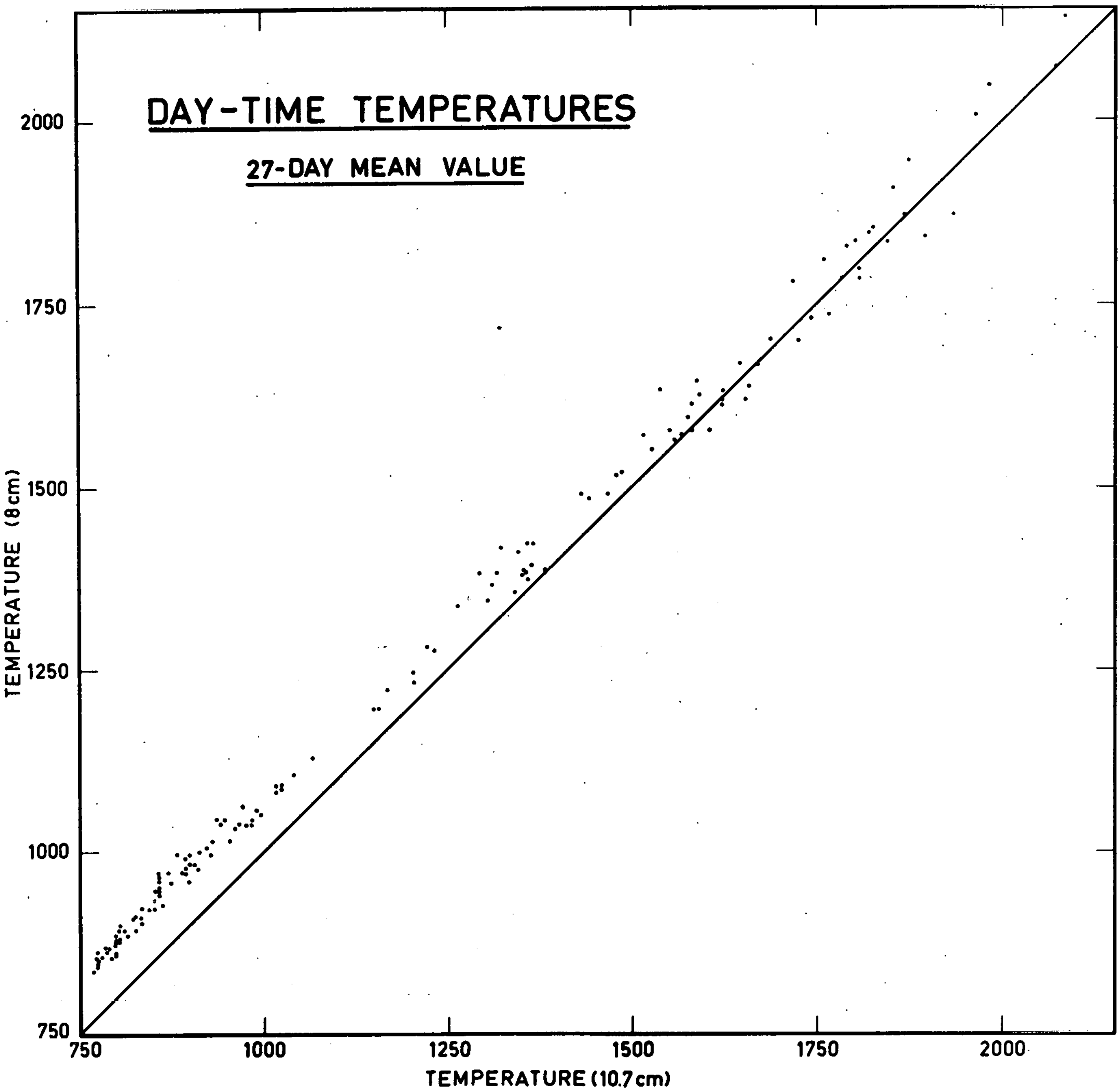


Fig. 15.- Differences in the determination of the thermopause temperatures according to ratio S_{27}(8 cm)/S_{27}(10.7 cm) used as found in Fig. 11.

fluxes. These must be interpreted as fluctuations representing possible errors when use is made of a solar radioindex which is measured with very great precision.

The possible error of about $\pm$ 0.25 S was not included in the following Table II, which gives, for various temperatures of the thermopause, the corresponding night-time and day-time radiofluxes. These fluxes correspond to 27-day mean values at 8 cm and 10.7 cm. Table III gives all 27-day means of the temperature values from 1952 to 1962, including the minimum-to-maximum values for each period. They are based on the linear relationships deduced in the preceding paragraph by using the 8 cm radioflux. Figs 16 and 17 yield a clear representation of the average temperatures at the thermopause level for a 27-day period. The vertical lines indicate the extreme minimum and maximum temperatures which have been reached during each period. The minimum temperatures are 650°K and 850°K for day and night-time temperatures ; respectively. The highest 27-day mean value for night-time conditions was reached in 1957 and is of the order of 1600°K. The maximum night-time value, of the order of 1800°K was, however, attained during that period. The highest 27-day mean value for day-time conditions is of the order of 2150°K while the maximum day-time value reached 2400°K.

On conclusion, it should be noted that the effect of magnetic storms has not been introduced and should be incorporated in the determinations of temperature by using Jacchia's formula along with Ap indices.

TABLE II.- Thermopause temperatures and solar radiofluxes (*)

Temperature (°K)	NIGHT-TIME $\bar{S}_{27}$(8 cm)	NIGHT-TIME $\bar{S}_{27}$(10.7 cm)	DAY-TIME $\bar{S}_{27}$(8 cm)	DAY-TIME $\bar{S}_{27}$(10.7 cm)
650	80	68		
700	91	80		
750	102	93		
800	113	105		
850	124	118	79	68
900	135	130	87	76
950	146	143	95	85
1000	157	155	104	94
1050	167	168	112	104
1100	178	180	120	113
1150	189	193	128	122
1200	200	205	136	132
1250	211	217	145	141
1300	222	228	153	151
1350	233	239	161	160
1400	244	250	169	169
1450	255	261	177	178
1500	265	272	186	188
1550	276	282	194	197
1600	287	293	202	206
1650	298	304	210	215
1700	309	315	218	223
1750			227	232
1800			235	240
1850			243	248
1900			251	257

(*) Solar radiofluxes given with precision of $\pm$ 0.25 S corresponding to differences in observational data.

TABLE II.- Thermopause temperatures and solar radiofluxes (*) (Continued)

Temperature (°K)	NIGHT-TIME $\bar{S}_{27}$(8 cm)	$\bar{S}_{27}$(10.7 cm)	DAY-TIME $\bar{S}_{27}$(8 cm)	$\bar{S}_{27}$(10.7 cm)
1950			259	265
2000			268	273
2050			276	282
2100			284	290
2150			292	298
2200			300	306

(*) Solar radiofluxes given with precision of ± 0.25 S corresponding to differences in observational data.

TABLE III.- Day-time and night-time temperatures at the thermopause.

Rotation	Date (± 13 days)			Day-time Max.	Day-time Average	Day-time Min.	Night-time Max.	Night-time Average	Night-time Min.
1623	1952	January	17	1092	1045	1013	821	786	762
1624		February	13	1043	990	951	784	744	715
1625		March	11	942	910	895	708	684	673
1626		April	7	978	966	924	735	726	695
1627		May	4	986	947	920	741	712	692
1628		May	31	964	923	903	725	694	679
1629		June	27	1055	1001	948	793	753	713
1630		July	24	1065	996	947	801	749	712
1631		August	20	1109	1045	1013	834	786	762
1632		September	16	1003	947	920	754	712	692
1633		October	13	1003	959	935	754	721	703
1634		November	9	1032	971	932	776	730	701
1635		December	7	1045	996	940	786	749	707
1636	1953	January	2	1015	971	922	763	730	693
1637		January	29	966	910	895	726	684	673
1638		February	25	879	867	852	661	652	641
1639		March	24	914	879	859	687	661	646
1640		April	21	996	923	879	749	694	661
1641		May	17	904	860	846	680	647	636
1642		June	13	887	872	863	667	656	649
1643		July	10	875	855	843	658	643	634
1644		August	6	946	892	863	711	671	649
1645		September	2	899	872	858	676	656	645
1646		September	29	916	899	887	689	676	667
1647		October	26	903	879	874	679	661	657
1648		November	22	872	867	855	656	652	643
1649		December	19	872	867	862	656	652	648
1650	1954	January	15	864	862	850	650	648	639
1651		February	11	860	855	855	647	643	643

TABLE III.- Day-time and night-time temperatures at the thermopause. (continued)

Rotation	Date (± 13 days)			Day-time Max.	Day-time Average	Day-time Min.	Night-time Max.	Night-time Average	Night-time Min.
1652	1954	March	10	918	879	867	690	661	652
1653		April	6	860	855	850	647	643	639
1654		May	3	851	848	846	640	638	636
1655		May	30	848	843	838	638	634	630
1656		June	26	839	836	834	631	629	627
1657		July	23	858	848	846	645	638	636
1658		August	19	874	862	852	657	648	641
1659		September	15	867	862	859	652	648	646
1660		October	12	902	892	883	678	671	664
1661		November	8	910	886	871	684	666	655
1662		December	5	910	886	874	684	666	657
1663	1955	January	1	1003	947	912	754	712	686
1664		January	28	964	935	908	725	703	683
1665		February	24	922	910	900	693	684	677
1666		March	23	888	886	883	668	666	664
1667		April	19	907	892	883	682	671	664
1668		May	16	963	928	904	724	698	680
1669		June	12	1057	984	946	795	740	711
1670		July	9	986	959	932	741	721	701
1671		August	5	1067	984	926	802	740	696
1672		September	1	1043	996	940	784	749	707
1673		September	28	1071	1015	976	805	763	734
1674		October	25	1200	1106	1031	902	832	775
1675		November	21	1228	1198	1174	923	901	883
1676		December	18	1253	1198	1158	942	901	861
1677	1956	January	14	1415	1283	1190	1064	965	895
1678		February	10	1734	1418	1237	1304	1066	930
1679		March	8	1487	1382	1329	1118	1039	999
1680		April	4	1470	1387	1297	1105	1043	975

TABLE III.- Day-time and night-time temperatures at the thermopause. (continued)

Rotation	Date (± 13 days)			Day-time Max.	Day-time Average	Day-time Min.	Night-time Max.	Night-time Average	Night-time Min.
1681	1956	May	1	1486	1412	1305	1117	1062	981
1682		May	28	1455	1382	1309	1094	1039	984
1683		June	24	1462	1368	1298	1099	1029	976
1684		July	21	1483	1424	1351	1115	1071	1016
1685		August	17	1722	1632	1541	1295	1227	1159
1686		September	13	1807	1644	1553	1359	1236	1168
1687		October	10	1673	1571	1483	1258	1181	1115
1688		November	6	2071	1871	1705	1557	1407	1282
1689		December	3	1885	1785	1670	1417	1342	1256
1690		December	30	2068	1907	1766	1555	1434	1328
1691	1957	January	26	1782	1626	1541	1340	1223	1159
1692		February	22	1523	1491	1452	1145	1121	1092
1693		March	21	1595	1571	1544	1199	1181	1161
1694		April	17	1641	1565	1487	1234	1177	1118
1695		May	14	1721	1613	1511	1294	1213	1136
1696		June	10	1975	1785	1626	1485	1342	1223
1697		July	7	2040	1780	1607	1534	1338	1208
1698		August	3	1760	1596	1506	1323	1200	1132
1699		August	30	1971	1810	1649	1482	1361	1240
1700		September	26	2212	2048	1931	1663	1540	1452
1701		October	23	2269	2140	1996	1706	1609	1501
1702		November	19	1938	1841	1770	1457	1384	1331
1703		December	16	2391	2072	1835	1798	1558	1380
1704	1958	January	12	2027	1871	1701	1524	1407	1279
1705		February	8	1772	1620	1515	1332	1218	1139
1706		March	7	1818	1700	1563	1368	1278	1175
1707		April	3	2264	2006	1730	1702	1508	1301
1708		April	30	1904	1797	1685	1432	1351	1267

TABLE III.- Day-time and night-time temperatures at the thermopause. (continued)

Rotation	Date (± 13 days)			Day-time Max.	Day-time Average	Day-time Min.	Night-time Max.	Night-time Average	Night-time Min.
1709	1958	May	27	1749	1620	1549	1315	1218	1165
1710		June	23	1721	1638	1541	1294	1232	1159
1711		July	20	1887	1700	1583	1419	1278	1190
1712		August	16	1835	1736	1680	1380	1305	1263
1713		September	12	1948	1834	1744	1465	1379	1311
1714		October	9	1920	1730	1596	1444	1301	1200
1715		November	5	1709	1577	1472	1285	1186	1107
1716		December	2	1938	1853	1660	1457	1393	1248
1717		December	29	1983	1827	1713	1491	1374	1288
1718	1959	January	25	2246	1944	1734	1689	1462	1304
1719		February	21	1698	1613	1531	1277	1213	1151
1720		March	20	1998	1834	1661	1502	1379	1249
1721		April	16	1636	1577	1519	1230	1186	1142
1722		May	13	1874	1669	1576	1409	1255	1185
1723		June	9	1722	1632	1530	1295	1227	1150
1724		July	6	1869	1669	1532	1405	1255	1152
1725		August	2	1692	1577	1495	1272	1186	1124
1726		August	29	2077	1846	1700	1562	1388	1278
1727		September	25	1480	1387	1326	1113	1043	997
1728		October	22	1452	1394	1350	1092	1048	1015
1729		November	18	1685	1522	1410	1267	1144	1060
1730		December	15	1623	1491	1423	1220	1121	1070
1731	1960	January	11	1636	1516	1434	1230	1140	1078
1732		February	7	1708	1552	1415	1284	1167	1064
1733		March	5	1252	1234	1208	941	928	908
1734		April	1	1539	1424	1325	1157	1071	996
1735		April	28	1418	1357	1301	1066	1020	978
1736		May	25	1443	1382	1350	1085	1039	1015

TABLE III.- Day-time and night-time temperatures at the thermopause. (continued)

Rota-tion	Date (± 13 days)			Day-time Max.	Day-time Average	Day-time Min.	Night-time Max.	Night-time Average	Night-time Min.
1737	1960	June	21	1531	1375	1275	1151	1034	959
1738		July	18	1526	1345	1283	1147	1011	965
1739		August	14	1664	1486	1322	1251	1117	994
1740		September	11	1472	1382	1282	1107	1039	964
1741		October	7	1338	1277	1194	1006	960	898
1742		November	3	1514	1338	1245	1138	1006	936
1743		November	30	1339	1246	1168	1007	937	878
1744		December	27	1357	1222	1137	1020	919	855
1745	1961	January	23	1141	1088	1049	858	818	789
1746		February	19	1073	1039	1021	807	781	768
1747		March	18	1112	1051	1019	836	790	766
1748		April	14	1106	1045	1011	832	786	760
1749		May	11	1097	1039	1000	825	781	752
1750		June	7	1150	1057	1008	865	795	758
1751		July	4	1204	1130	1072	905	850	806
1752		July	31	1140	1081	1020	857	813	767
1753		August	27	1125	1093	1052	846	822	791
1754		September	23	1178	1093	1047	886	822	787
1755		October	20	1056	1015	983	794	763	739
1756		November	16	1025	984	958	771	740	720
1757		December	13	1055	1008	967	793	758	727
1758	1962	January	9	1048	978	946	788	735	711
1759		February	5	1094	1039	990	823	781	744
1760		March	4	1177	1063	990	885	799	744
1761		March	31	1129	1039	978	849	781	735
1762		April	27	1085	1039	990	816	781	744
1763		May	24	1076	1032	991	809	776	745
1764		June	20	998	978	966	750	735	726

TABLE III.- Day-time and night-time temperatures at the thermopause. (continued)

Rotation	Date (± 13 days)			Day-time Max.	Day-time Average	Day-time Min.	Night-time Max.	Night-time Average	Night-time Min.
1765	1962	July	17	943	923	899	709	694	676
1766		August	13	939	904	887	706	680	667
1767		September	9	1015	971	924	763	730	695
1768		October	6	1000	971	954	752	730	717
1769		November	2	986	959	942	741	721	708
1770		November	29	984	940	926	740	707	696

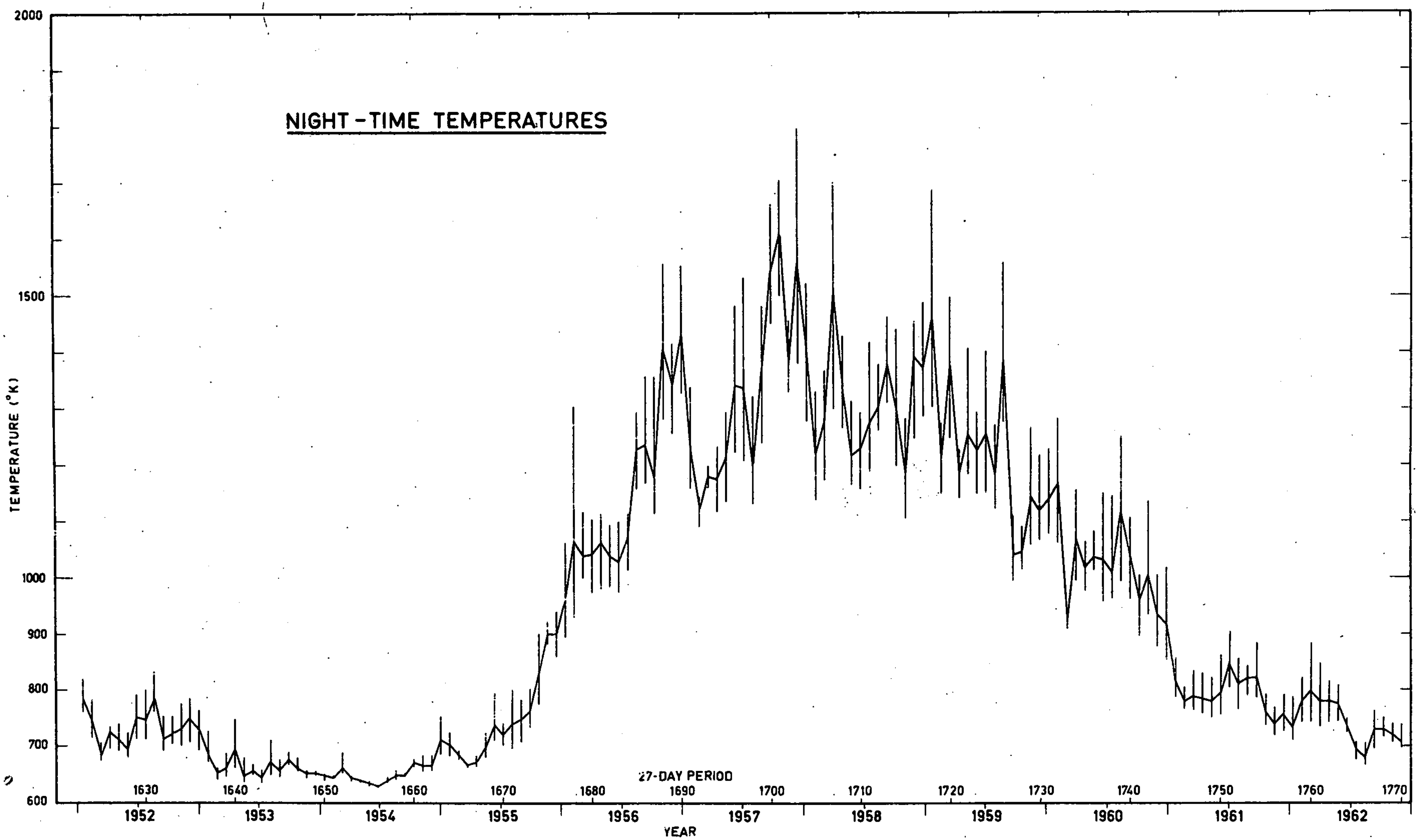


Fig. 16.- Average night-time temperatures at the thermopause with minimum-to-maximum values during a 27-day period.

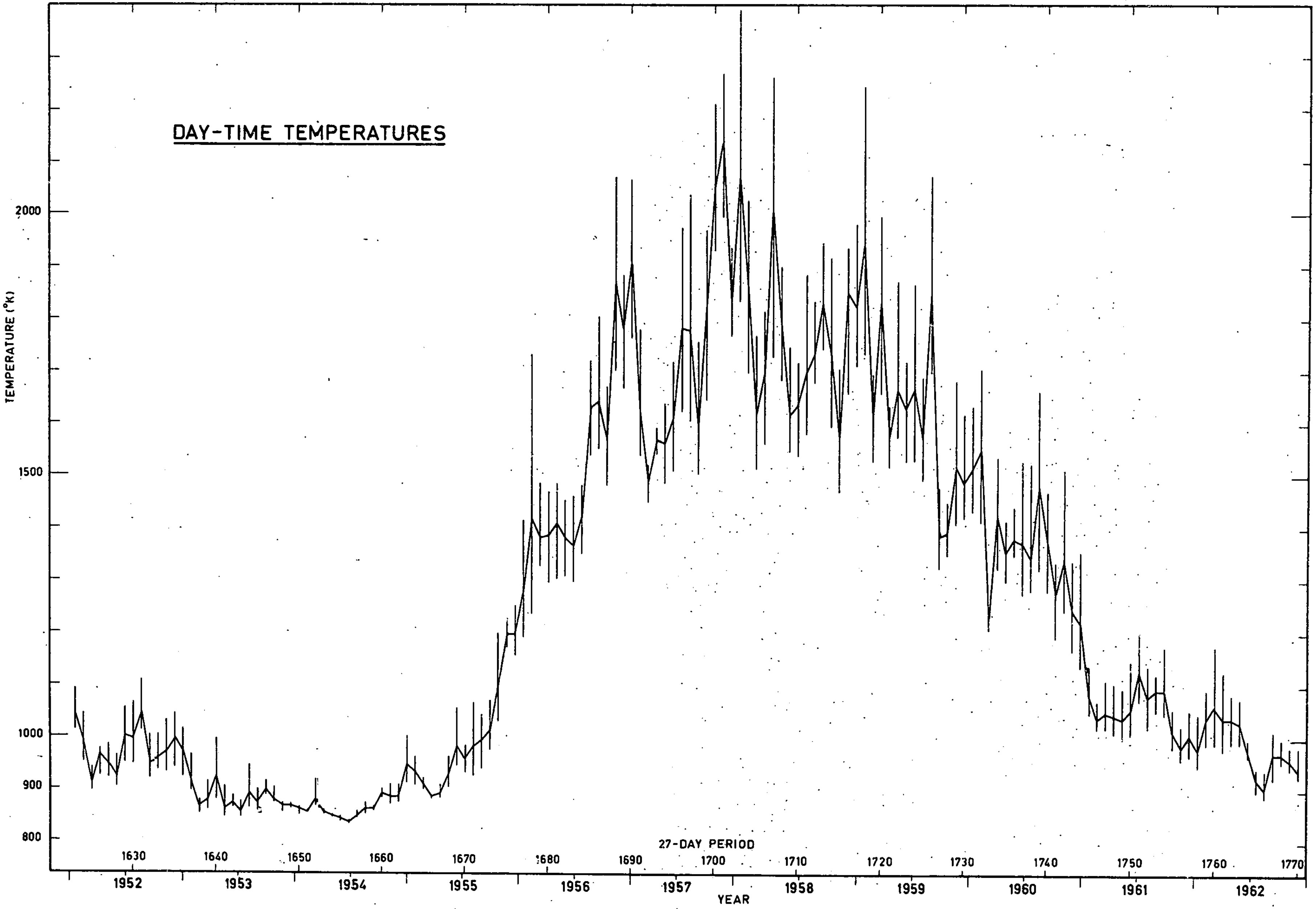


Fig. 17.- Average daytime temperatures at the thermopause with minimum-to-maximum values during a 27-day period.

REFERENCES

[1] M. Nicolet, Les variations de la densité et du transport de chaleur par conduction dans l'atmosphère supérieure, Proc. First Int. Space Science Symp., North-Holland Pub. Cy, Amsterdam p. 46 (1960)

[2] M. Nicolet, Structure of the thermosphere, Planetary and Space Science, 5, 1(1961)

[3] A.E. Covington, Solar noise observations on 10.7 centimeters, Proc. IRE, 36, 454 (1958)

[4] W.J. Medd and A.E. Covington, Discussion of 10.7 cm solar radio flux measurements and an estimation of the accuracy of the observations, Proc. IRE, 46, 112 (1958)

[5] A.E. Covington, Internal precision of the daily radio flux observations at 10.7 cm, J. Roy. Astr. Soc., Canada, 53, 156 (1959)

[6] A.E. Covington, and W.J. Medd, Variations of the daily level of the 10.7 centimetre solar emission, J. Roy. Astr. Soc., Canada, 48, 136 (1954)

[7] H. Tanaka and T. Kakinuma, Observations of solar radio noise at 3750 Mc., Proc. Res. Inst. Atm. Nagoya Univ., 1, 103 (1953)

[8] H. Tanaka, Some notes on the solar radio emission at centimetre region around the period of sunspot minimum, Proc. Res. Inst. Atm. Nagoya Univ., 3, 117 (1955).

[9] H. Tanaka and T. Kakinuma, Equipment for the observation of solar radio emission at 9400, 3750, 2000 and 1000 Mc/s. Proc. Res. Inst. Atm. Nagoya Univ., 4, 60 (1956)

[10] H. Tanaka and T. Kakinuma, Observations of solar radio emission at microwave frequencies, Proc. Res. Inst. Atm. Nagoya Univ., 5, 81 (1958)

[11] M.R. Kundu, Solar radio emission on centimeter waves and ionization of the E layer of the ionosphere, J. Geophys. Res., 65, 3903 (1960)

[12] H. Friedman, Solar radiation, Astronautics, 7, n° 8, 14 (1962)

[13] C.W. Allen, The variation of decimetre-wave radiation with solar activity, Monthly Notices R.A.S., 117, 174 (1957)

[14] A.E. Covington and G.A. Harvey, The visibility of the 10-cm radio emissive region and its application in finding the 10 cm quiet sun, Astrophys. J., 132, 435 (1960)

[15] M.K. Das Gupta and D. Basu, Slowly varying component of solar radio emission, Nature, 197, 442 (1962)

[16] A.E. Covington, Solar emission at ten centimetre wave-length, J. Roy. Astronom. Soc. Canada, 55, 167 (1961)

[17] L.G. Jacchia, A working model for the upper atmosphere, Nature, 192, 1147 (1961)

[18] M. Nicolet, Density of the heterosphere related to temperature, Smithsonian Astrophys. Obs. Special Report, n° 75 (1961)

[19] I. Harris and W. Priester, Heating of the upper atmosphere, Proc. Third Int. Space Science Symp., North-Holland Pub. Cy, Amsterdam, p. 53 (1963)

[20] H.K. Paetzold, Solar activity in the upper atmosphere deduced from satellite observations, Proc. Third Int. Space Science Symp., North-Holland Pub. Cy, Amsterdam, p. 28 (1963)

[21] L.G. Jacchia, Electromagnetic and Corpuscular heating of the upper atmosphere, Proc. Third Int. Space Science Symp., North-Holland Pub. Cy, Amsterdam, p. 3 (1963)

[22] L.G. Jacchia and J. Slowley, Accurate drag determinations for eight artificial satellites, Smithsonian Astrophys. Obs., Spec. Rep. 100 (1962)