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Theoretical Models for the Solar-Cycle Variation of the Upper Atmosphere

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Abstract. Models of the upper atmosphere for different levels of solar activity have been calculated by solving the heat conduction equation under quasi-hydrostatic conditions by means of the procedure described in detail in a previous paper. In these calculations the fluxes of both heat sources (EUV and corpuscular heat source) are varied in proportion to the long term averages of the 10.7-cm solar fluxes in order to account for different levels of solar activity during the solar cycle. The resulting temperatures of the exosphere can be represented by $T_{min} = 4.5 \cdot S + 275$ (°K) and $T_{max} = 7.1 \cdot S + 372$ (°K) where T_{min} and T_{max} are the diurnal minimum and maximum temperatures respectively, and S is the monthly average of the 10.7-cm solar flux in units of 10^{-22} w/m^2 cps. The slope for T_{min} is in good agreement with that found by L. G. Jacchia from analysis of satellite drag. In this paper the physical properties (temperature, density, scale height, and mean molecular weight) are illustrated as functions of local time and of altitudes between 120 and 2050 km for five different values of S.

From an analysis of the physical behavior of the upper atmosphere we have found that in addition to the heating of the thermosphere by absorption of solar extreme ultraviolet (EUV) radiation another heat source must be present which provides roughly the same amount of heating as the EUV radiation [*Harris and Priester,* 1962]. It is probable that this heat source derives its energy ultimately from the solar corpuscular radiation and/or its 'steady' component, the solar wind.

Conclusive evidence of the existence of this so-called 'corpuscular' heat source has also been obtained from the analysis of the changes in the orbital elements of artificial satellites [*Jacchia,* 1962; *Paetzold,* 1962].

Both heat sources are expected to vary considerably during the solar cycle. In order to obtain information as to how these heat sources vary in comparison with the indices of solar activity, we calculated theoretical models of the physical properties of the upper atmosphere for five different sets of flux values for the EUV heat source and the corpuscular heat source. The models are obtained by solving the time-dependent heat conduction equation under quasi-hydrostatic conditions, as described in detail in our previous paper [*Harris and Priester,* 1962].

In that paper we also gave a description of the four main effects which influence the physical properties of the upper atmosphere. These effects have been discovered during the years since 1958.

In this paper we will understand the term 'solar-cycle variation' as the change of the atmospheric properties during the eleven-year period of the solar cycle after the 27-day variations of the 'solar activity effect' and the semi-annual variations have been averaged out or removed from the observed data by reduction to average levels of solar activity or yearly averages, respectively. The solar-cycle variation of the upper atmosphere, therefore, describes the reaction of the upper atmosphere to the long-term decrease and increase of both heat sources, the EUV heat source and the corpuscular heat source.

Observational evidence indicates that the 27-day variations are caused mostly by fluctuations of the EUV heat source, the flux of which probably parallels the solar decimeter radiation in the 3- to 30-cm wavelength range. This can be seen from the fact that the decrease of the exospheric temperature obtained from the 27-day fluctuations in density for the years 1958

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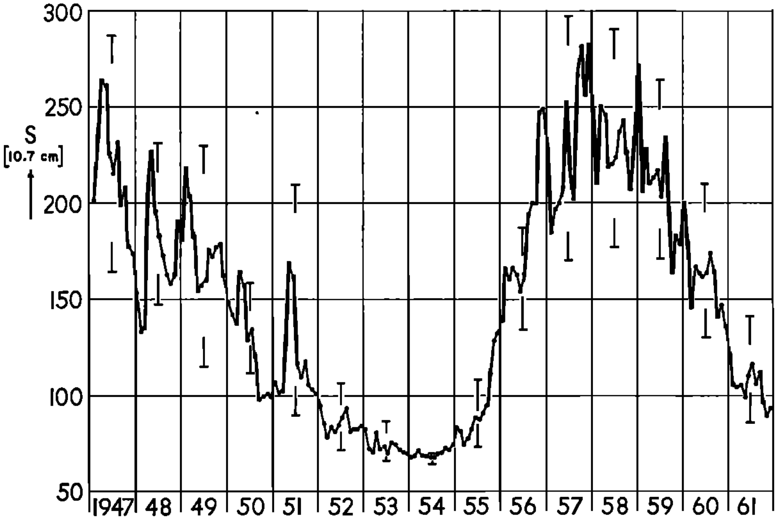

Fig. 1. Variation of the monthly averages of the 10.7-cm solar flux, according to the measurements of the National Research Council of Canada The bars indicate the monthly fluctuations in June and July of each year.

to 1961 has a considerably smaller slope than the slope obtained from the decrease of the yearly averages of density [*Jacchia*, 1962; *Paetzold*, 1962; see also *Priester*, 1961, and *King-Hele and Walker*, 1961].

It seems plausible that the corpuscular heat source has in general no pronounced variation with the solar rotational period of 27 days, though this may be an oversimplification. The corpuscular heat source, however, must have a semiannual variation occurring more regularly than the geomagnetic semiannual variation. The atmospheric semiannual variation in density is well pronounced in all years from 1958 through 1961, whereas the semiannual variation in geomagnetic indices can be found conclusively only from data of several years.

The relatively steep decrease of the yearly averages of density for 1958 to 1961 indicate that both heat sources have a pronounced variation in both their monthly and yearly average fluxes over the eleven-year solar cycle. It therefore seems reasonable as a working hypothesis to assume the average fluxes of both sources to be proportional to either the monthly or yearly averages of the solar decimeter radiation.

The model we presented in our previous paper corresponds to an average 10.7-cm solar flux of 200 × 10^{-22} w/m² cps according to the reference level of the observational model [*Martin*

TABLE 1. Peak Fluxes of EUV Heat Source and of Corpuscular Heat Source Used in Calculating Our Five Models

The models are labeled by S = 250, 200, 150, 100, and 70. Further, the exospheric temperature at 14h and 04h local time are given (T_{14}, T_4), as are the diurnal maximum and minimum temperatures of the exosphere together with the local times of the occurence.

S	EUV Flux, erg/cm² sec	Cornuscular Flux, erg/cm² sec	T_{14}, °K	T_4, °K	T_{max}, °K	Local Time, hours	T_{min}, °K	Local Time, hours
250	1.159	1.29	21.21	1392	2135	15	1392	4
200	0.927	1.03	1768	1163	1768	14	1161	3
150	0.695	0.77	1409	943	· 1416	13	934	2
100	0.464	0.52	1046	737	1073	12	716	1
70	0 325	0.36	827	612	866	12	588	0

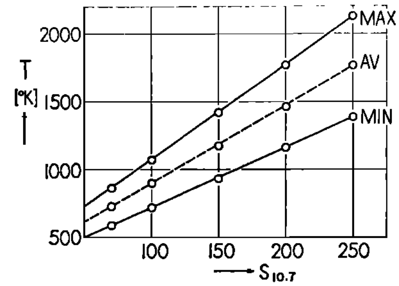

Fig. 2. The variation of the exospheric temperature for the diurnal maximum and minimum as a function of the monthly averages of the 10.7-cm flux. The mean of the maximum and minimum temperature is also given.

et al., 1961], with which it is in good agreement. We have here selected four other reference values of the 10.7-cm radiation, 250, 150, 100, and 70 (in units of 10^{-22} w/m² cps). They cover the entire range of the variation of the 10.7-cm flux during a solar cycle. Figure 1 shows the behavior of the monthly averages of the 10.7-cm flux for the period from 1947 to 1961 according to the measurements of the National Research Council of Canada. The maximum and minimum of the 10.7-cm flux for the sixty-day period of June and July of each year are given by bars to demonstrate the amplitude of the 27-day fluctuations and its behavior throughout the solar cycle.

According to our working hypothesis, the fluxes of both heat sources have been changed

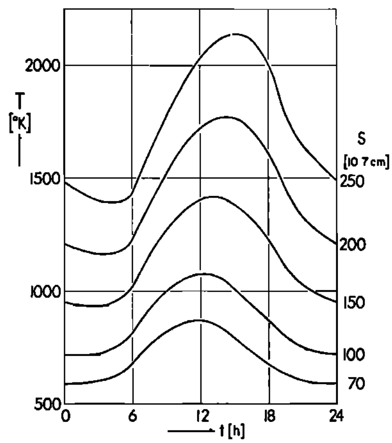

Fig. 3. Diurnal variation of the exospheric temperature as a function of local time for the five models labeled S = 250, 200, 150. 100, and 70.

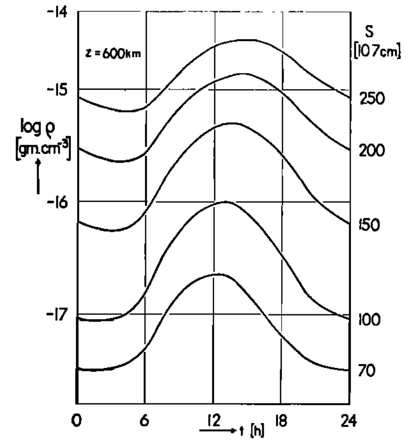

Fig. 4. Diurnal variation of density at 600 km.

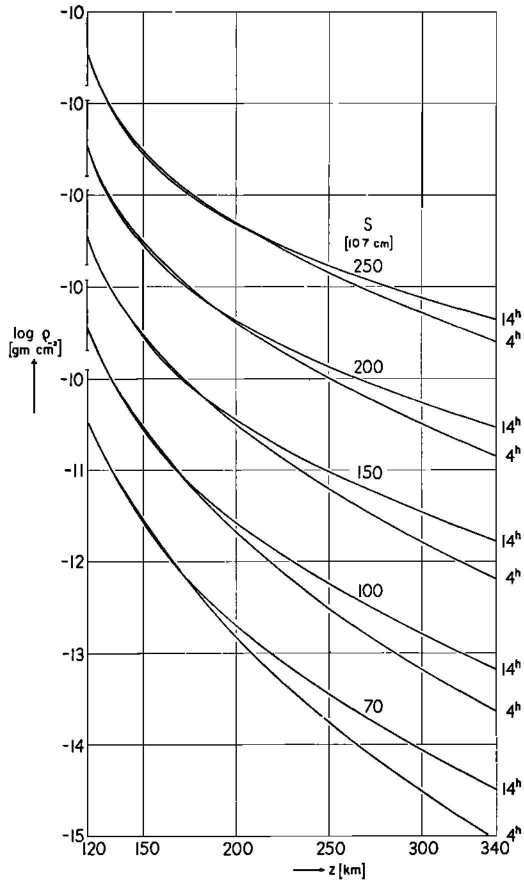

Fig. 5. Variation of density with altitude from 120 to 350 km for the five models, at 14h and 04h local time. The ordinate scale is shifted by one unit each.

in proportion to the 10.7-cm flux with the fluxes obtained in our previous paper as the reference level. The peak values of these fluxes for the five different models are given in Table 1.

The theoretical models of the upper atmosphere derived from these values for the heat source fluxes are intended to be helpful aids in deriving densities and temperatures from satellite data during the coming years. They are furthermore intended, by means of comparison with future density data obtained by observation, to yield information as to the actual variation of the heat sources during the eleven-year solar cycle. Since the real variation is not yet known, the 10.7-cm flux indices are mainly model numbers used to distinguish between the models in a self-evident manner.

In calculating these models the following simplifications have been made. It is assumed that the boundary conditions at 120 km do not change throughout the solar cycle. We used in this paper the boundary conditions mentioned in our previous paper as 'set 1.' Furthermore, we have assumed that the shape of the diurnal variation and the height dependence of the corpuscular heat source do not vary throughout the solar cycle. In all other details of the calculations we followed exactly the procedure described in that paper. The results for the five models are presented in Figures 2 through 11.

Figure 2 shows how the exospheric temperature varies if the heat fluxes are proportional to the monthly averages of the 10.7-cm radiation. The diurnal maximum, minimum, and averages are given. They can be represented by straight lines described by the following expressions:

$$T_{\min} = 4.47S + 275 \qquad (°K)$$

$$T_{\max} = 7.05S + 372 \qquad (°K)$$

where $T_{\min}$ and $T_{\max}$ are the diurnal minimum and maximum exospheric temperature, respectively, and S is the monthly average of the 10.7-cm flux in units of 10^{-22} w/m^2 cps. The factor 4.47 in the first equation is in agreement with the value 4.5 obtained by *Jacchia* [1962] from orbital analysis of satellites. This can be considered as a confirmation that our working hypothesis is reasonable, but further checking

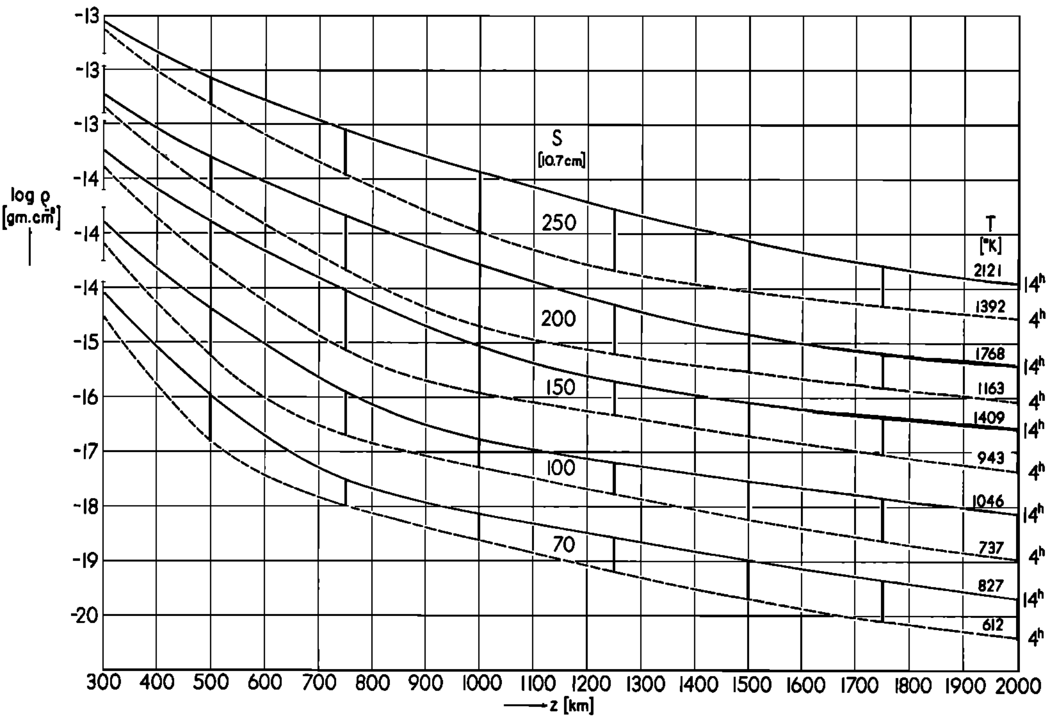

Fig. 6. Same as Figure 5 for the altitude range from 300 to 2000 km.

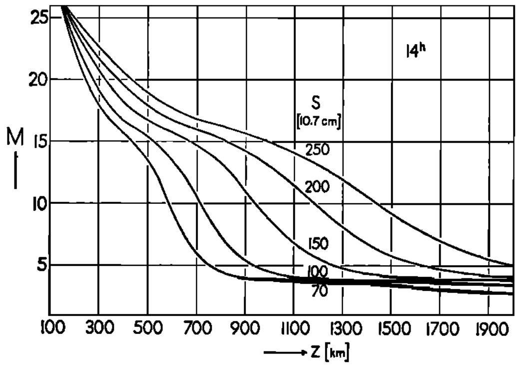

Fig. 7. The mean molecular weight as a function of altitude from 120 to 2000 km for the five models for 14h local time.

during the coming years of solar minimum activity is needed to obtain final conclusions.

The numerical values of the maximum and minimum exospheric temperatures for our five models are given in Table 1 together with the local time (in hours) when the maximum or minimum occurs. Furthermore, the exospheric temperatures at 14h and 04h local time are given (labeled T_{14} and T_4). In Figure 3 the entire diurnal variation of the exospheric temperature is shown for the five models. It can be seen that the temperature maximum in the models is shifted in local time from 15h for years with very high solar activity toward noon, which is reached during low solar activity.

This behavior results from keeping the time at which the maximum heating from the corpuscular heat source occurs constant with solar activity. However, the local time of the maximum of the diurnal variation of the corpuscular heat source may change in a manner such that the local time of the maximum in the diurnal temperature variation may not change appreciably during the solar cycle. There is insufficient data at present to determine the behavior of the maximum of the exospheric temperature as a function of solar activity. It seems, however, to be plausible from considerations about the refraction of hydromagnetic waves in the area of the equatorial bulge (D. G. Wentzel, personal communication) that the diurnal maximum of the corpuscular heat source shifts from 09h toward noon, when the solar activity decreases. These considerations would imply, of course, that the physical nature of the corpuscular heat source is in fact the power dissipation of hydromagnetic waves in the ionospheric F layer.

In Figure 4 the diurnal variation of the density at 600 km is given, again for the five models. The density shows the same behavior with respect to the shifting of the maximum as the diurnal variation of the temperature.

In Figures 5 and 6 we give the density as a function of altitude and solar activity for 14h and 04h local time in the altitude ranges from 120 to 300 km, and from 300 to 2050 km, respectively. The corresponding exospheric temperatures are also given. In the construction of these curves the ordinate scales corresponding to the first four values of S have been shifted by one unit each as indicated in the ordinate scale.

Figure 5 shows the range between 130 and 200 km where the daytime densities are lower than the nighttime densities. This behavior is to be expected as most of the heating takes place in this altitude range. A crossing of the daytime and nighttime density curves between 170 and 200 km is further required in order to conserve the mass of the upper atmosphere during the diurnal variation. The solutions of the heat conduction equation under quasi-hydrostatic conditions provide the conservation of mass automatically.

The influence of helium on the behavior of the amplitude of the diurnal variation of density is noticeable in Figure 6. The amplitude increases initially as a function of altitude owing to the predominance of N_2, O_2, and O, and then as helium begins to contribute appreciably to the density, it decreases. At greater altitudes, however, it increases again by a small amount.

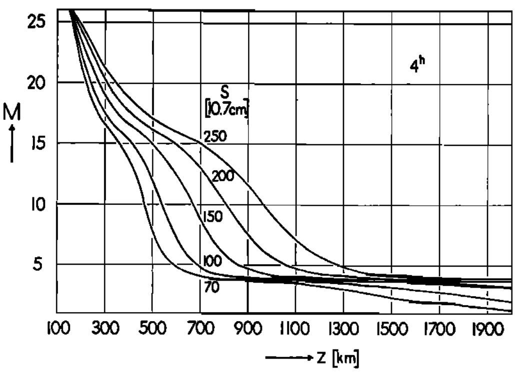

Fig. 8. Same as Figure 7 for 04h local time.

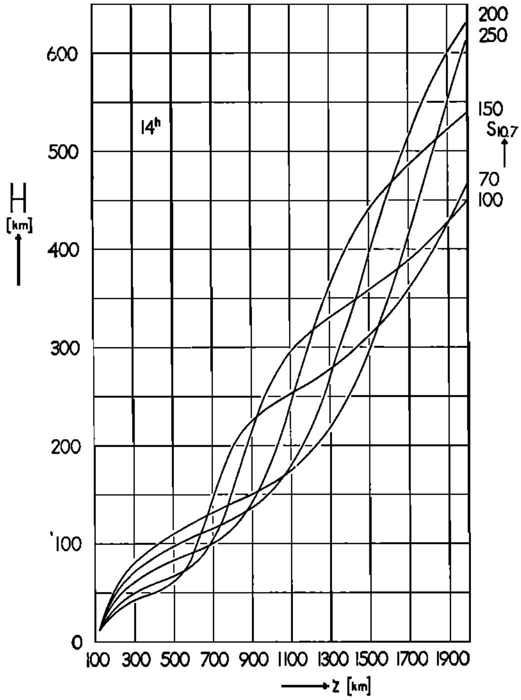

Fig. 9. The pressure scale height as function of altitude for 14h local time.

When hydrogen becomes the predominant constituent a similar decrease and final increase of the diurnal amplitude in density can be expected again. The peculiar behavior of the diurnal amplitude in density with varying solar activity is also shown in Figure 6. At 500 km the relative amplitude increases with decreasing solar activity, as is marked by the variation of the length of the bars in this Figure at $z = 500$ km. At an altitude of 1000 km, however, the opposite behavior occurs. The amplitude decreases with decreasing solar activity. At 1750 km the amplitude remains almost constant during the solar cycle. All these properties are easily understood from the expansion-contraction of the upper atmosphere during the eleven-year solar cycle and the corresponding changes in the mean molecular weight.

The expected changes of the thermospheric composition as a function of altitude during the solar cycle and during the day from day (14h local time) to night (04h local time) are illustrated in Figures 7 and 8, where the mean molecular weight is plotted as a function of altitude. During very low solar activity helium may begin to dominate the composition at an altitude as low as 600 km during night and 750 km during daytime. The importance of hydrogen at altitudes above 1500 km is also obvious for years with low solar activity, particularly during nighttime.

In Figures 9 and 10 the variation of the pressure scale height is given in the same manner as the mean molecular weight of both the previous figures. These figures reveal the complicated behavior of the upper atmosphere due to the combination of heating by absorption of solar energy and heat conduction. In the past it has often been thought that the scale height as a function of altitude can be approximated by straight lines (constant scale height gradient). Figures 9 and 10 show that an approximation of this kind can only be made for very short ranges of altitude. It is therefore without physical significance.

Figure 11 shows the density at different altitudes (200 km to 1000 km) plotted as function of the temperature at these altitudes. The local time is the curve parameter. The data are given for 14h and 04h local time. It can be seen that

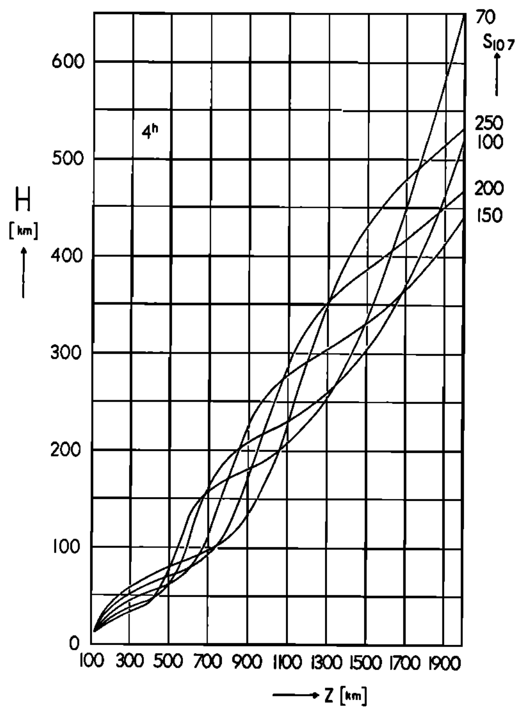

Fig. 10. Same as Figure 9 for 04h local time.

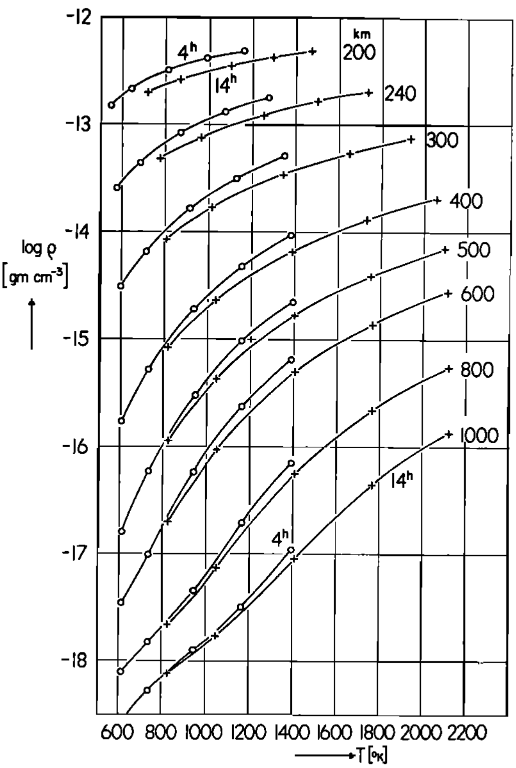

Fig. 11. The density as functions of temperature at seven selected altitudes from 200 to 1000 km for 14h and 04h local time. The circles are the individual results from the five models for 04h local time, the crosses for 14h local time.

the nighttime densities are between 20 and 50 per cent higher for equal values of temperature, which can occur for different solar activity. If we try to obtain information about the atmospheric temperatures from measured densities, we have to take into account the local time of the measurement. The use of a one-parameter family of atmospheric models like that given by *Nicolet* [1961] would lead to systematic errors and to a too-small amplitude for the diurnal temperature variation. For years of very high solar activity these systematic errors can amount to 300°K at 200 km altitude, 250°K at 300 km, 120°K at 500 km, and 70°K at 800 km. For lower solar activity these errors would become gradually smaller, as can be seen from Figure 11.

The five models we present here are intended to give some insight into what variations in the properties of the upper atmosphere are to be expected during an eleven-year solar cycle. The comparison with future data for years of low solar activity will yield information concerning the general behavior of the heat sources. For comparison with observational densities it is necessary that the data be reduced for the 27-day variation (solar activity effect) first, since the models do not account for this effect. Similar reductions have also to be made for the semi-annual variation.

Complete tables of the atmospheric properties (temperature, density, pressure, scale height, mean molecular weight, and the number densities of N_2, O_2, O, He, and H) as a function of local time and mean solar activity are published as NASA Technical Note No. D-1444.

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