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AN AUTOMATED MODEL FOR PREDICTING THE KINETIC TEMPERATURE OF THE AEROSPACE ENVIRONMENT FROM 100 TO 60,000 KILOMETERS ABOVE THE SURFACE OF THE EARTH

by ROBERT E. SMITH
Aero-Astrodynamics Laboratory

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George C. Marshall Space Flight Center, Huntsville, Alabama

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ABSTRACT

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This paper describes the derivation of a series of equations capable of predicting the kinetic temperature of the aerospace environment from 100 to 60,000 kilometers above the surface of the earth. The equations, which are programmed on a GE 225 computer, can be used to predict temperature-height profiles for any time through December 1992.

Author

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AERO-ASTROPHYSICS OFFICE
SPACE ENVIRONMENT GROUP
AERO-ASTRODYNAMICS LABORATORY
RESEARCH AND DEVELOPMENT OPERATIONS

DEFINITION OF SYMBOLS

Symbol	Definition
a_p	geomagnetic activity index
FT	correction factor for diurnal heating effect
FT1	correction factor for variability of daily mean value of solar flux
FT2	correction factor for variability of the monthly mean value of solar flux
FZ	altitude variation of thermosphere lapse rate
FZ1	altitude variation of correction factor for the diurnal heating effect
S_D	daily mean value of 10.7 centimeter solar radio noise flux (x 10^{-22}watts per meter^2 per cycle per second)
S_F	monthly mean value of 10.7 centimeter solar radio noise flux (x 10^{-22} watts per meter^2 per cycle per second)
S_Y	yearly mean value of 10.7 centimeter solar radio noise flux (x 10^{-22} watts per meter^2 per cycle per second)
SS	annual mean sunspot number
t_L	Local Standard Time in hours and tenths
Z	altitude in kilometers
Z_T	altitude of thermopause in kilometers

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AN AUTOMATED MODEL FOR PREDICTING THE KINETIC TEMPERATURE OF THE AEROSPACE ENVIRONMENT FROM 100 TO 60,000 KILOMETERS ABOVE THE SURFACE OF THE EARTH

SUMMARY

A set of analytical expressions for predicting a time, solar flux, and geomagnetic activity dependent kinetic temperature-height profile of the upper atmosphere above the earth's surface is derived from the data presented by L. G. Jacchia in Smithsonian Institution Astrophysical Observatory Research in Space Science Special Report No. 150, dated 22 April 1964 [1]. Although the data sample is far from adequate and the concept of kinetic temperature in this altitude range is very nebulous, the data that can be provided by this automated predictive model is required to insure the orderly refinement of space vehicle design criteria. Values of kinetic temperature predicted by this model are compared in Figure 1 with the 1959 ARDC Standard and the 1962 U. S. Standard Atmosphere.

I. INTRODUCTION

In a previous paper [2], a model for predicting density-height profiles in the aerospace environment from 200 to 60,000 kilometers above the earth's surface was developed through an analysis of current satellite observations. This is the second model of the series whose final model will be one which predicts the vertical distribution of the molecular weight of the aerospace gas and its temporal and spatial variability. An approach similar to the one employed in Reference 2 was used in this development.

II. DISCUSSION

The first step was the fitting of a curve by the least squares method to the data presented by Jacchia in Reference 1 combined with the kinetic temperature at 100 kilometers quoted in the 1963 Patrick Reference Atmosphere [3] assuming an almost isothermal structure above a thermopause whose height varies with solar activity [1]. Equation (1), below, is a general equation for the temperature-height profile above 100 kilometers above the earth's surface at 0400 Local Standard Time (LST) when the 10.7 centimeter solar radio noise flux is 67 x 10^{-22} watts per meter^2 per cycle per second and the geomagnetic activity index, a_p, is zero.

$$T_{(04,67,67,Z)} = (Z - 100)/(0.002022168Z - 0.19844) + 210.00. \tag{1}$$

Equation 2 will predict the height of the thermopause based on the monthly mean value of the 10.7 cm solar radio noise flux assuming a linear variation between Jacchia's heights of 220 kilometers at 70 x 10^{-22} w/m^2-c-s and 400 kilometers at 220 x 10^{-22} w/m^2-c-s [1].

$$Z_T = (6/5)\ S_F + 135. \tag{2}$$

Equation (3), below, which will predict a kinetic temperature envelope at any altitude, Z, at any time of the day, t_L, for any solar radio noise flux, S_D and S_F, and any geomagnetic activity condition, a_p, incorporates all the corrective factors derived by Jacchia [1].

$$T_{(t_L,S_D,S_F,Z,a_p)} = \left[T_{(04,67,67,Z)} + (3.1 \pm 1.9)\ a_p\right]\left[1 + FT(FZ1)\right]$$

$$+ FZ\left[FT1\ (S_D - 67) + FT2\ (S_F - 67)\right]. \tag{3}$$

The variability of the coefficient of a_p is due to the latitude dependence of the geomagnetic activity effect. The lower value, 1.2, should be used in mid-latitude regions, 30° - 40°, while the higher value, 5.0, should be used in the auroral zones, 70° - 80°. If the a_p values are unknown, then zero should be used in the equation and the resulting temperature will be the temperature predicted for a geomagnetically quiet day [4].

In Equation (3), FT is a factor which will adjust the basic temperature-height profile for the diurnal heating effect. The equation for this factor which varies from a minimum of 0.0 at 0400 LST to a maximum of 0.3 at 1400 LST is

$$FT = \sum_{i=0}^{6} a_i \cos i\theta + b_i \sin i\theta \tag{4}$$

where

$a_o = 0.1505$

$a_1 = 0.14347377$ $\qquad b_1 = 0.3674753 \times 10^{-1}$

$a_2 = 0.8 \times 10^{-2}$ $\qquad b_2 = -0.11835672 \times 10^{-1}$

$a_3 = -0.11666666 \times 10^{-2}$ $\qquad b_3 = -0.21666666 \times 10^{-2}$

$a_4 = 0.15 \times 10^{-2}$ $\qquad b_4 = -0.13333333 \times 10^{-2}$

$a_5 = -0.23071033 \times 10^{-2}$ $\qquad b_5 = 0.858005 \times 10^{-4}$

$a_6 = 0.000.$

In equation (3), FZ1 is the factor which makes the diurnal heating effect altitude dependent so that the diurnal variation increases from zero at 100 kilometers to 1.3 at and above 120 kilometers.

$$FZ1 = (0.38 - 0.00275Z)\ (Z - 100.0) \tag{5}$$

for $100 \leqq Z = 120$ kilometers and FZ1 = FZ1 evaluated at 120 kilometers for $Z > 120$ kilometers.

In equation (3), FZ is a factor which makes the temperature lapse rate in the thermosphere altitude as well as solar activity dependent. The equation for this factor, which varies from 0.00 at 100 kilometers to approximately 0.85 at a 400 kilometer thermopause, is

$$FZ = (Z - 100.0)/(1.1096938Z - 92.828785) \tag{6}$$

for $Z \leqq Z_T$ and FZ = FZ evaluated at Z_T for $Z > Z_T$.

FT1, a factor which adjusts the predicted temperature for the daily variation, S_D, in the mean solar radio noise flux, varies from a minimum value of 1.9 at 0400 LST to a maximum value of 2.4 at 1400 LST. If the daily mean value of the 10.7 cm solar flux is unknown, then the value for S_F should be used.

$$FT1 = \sum_{i=0}^{6} c_i \cos i\theta + d_i \sin i\theta \tag{7}$$

where

$c_o = 2.15083333$

$c_1 = 0.23646679$ $\qquad d_1 = 0.58034166 \times 10^{-1}$

$c_2 = 0.14166666 \times 10^{-1}$ $\qquad d_2 = -0.24537375 \times 10^{-1}$

$c_3 = 0.16666666 \times 10^{-2}$ $\qquad d_3 = -0.16666666 \times 10^{-2}$

$c_4 = -0.83333333 \times 10^{-3}$ $\qquad d_4 = -0.16666666 \times 10^{-2}$

$c_5 = -0.31334583 \times 10^{-2}$ $\qquad d_5 = 0.29916666 \times 10^{-3}$

$c = 0.83333333 \times 10^{-3}$.

In Equation (3) FT2 is the factor which adjusts the predicted temperature for the variation in the monthly mean solar radio noise flux. The magnitude of this factor varies from a minimum of 4.5 at 0400 LST to a maximum of 6.0 at 1400 LST.

$$FT2 = \sum_{i=0}^{6} e_i \cos i\theta + f_i \sin i\theta \tag{8}$$

where

$e_0 = 5.26416666$

$e_1 = 0.70135016$ $\qquad$ $f_1 = 0.16649887$

$e_2 = 0.50833333 \times 10^{-1}$ $\qquad$ $f_2 = -0.11833333$

$e_3 = -0.83333333 \times 10^{-2}$ $\qquad$ $f_3 = 0.00000000$

$e_4 = -0.91666666 \times 10^{-2}$ $\qquad$ $f_4 = -0.14433705 \times 10^{-2}$

$e_5 = -0.30168333 \times 10^{-2}$ $\qquad$ $f_5 = 0.13501121 \times 10^{-1}$

$e_6 = 0.41666666^{-2}$.

In equations (4), (7), and (8), $\theta = (t_L - 14.00)\pi/12$ where t_L = Local Standard Time in hours and tenths on a twenty-four hour clock.

The following set of equations was extracted from Reference 2. They will provide the solar activity predictions for use as input data. Equation (9) is used to convert either the known or predicted mean annual sunspot number, SS, to the mean annual value of 10.7 cm solar radio noise flux, S_Y. Equations (10a) and (10b) then convert this mean annual value to the mean monthly value, S_M, that would be predicted if the earth's orbit about the sun were circular. Equation (11) corrects this monthly mean value for the eccentricity of the earth's orbit according to the data presented by Das Gupta [5]. These equations, when combined with a subjective prediction of the annual mean sunspot number from Figure 2, will provide all the data required to compute the predicted temperature-height profile envelopes.

$$S_Y = \sum_{j=0}^{8} g_j \, SS^j \tag{9}$$

where

$g_o = 67.80036$

$g_1 = 0.414498444$

$g_2 = 0.427501471 \times 10^{-2}$

$g_3 = -0.469543503 \times 10^{-4}$

$g_4 = 0.660862973 \times 10^{-6}$

$g_5 = -0.261604186 \times 10^{-8}$

$g_6 = -0.159036136 \times 10^{-10}$

$g_7 = 0.140461971 \times 10^{-12}$

$g_8 = -0.274461310 \times 10^{-15}$

$$S_M = S_Y + \frac{M - 6}{12} (S_{Y+1} - S_Y) \quad \text{when } M \geq 6 \tag{10a}$$

$$S_M = S_Y - \frac{6 - M}{12} (S_Y - S_{Y-1}) \quad \text{when } M < 6 \tag{10b}$$

$$S_F = S_M \sum_{i=0}^{6} h_i \cos i\emptyset + k_i \sin i\emptyset \tag{11}$$

where

$$h_o = 1.00$$

$$h_1 = -0.28737186 \times 10^{-1} \qquad k_1 = -0.13090493 \times 10^{-1}$$

$$h_2 = -0.10333333 \times 10^{-1} \qquad k_2 = -0.12701714 \times 10^{-1}$$

$$h_3 = 0.150 \times 10^{-2} \qquad k_3 = -0.350 \times 10^{-2}$$

$$h_4 = -0.50 \times 10^{-3} \qquad k_4 = -0.20207273 \times 10^{-2}$$

$$h_5 = 0.20601563 \times 10^{-2} \qquad k_5 = -0.24095063 \times 10^{-2}$$

$$h_6 = 0.28333333 \times 10^{-2}$$

and $\emptyset = (M - 6)\ \pi/6$ where M is the month of the year beginning with January = 1, February = 2, etc.

EDP Routine

The following routine is programmed for use on a GE 225 computer. Input data for this program consists of the time of day, t_L, the month of the year, M, the geomagnetic index, a_p, the sunspot number, SS, the daily mean 10.7 cm solar radio noise flux, S_D, and the altitude, Z. The output consists of the time of day, TL, the geomagnetic index, AP, the sunspot number, SS, the month of the year, M, the altitude Z, the computed temperature, T, and the 10.7 cm solar radio noise flux, SF.

```
C       MODEL FOR COMPUTING UPPER ATMOSPHERE TEMPERATURE
C       R.E. SMITH JOB NUMBER 550120
              COMMON SS(30), FM(12), Z(50),SFH(7),SFK(7),G(9),
             1E(7),F(7),C(7),D(7),A(7),B(7),SY(30)
              PI6=.52359878
              A=.1505
              A(2)=.14347377
              A(3)=.8E-2
              A(4)=-.11666666E-2
              A(5)=.15E-2
              A(6)=-.23071033E-2
              A(7)=0.
              B=0.
              B(2)=.3674753E-1
              B(3)=-.11835671E-1
              B(4)=-.21666666E-2
              B(5)=-.13333333E-2
              B(6)=.858005E-4
              B(7)=0.
              C=2.15083333
              C(2)=.23646679
              C(3)=.14166666E-1
              C(4)=.16666666E-2
              C(5)=-.83333333E-3
              C(6)=-.31334583E-2
              C(7)=.83333333E-3
              D=0.
              D(2)=.58034166E-1
              D(3)=-.24537375E-1
              D(4)=-.16666666E-2
              D(5)=-.1666666E-2
              D(6)=.29916666E-3
              D(7)=0.
              E=5.26416666
              E(2)=.70135016
              E(3)=.50833333E-1
              E(4)=-.83333333E-2
              E(5)=-.91666666E-2
              E(6)=-.30168333E-2
              E(7)=.41666666E-2
              F=0.
              F(2)=.16649887
              F(3)=-.11833333
              F(4)=0.
              F(5)=-.14433705E-2
              F(6)=.13501121E-1
              F(7)=0.
              G=67.80036
              G(2)=.419498444
              G(3)=.427501471E-2
              G(4)=-.469543503E-4
              G(5)=.660862973E-6
              G(6)=-.261604186E-8
              G(7)=-.159036136E-10
              G(8)=.140461971E-12
              G(9)=-.27446131E-15
```

```
C       MODEL FOR COMPUTING UPPER ATMOSPHERE TEMPERATURE
                 SFH=1.0
                 SFH(2)=-.28737186E-1
                 SFH(3)=-.10333333E-1
                 SFH(4)=.15E-2
                 SFH(5)=-.5E-3
                 SFH(6)=.20601563E-2
                 SFH(7)=.283333333E-2
                 SFK=0.
                 SFK(2)=-.13090493E-1
                 SFK(3)=-.12701714E-1
                 SFK(4)=-.35E-2
                 SFK(5)=-.20207273E-2
                 SFK(6)=-.24095063E-2
                 SFK(7)=0.
             1   RCD,IOP
                 PRINT 5
             5   FORMAT(1H1)
                 GO TO (15,20),IOP
            15   RCD,NM,NZ,TL,AP,SD,SS(1),(FM(I),I=1,NM),(Z(I),I=1,NZ)
                 NS=1
                 GO TO 30
            20   RCD,NM,NS,TL,AP,SD,Z(1),(FM(I),I=1,NM),(SS(I),I=1,NS)
                 NZ=1
C       SY CALCULATION  *  *  *  *  *  *  *  *  *
            30   DO 35 I=1,NS
                 SY(I)=G
                 DO 32 K=2,9
            32   SY(I)=SY(I)+G(K)*SS(I)**(K-1)
            35   CONTINUE
                 DO 150 IZ=1,NZ
            40   T1=(Z(IZ)-100.)/(2.022168E-3*Z(IZ)-.19844)+210.
                 IF(Z(IZ)-120.)41,41,42
            41   ERR=Z(IZ)
                 GO TO 43
            42   ERR=120.
            43   CONTINUE
                 FZ1=(.38-.00275*ERR)*(ERR-100.)
                 DO 145 IS=1,NS
                 DO 140 IM=1,NM
                 IF(FM(IM)-6.)80,50,50
            50   IF(IS-NS)70,60,60
            60   SM=SY(IS)
                 GO TO 90
C       EQTN 9 A   *  *  *  *  *  *  *  *  *  *  *  *
            70   SM=SY(IS)+(FM(IM)-6.)/12.*(SY(IS+1)-SY(IS))
                 GO TO 90
            80   IF(IS-1)60,60,85
            85   SM=SY(IS)-(6.-FM(IM))/12.*(SY(IS)-SY(IS-1))
            90   PHI=(FM(IM)-6.)*PI6
                 SF=SFH
                 DO 95 I=2,7
                 FI=I-1
                 ANG=FI*PHI
            95   SF=SF+SFH(I)*COSF(ANG)+SFK(I)*SINF(ANG)
                 SF=SM*SF
```

```
C     MODEL FOR COMPUTING UPPER ATMOSPHERE TEMPERATURE
      ZT=6.*SF/5.+135.
      TH=(TL-14.)*PI6/2.
      FT=A
      FT2=E
      FT1=C
      DO 105 I=2,7
      FI=I-1
      ANG=FI*TH
      SANG=SINF(ANG)
      CANG=COSF(ANG)
      FT2=FT2+E(I)*CANG+F(I)*SANG
      FT1=FT1+C(I)*CANG+D(I)*SANG
  105 FT=FT+A(I)*CANG+B(I)*SANG
      IF(Z(IZ)-ZT)110,110,120
  110 FZ=(Z(IZ)-100.)/(1.1096938*Z(IZ)-92.828785)
      GO TO 130
  120 FZ=(ZT-100.)/(1.1096938*ZT-92.828785)
  130 IF(SD-1.0)131,131,132
  131 ERR=SF
      GO TO 134
  132 ERR=SD
  134 T=(1.+FT*FZ1)*(T1+1.2*AP)+FZ*(FT1*(ERR-67.)+
     1FT2*(SF-67.))
      PRINT 136,TL,AP,SS(IS),FM(IM),Z(IZ),
     1T,SF
  136 FORMAT(////2HTLE17.9,2X2HAPE17.9,2X2HSSE17.9,
     12X2HM E17.9//2HZ E17.9,2X2HT E17.9,2X2HSFE17.9)
  140 CONTINUE
  145 CONTINUE
  150 CONTINUE
      GO TO 1
      END
```

III. RESULTS

Figure 3 depicts the diurnal variation of the temperature-height profile on a geomagnetically quiet day in the mid-latitudes when the 10.7 cm solar radio noise flux is 100 x 10^{-22} w/m^2-c-s.

Figure 4 depicts the diurnal variation of the temperature-height profile on a geomagnetically quiet day in the mid-latitudes when the 10.7 cm solar radio noise flux is 250 x 10^{-22}w/m^2-c-s.

Figure 5 depicts the variation with solar activity of the temperature height profile in the mid-latitudes at 0900 LST.

Figure 6 depicts the variation with solar activity of the temperature at mid-latitudes at 0900 LST at constant heights of 200 and 600 kilometers above the earth's surface during the period from July 1964 through December 1992.

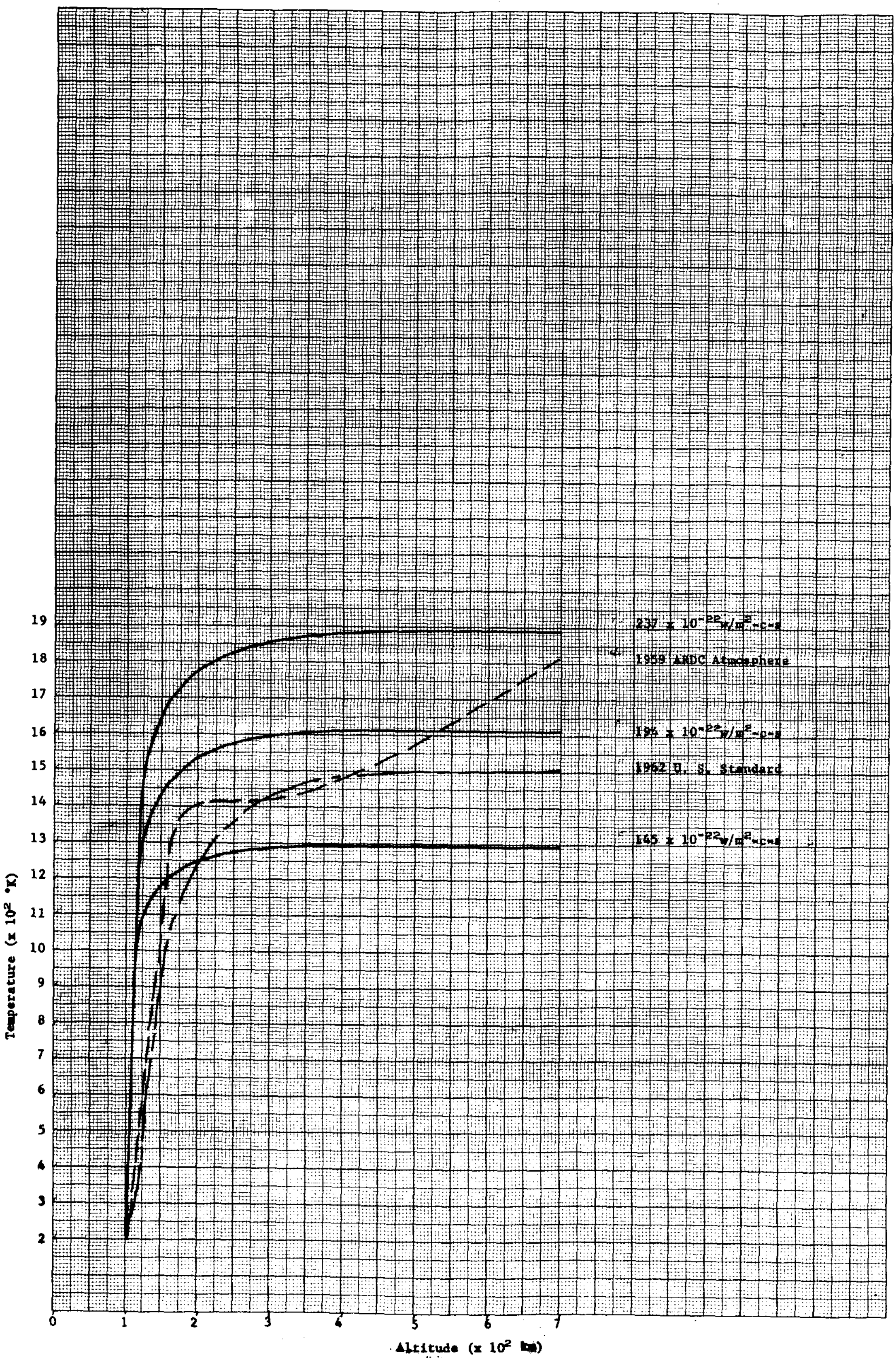

FIGURE 1. COMPARISON OF 1959 ARDC, 1962 U.S. STANDARD AND COMPARABLE TEMPERATURES PREDICTED BY THIS MODEL

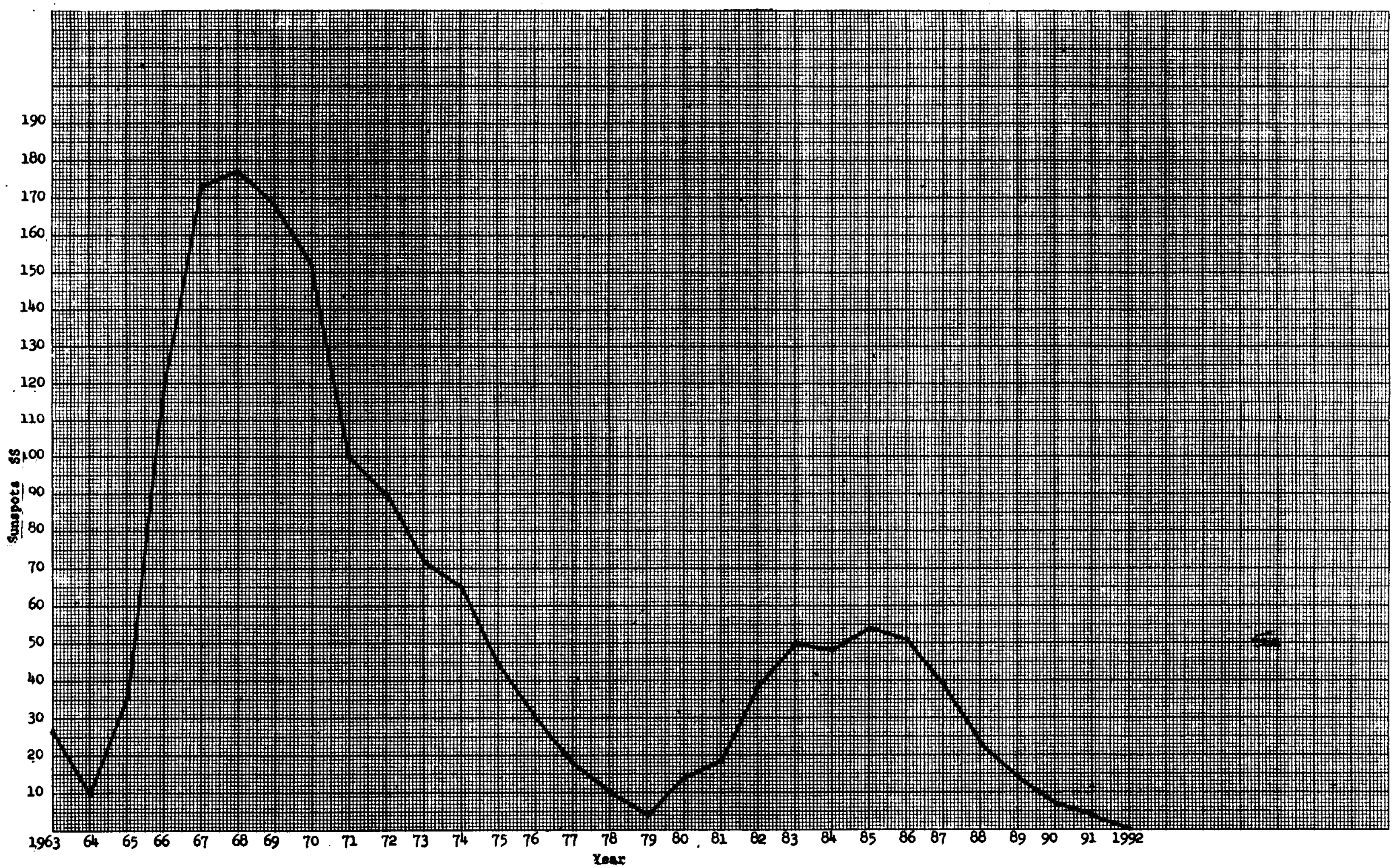

FIGURE 2. PREDICTED MEAN ANNUAL SUNSPOT NUMBER FOR SOLAR CYCLES 20 AND 21

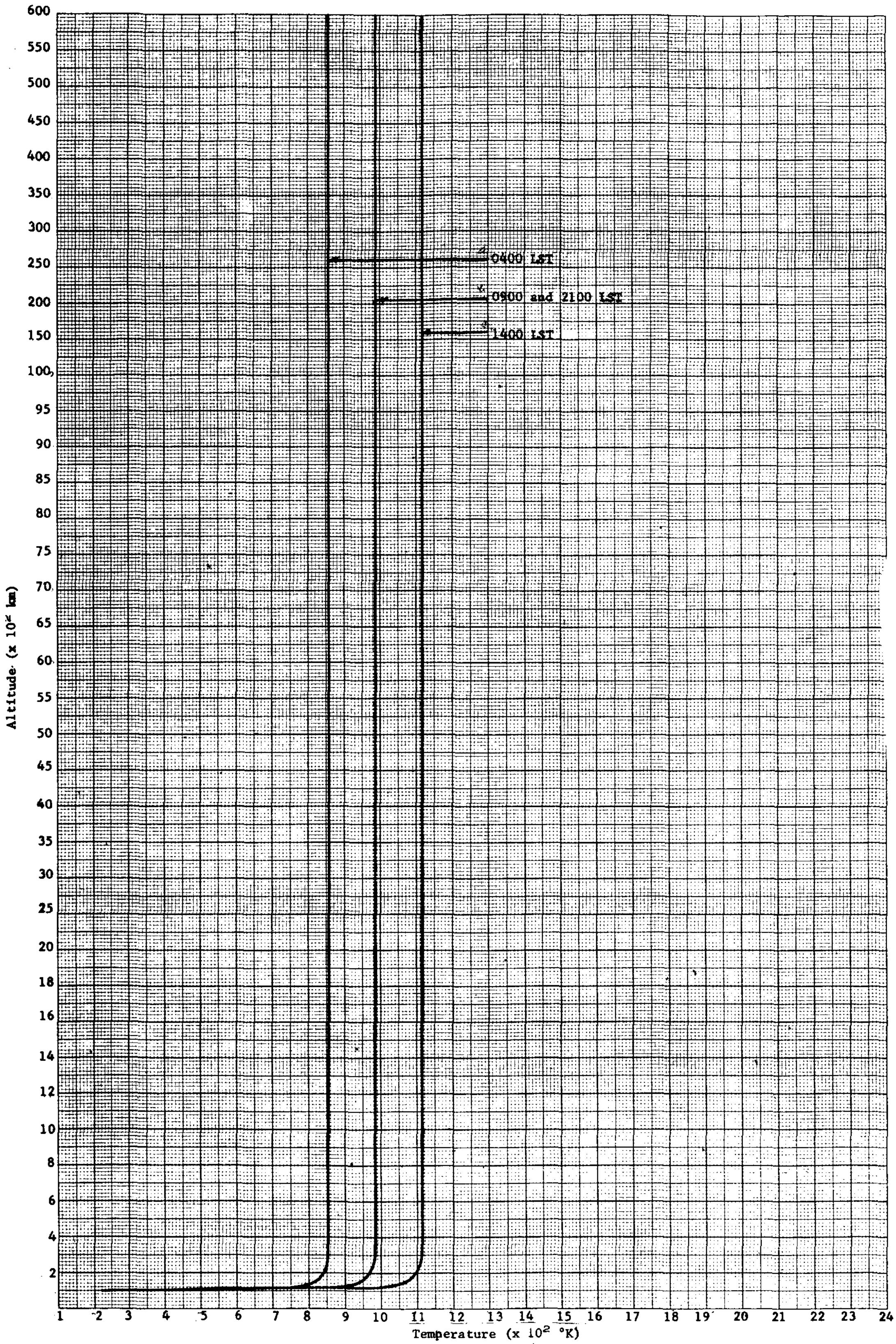

FIGURE 3. DIURNAL VARIATION IN TEMPERATURE-HEIGHT PROFILE AT 96 x 10^{-22} w/m^2-c-s UNITS OF 10.7 CM SOLAR RADIO NOISE FLUX

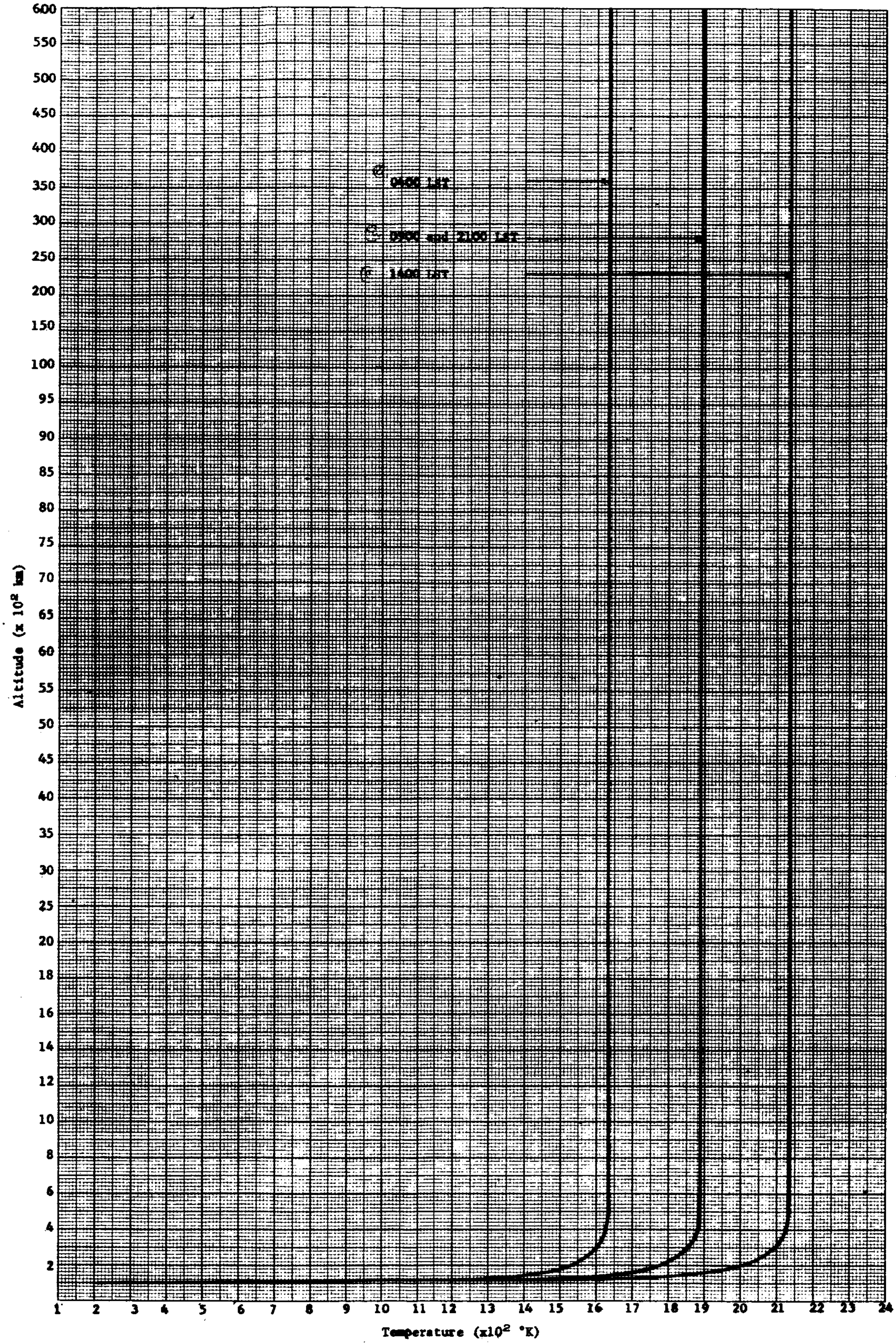

FIGURE 4. DIURNAL VARIATION IN TEMPERATURE-HEIGHT PROFILE AT 237 x 10^{-22} w/m^2-c-s UNITS OF 10.7 CM SOLAR RADIO NOISE FLUX

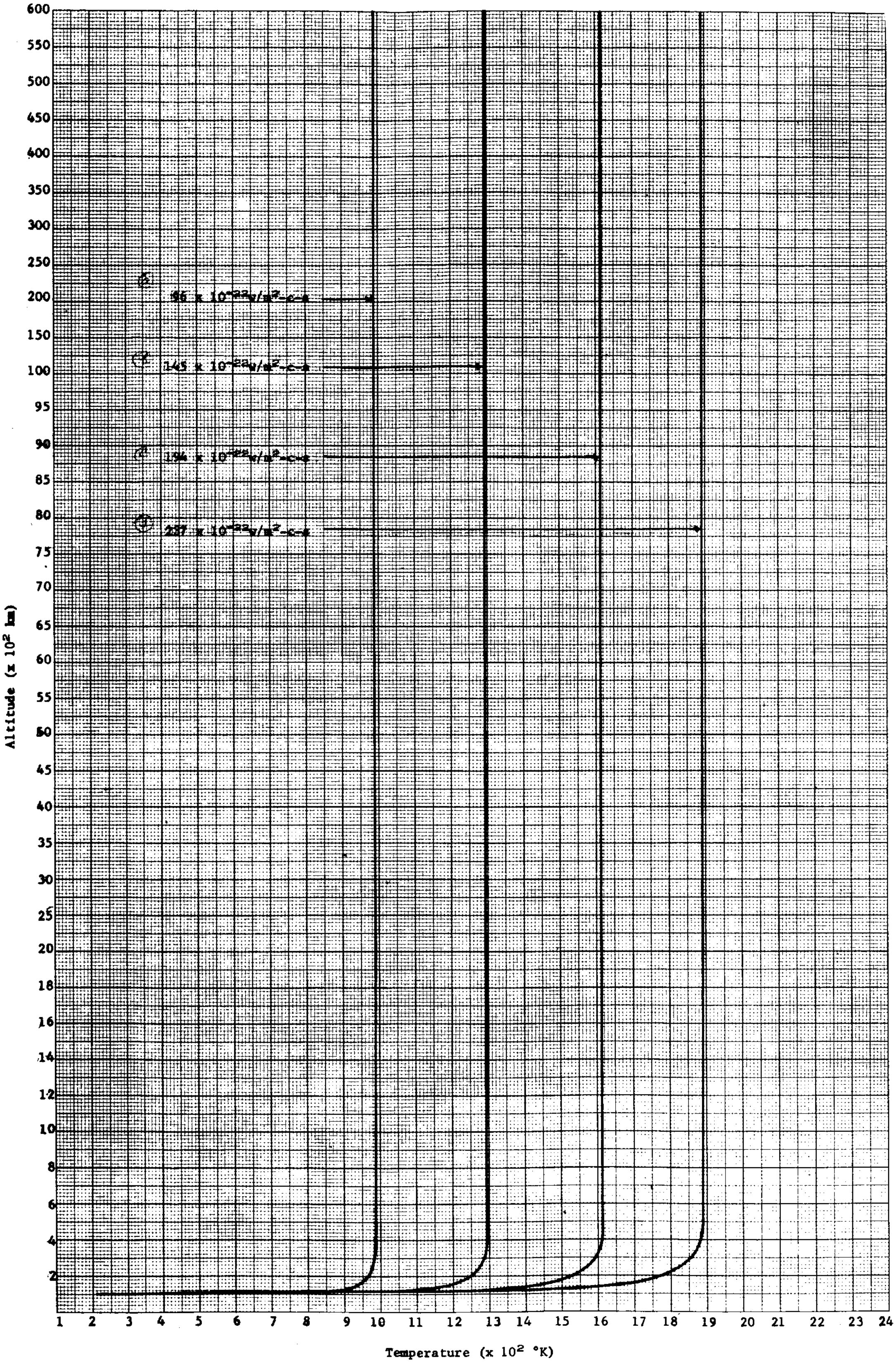

FIGURE 5. VARIATION IN TEMPERATURE-HEIGHT PROFILE AT 0900 LST WITH SOLAR RADIO NOISE FLUX

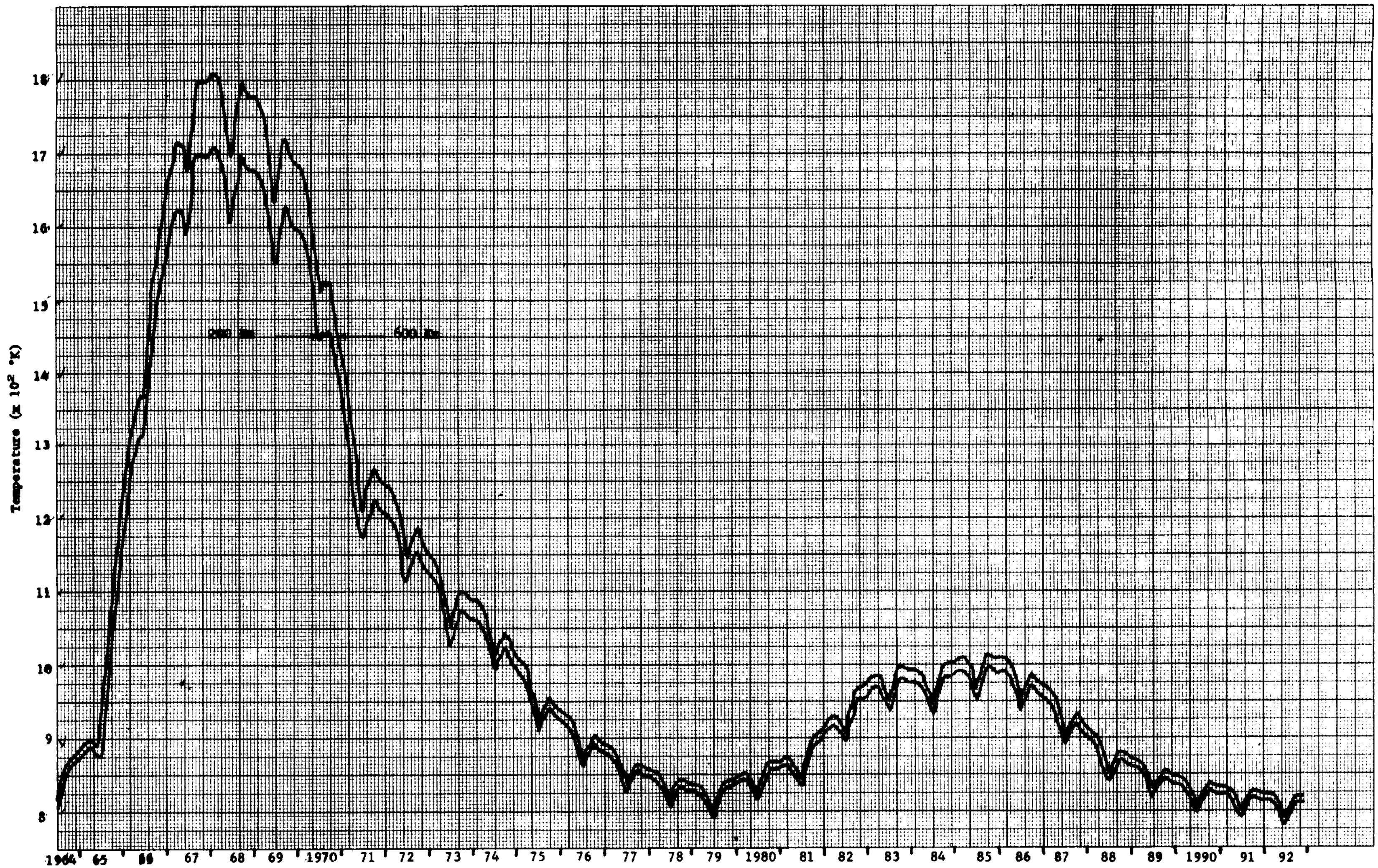

FIGURE 6. VARIATION OF TEMPERATURE AT 200 AND 600 KILOMETERS DURING SOLAR CYCLES 20 AND 21

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The information in this report has been reviewed for security classification. Review of any information concerning Department of Defense or Atomic Energy Commission programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

This document has also been reviewed and approved for technical accuracy.

Wm W. Vaughan

W. W. Vaughan
Chief, Aero-Astrophysics Office

Geissler

E. D. Geissler
Director, Aero-Astrodynamics Laboratory

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