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DENSITY VARIATIONS IN THE HETEROSPHERE

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Abstract.--Five separate types of density variations are recognized in the upper atmosphere at satellite heights. These are: 1) day-to-night variations, 2) variations with solar activity, 3) variations with geomagnetic activity, 4) semiannual variations, and 5) latitude-dependent seasonal variations. Each type of variation is reviewed, together with the present state of knowledge concerning its origin.

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1. Temperature and density variations

In the homosphere, i.e., the region in which mixing keeps the relative composition of the atmosphere constant, a given temperature profile uniquely determines the corresponding density profile starting from a given boundary value. If we vary the temperature profile, we can easily compute the corresponding density variations.

When we cross from the homosphere into the heterosphere, where diffusive separation of the major atmospheric constituents prevails, the situation becomes more complicated. First we have to cross the transition zone — i.e., the region of oxygen dissociation and the turbopause, where the composition changes, but there is no diffusive equilibrium as yet. This region is not paper thin. Oxygen dissociation starts at about 90 km and is not completed below 105 km; at this height, however, diffusive separation has set in, but it is not before we reach 120 km or so that we can be reasonably sure that mixing has become a negligible factor. Since oxygen dissociation varies with the seasons and there is no assurance that the height of the turbopause is immutable, we cannot expect to know exactly, at least at the present

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state of our knowledge, what the mean molecular mass is at any given height and any given time in this transition zone. Thus a given temperature profile will not define for us a density profile above the height of 90 km.

To avoid the troublesome transition zone, models of the heterosphere are generally constructed starting from boundary conditions at a height above which diffusive equilibrium can be safely assumed for the major atmospheric constituents. Most of the recent models (Nicolet, 1961; Harris and Priester, 1962a, 1964; Jacchia, 1964) have fixed their boundary conditions at 120 km — a height at which occasional rocket measurements of composition and of density are still available. For simplicity — and also because the scanty data gathered at that height do not permit one to do much else — these models assume that temperature, density, and composition are invariable at 120 km. This is not quite true, of course. Seasonal density variations have been found by Faire and Champion (1965) to exist at 120 km in mid-latitudes, and it appears practically certain that large day-to-day temperature variations occur at this height in phase with geomagnetic activity (Jacchia, 1964).

Any density variations at the base of the heterosphere must, by necessity, be propagated upward and be observable at greater heights, even if they did occur without a concomitant change in temperature and composition. Seasonal and latitudinal density variations in phase with those observed at 120 km have now been detected by us at satellite heights, confirming this point. Since it is inconceivable that density variations at 120 km should occur without changes in temperature, the response of the higher atmosphere to these variations becomes quite complicated and the interpretation of the observed latitudinal and seasonal density variations in terms of temperature changes becomes quite difficult.

The assumption of invariable boundary conditions at 120 km can be justified only if the temperature variations above 120 km are so large as to dwarf those occurring at the boundary surface. Such condition seems to be reasonably close to the truth and this explains the considerable success encountered by fixed-boundary in representing the observed density profiles. In spite of these successes we must remember that it is possible to obtain similar density profiles with a variety of temperature profiles with a proper change in the boundary conditions, so that the relation between temperature and density is not uniquely determined at the present state of our ignorance concerning the lower thermosphere. In a recent analysis of the situation, Stein and Walker (1965) estimated that the temperatures determined from satellite drag data reduced to densities could be in error by 25 percent.

The density variations observed in the heterosphere can be broadly divided into five categories:

1) Day-to-night variations;
2) Variations with solar activity;
3) Variations with geomagnetic activity;
4) Semiannual variations;
5) Latitude-dependent seasonal variations.

2. Day-to-night variations

The diurnal variation is the most regular of all the variations found at satellite levels. The density peaks at 2 P.M. local solar time and reaches a minimum around 4 A.M. The variation at any given geographic location is strongly dependent on latitude and on the declination of the sun, and this accounts for the occasional announcements of spurious latitude and seasonal effects. The simplest way to picture the distribution of density is to visualize an atmospheric bulge with its peak 30° east of the sub-solar point and degrading nearly symmetrically on all sides, only a little steeper on the morning side. This picture is now firmly established on the basis of drag observations of several long-lived, high-inclination satellites (Injun 3, Explorer 19, Explorer 24).

The hours of maximum and minimum remain remarkably constant throughout the solar cycle. Similarly constant is the relative global temperature range, i.e., the ratio of the maximum temperature at the center of the bulge to the minimum temperature in the opposite hemisphere. What this ratio actually amounts to depends on the atmospheric model which is used to derive temperatures from the observed densities. Using Jacchia's (1964) static model, the ratio turns out to be 1.28. The new Harris-Priester model (1964) gives essentially the same temperatures at night, but requires a much larger temperature change to give the observed density range; according to this model the maximum-to-minimum temperature ratio is 1.5. No matter which model is used, the variation with height of the amplitude of the density variation is in good agreement with the predicted value. The density distribution over the globe can be computed for any given height from a mathematical model of the bulge given by Jacchia (1964, 1965a). Figure 1 shows with remarkable clarity the effect on the observed densities of successive passages of a satellite perigee through night and day.

Nicolet (1963) believes that the diurnal variation is entirely due to EUV heating; Harris and Priester (1962b) believe that it is due to a roughly equal combination of heating by EUV and by a "second source," probably corpuscular, and King <u>et al.</u> (1964) are of the opinion that ion drifts alone are capable of explaining the diurnal variation, without any direct help from EUV heating. As we can see, the explanations run from one extreme to the other, so we can say with confidence that the truth must lie within this range.

3. Variations with solar activity

Solar activity, as characterized by sunspots, calcium plages, or integrated radio flux, undergoes large variations. As existing centers of activity fade and new ones are formed, the indexes of solar activity fluctuate from day to day. A characteristic of solar activity is that most of the time it is much more intense in one hemisphere than in the other, so that, viewed from the earth, solar-activity indexes vary with the period of rotation of the sun, 27 days; this periodicity often persists for one year or even longer. The day-to-day fluctuations in solar activity are superimposed on a large variation with an average period of 11 years.

All these variations of solar activity are faithfully mirrored in the density of the heterosphere (see Figures 1 and 3). Of the various indexes of solar activity the one whose variations most closely parallel those of atmospheric density is the integrated decimetric solar flux. Although it might be questioned whether it is the 8-cm, the 10.7-cm, or the 20-cm flux that shows the closest similarity, it has become the practice to use for comparison the 10.7-cm flux, which has been measured continuously for the longest period of time (since 1947) by the National Research Council at Ottawa with no important interruptions and without calibration troubles.

The correlation between the exospheric temperature and the 10.7 cm flux, as derived over the 11-year solar cycle (or, rather, from 1958 to 1964; i.e., from maximum to minimum), is just about linear, when temperatures are derived through the use of the Jacchia 1964 model (Figure 2). The slope of the regression curve is $3^\circ\!.6$ per unit flux in the nighttime minimum temperature and 1.28 times greater, or $4^\circ\!.6$, in the daytime maximum temperature. If we derive the correlation between temperature and solar flux from a shorter interval of time, covering only two or three solar rotations, we find that the temperature variation per unit flux turns out to be only one-half the value derived over the 11-year cycle.

This finding indicates that we have to deal with two sources of heating radiation. The first comes from the whole disk of the sun and varies slowly with the 11-year cycle. The other comes from the active areas and is superimposed on the first whenever such areas are present. Both the 10.7-cm solar flux and the solar EUV have a disk component and an active-area component. The disk component of the 10.7-cm flux is known to vary with the solar cycle: according to Hachenberg (1965) its intensity in 1958 was almost twice the intensity at sunspot minimum in 1954 and 1963. Concerning EUV radiation, all we know is that the HeII emission at $\lambda 304$ strongly contributes to the disk component, while the numerous lines of Fe XV, Fe XVI, of highly ionized Si and others in the spectral region between $\lambda 170$ and $\lambda 300$ are mostly originated in the active areas (Neupert et al., 1964; Purcell et al., 1964); nothing is known about the variation of the disk component with the solar cycle.

Since rocket-borne spectroscopes with photon-flux counters (Hinteregger, 1962) had shown that the energy radiated by the sun in the EUV is sufficient to account for some heating of the atmosphere, and since the height of the atmospheric region where this energy is absorbed is just about what is required to explain the amplitudes of the density variations that are observed at different heights, it was logical to assume that variable solar EUV had at least a role in producing the density fluctuations related to solar activity. In such case the correlation between atmospheric temperatures and the 10.7-cm solar flux would be a consequence of a correlation between this flux and solar EUV. Such a correlation was brilliantly confirmed by the three-month EUV monitoring of the OSO-I satellite (Neupert et al., 1964).

Nicolet (1963) believes that solar EUV must be overwhelmingly responsible for the heating of the upper atmosphere and for its variations with solar activity, and it must be said that there is considerable evidence in his favor. Doubts have been cast by MacDonald (1963) on the EUV explanation on the basis of a two-day lag found by him in the 27-day atmospheric oscillations with respect to those in the 10.7-cm flux, and since two days is the travel time from the sun of a 750 km/sec plasma wind, he concludes that the atmospheric variations are due to the solar wind. We know, however, from Mariner 2 observations, that the solar wind observed near the earth correlates with geomagnetic activity and not with the decimetric flux, and that its average velocity is closer to 450 than to 750 km/sec. Moreover, even if the two-day lag could be confirmed, it would not be significant unless the effect of geomagnetic disturbances were first eliminated in the atmospheric analysis. Since many of the recurrent disturbances originate in the solar areas that produce the enhanced decimetric flux and these are delayed one or two days in their effects on earth, a systematic lag of this magnitude can arise from the superimposition of these disturbances on the "clean" 27-day fluctuations (see Figure 4). At least part of the heating energy is deposited in the lowest thermospheric layers, where conduction time is high; this circumstance could also contribute to the lag of the atmospheric oscillations behind those of the decimetric flux.

In the meantime the lag itself cannot be considered as firmly established. Priester and Martin (1960) found a delay time of +0.5 ± 0.3 days from an analysis of Vanguard 2 fluctuations compared with those of the 20-cm flux. Bourdeau et al. (1964) have compared the density oscillations derived from the drag of the Explorer 9 with the EUV measurements made by the OSO-I satellite and have found an average delay of one day — but the analysis covers only a little over two cycles of the 27-day variation.

It must be understood that when we establish a correlation between atmospheric temperatures and the decimetric solar flux we are agnostic concerning the heating agent which mimicks the solar flux variations. We use the decimetric flux because we can successfully represent the atmospheric variations with solar activity using a simple function of the flux itself. Whether it be solar EUV alone, or with an admixture of plasma (either EUV-generated or coming from the sun), we cannot expect the decimetric flux to give us a perfect picture of the variations of the heating energy; therefore it is senseless to worry with Anderson (1965) because the 10.7-cm flux may not be a good index of solar EUV.

4. Variations with geomagnetic activity

Superimposed on the day-to-day fluctuations related to solar activity, the density of the heterosphere shows another type of fluctuations, very irregular in character, which are correlated with the variations in the magnetic field of the earth. Always difficult to detect in the drag of artificial satellites, these fluctuations are more noticeable at the time of intense magnetic storms, when the density at some height may increase by a factor of 3, 5, and even 10 in a matter of a few hours (Jacchia, 1961). The amplitude of the density variations increases with height in a manner very similar to that exhibited by the fluctuations induced by variable solar activity, indicating that the energy dissipation that causes the two phenomena must occur at a comparable height level. For both phenomena the increase in amplitude with height reaches a maximum and then decreases when the helium belt is reached. In a first approximation, then, we can assume that the energy input for the variations with geomagnetic activity follows the same height distribution as the heating responsible for the variations with solar activity, and we may feel justified in using the unperturbed atmospheric models for different degrees of solar heating to convert density variations into temperature variations.

When this is done, we find that during magnetic storms the temperature of the upper atmosphere increases proportionally to the three-hourly a_p index, which in turn is proportional to the amplitude of the variation of the magnetic field; there is a lag of approximately six hours in the atmospheric variations, caused in all probability by conduction time. Between storms, when the magnetic fluctuations are smaller, the temperature variations are proportional not to the a_p index, but to its logarithmic counterpart, the K_p index. In other words, the relation between the variations of the magnetic field and those in the atmospheric temperature is strongly nonlinear: the reaction of the atmosphere to small variations of the magnetic field is relatively much larger than the reaction to violent perturbations (Figure 5). Using Jacchia's 1964 model to derive temperatures, we find (Jacchia and Slowey, 1964b) that the relation between the temperature increase ΔT and the a_p index can be expressed as

$$\Delta T = 1\overset{\circ}{.}0 \, a_p + 125^\circ [1 - \exp(- 0.08 \, a_p)] \ . \tag{1}$$

It is interesting to note that a similar nonlinearity was pointed out by Ondoh and Hakura (1964) to exist in the relation between solar-plasma velocities and geomagnetic indexes. The solar-wind velocities measured by the Mariner 2, which all refer to relatively quiet conditions, correlate linearly with the K_p index, while the plasma velocities computed from the time interval between the appearance of a solar flare and the peak of the ensuing magnetic storm correlate linearly with the a_p index. In other words, it looks as though a linear correlation could be found between atmospheric temperatures and solar-wind velocities, covering both storms and quiet periods. Combining the Mariner 2 and the storm data, we find (Jacchia, 1965b)

$$\Delta T = 0.50 \, (v - 330) \, , \tag{2}$$

when the plasma velocity v is expressed in km/sec.

There is indication that the variations with geomagnetic activity are enhanced in high geomagnetic latitudes (Jacchia and Slowey, 1964a), but the subject requires more observational evidence.

Very little can be said with assurance concerning the mechanism by which the atmosphere is heated when the earth's magnetic field varies. A clue may be provided by establishing the height at which the heating occurs, and in this connection it is important to point out that lively variations in phase with those at greater heights are found to exist at heights as low as 160 km (Zirm, 1964); this shows that the heating occurs considerably lower, probably in the E layer.

Unless the heating energy involved in this type of variation also varies with the solar cycle, one would expect the smaller density fluctuations during near-quiet days to become imperceptible around sunspot maximum, when the heat content of the atmosphere is much greater. Unfortunately the imprecise data of the few satellites aloft in 1958-1959 are not sufficient to draw any conclusions on this point; during those years the difficulty was compounded by the large day-to-day fluctuations in solar activity, which tended to mask any smaller variations.

The geomagnetic indexes K_p and a_p give us a measure of the <u>variations</u> of the magnetic field, and we find that these variations are reflected in the atmospheric temperature. The basic question that logically arises is: are the temperature changes that we observe caused by variations of an ever-present heat source important also when $K_p = 0$, or does the heating arise only when $K_p > 0$? Or, in other words, is there another heat source in the ionosphere, which even under quiet geomagnetic conditions supplements EUV heating? Could this be the "second source" advocated by Harris and Priester to correct their discrepant results on the diurnal variation when EUV alone was used as a heat source? These questions require more investigation before they can be given an answer.

5. The semiannual variation

All the variations hitherto described are superimposed on a global density variation with a half-year period, with maxima in April and October and minima in January and July; the October maximum is more pronounced than the one in April, and the July minimum is deeper than the one in January (Paetzold and Zschörner, 1961). The amplitude of the variation varies with solar activity and is roughly proportional to the 10.7-cm solar flux (Jacchia, 1965a).

The variation with height of the semiannual density fluctuations is similar to that of the other types of variation, so that it is safe to assume that it is the result of temperature variations in the thermosphere. Where exactly the heating occurs cannot, unfortunately, be determined from the orbital drag of satellites. All we can say is that the variation is present at the height of 250 km; below this height, however, the lifetimes of artificial satellites are so short, that they are not suited for the study of a variation with a semiannual cycle.

The height of the F_2 layer, derived from critical-frequency observations, exhibits a semiannual variation almost exactly in phase with the thermal variations. In Becker's (1965) curves obtained from measurements at Lindau/Harz, Germany, the dates of the maxima and minima are almost identical with those of the thermal variation; the only difference is that the primary maximum is the one in April, not the one in October, and the primary minimum is the one in January, not the one in July.

In spite of this difference, which may not necessarily be world-wide, the similarity between the two curves appears too great to be due to chance; moreover, the amplitude of the ionospheric variation greatly decreased from sunspot maximum to sunspot minimum, exactly as in the case of the thermal variations.

Another indication of a semiannual variation was found by Matsushita and Maeda (1965) in the electric currents responsible for the variations of the geomagnetic solar quiet daily variation field, S_q. The analysis covered the year 1958, which was divided into three seasons: D months (January, February, November, and December), E months (March, April, September, and October and J months (May, June, July, and August, and it was found that the currents are strongest in the E months – i.e., in the spring and in autumn, more or less as in the thermal variation; according to Matsushita (1965) a similar analysis for a year of sunspot minimum showed a decreased intensity in the current system and a smaller seasonal variation.

As to the origin of the semiannual atmospheric variation, it should be emphasized that it must be kept distinct from that of the semiannual variation in the geomagnetic index, which only reflects the greater number of geomagnetic disturbances around the equinoxes, when the earth crosses the plane of the solar equator. This greater equinoctial frequency of disturbances is observed, of course, also in the atmosphere, and is completely accounted for on the basis of the geomagnetic indexes.

6. Seasonal variations

As we mentioned earlier, the diurnal variation is dependent on season and latitude; this dependence, however, does not constitute a true seasonal effect, because it can be accounted for by the migration in latitude of the diurnal bulge with the change in declination of the sun. Once the effect of the bulge is removed using a suitable model, we do, however, still find some evidence of a seasonal variation whose amplitude increases toward the poles. If this effect consisted in an excess of temperature near the summer pole and in a deficit of heat around the winter pole, we could ascribe it to the long duration of the polar days in summer and of the polar nights in winter, and somehow incorporate it in the diurnal effect. It turns out, however, that the effect is in the opposite direction: at satellite levels the atmosphere is colder above the summer pole and warmer above the winter pole. Or rather, the atmospheric density is higher above the winter pole and lower above the summer pole, just as Faire and Champion (1965) found to be the case at heights between 90 and 120 km; at those heights, however, the temperature picture is inverted: colder in winter and warmer in summer. Owing to diffusion, an excess density with lower temperature will whittle away with increasing height and eventually turn negative, so we can be relatively confident that if we observe, as we do, a large excess of density at 600 km, this means that the temperature, somewhere above 120 km, had a larger positive gradient, resulting in a higher temperature above the thermopause. According to Champion (1965) the density at 120 km varies by a factor of two from summer to winter.

Seasonal variations as described in the previous paragraph have been detected by Jacchia and Slowey (1965) in the densities derived from the drag of Explorer 19 and Explorer 24, two 12-foot balloon satellites in near-polar orbits, with mean perigee heights of 615 and 545 km, respectively. At those heights the semiamplitude of the seasonal variation at the poles is a factor of 1.8 in the density. This would correspond to about 100° in the temperature if we could use a model with fixed boundary conditions at 120 km: since, however, we have a seasonal variation at that height, the conversion of density range into temperature range becomes unreliable. The existence of the seasonal variation has been confirmed also by Römer (1965) from precision drag analysis of the Explorer 9 satellite, whose orbital inclination was 39°.

If we take a continuous series of density data obtained from the drag of an individual satellite and remove the effects of the diurnal, solar-activity, geomagnetic, and semiannual variations, we are left with a curve of residuals as a function of time. To see if these residuals can be accounted for by a seasonal effect increasing with latitude, we must compare them with a theoretical curve computed from a reasonable model of this effect. To achieve this we can first assume that at a given latitude the effect is a sinusoidal oscillation with a maximum at mid-winter, i.e., that it is proportional to $\pm \cos \frac{2\pi}{T}$ (d - Jan. 20), where d is the day of the year and T the tropical year in days; the plus sign is for the northern hemisphere and the minus sign for the southern hemisphere. After that we can assume that the amplitude of the variation increases with the latitude φ in such a way as to be continuous at the equator and at the poles; the function $\sin^2\varphi$ seems to be a natural choice for the purpose. We can thus write

$$\underset{(\text{or } \Delta T)}{\Delta \log \rho} = \pm C \sin^2\varphi \cos \frac{2\pi}{T} (d - \text{Jan. } 20) \qquad (3)$$

where C is a constant and, again, the upper sign is to be used when φ is positive and the lower when φ is negative.

A comparison of the residuals of the Explorer 19 (Figure 7) and Explorer 24 with a curve computed with this formula shows that the principal maxima and minima are mainly accounted for, although there are some discrepancies, as one could expect if the seasonal variations in the heterosphere are, at least in part, an extension of those in the homosphere. As is well known, the seasonal variations in the stratosphere are beset with large irregularities, of which the most important ones are the sudden winter warmings occurring anywhere from December to April in the northern hemisphere and from June to October in the southern hemisphere; similar irregularities exist in the mesospheric winter temperatures. In addition we might expect some systematic differences between the corresponding seasons in the two hemispheres, as well as imperfections in our unsophisticated model of the variation.

7. Conclusions

If we cast a surveying glance to all the different types of density variations in the heterosphere, we must come to the conclusion that, although we have succeded in correlating them with solar, geomagnetic , and geographic parameters, and so closely that densities can be computed quite accurately when these parameters are known, we still lack a deep understanding of the mechanisms that originate the variations.

Solar EUV must be an all-important agent because it is there — but does it heat through direct absorption or also through production of ions which are then driven by the earth's magnetic field? Why are the small variations of the earth's magnetic field accompanied by substantial heating effects? Is there a permanent corpuscular heat source in the ionosphere? What causes the semiannual variation? How much of the seasonal variations is originated in the homosphere and how much is added to them in the thermosphere? These are difficult questions, for whose solution we must probably wait for new experiments in many fields of space physics.

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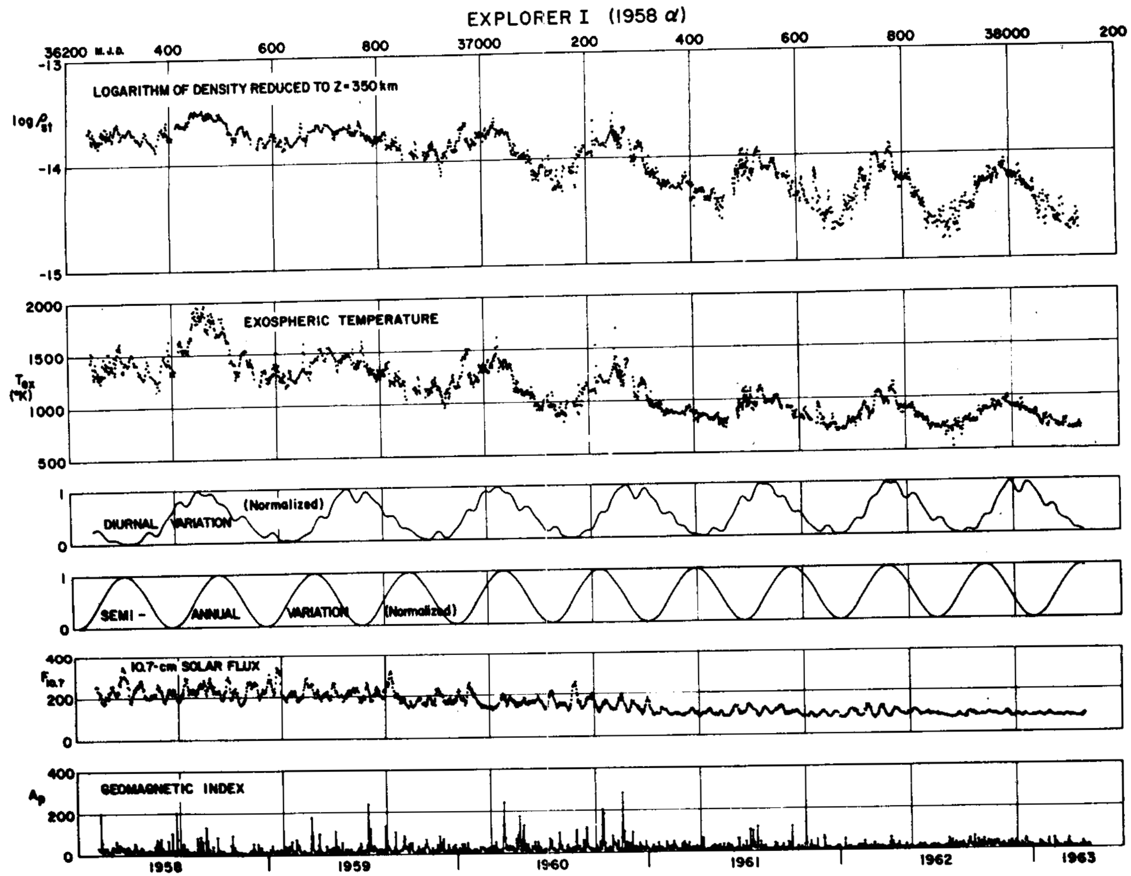

Figure 1. Densities and temperatures derived from the drag of the Explorer I satellite (1958 α), compared with solar and geomagnetic parameters. Notice the decrease in density and temperature which paralleled the decrease in the 10.7-cm solar flux during the five years covered by the diagram. The regular oscillations with a period of about 250 days are caused by the motion of the satellite perigee in and out of the diurnal bulge. Visible are also the 27-day oscillations in phase with those of the 10.7-cm flux and a few perturbations caused by major magnetic storm. Schematic curves of the diurnal and of the semiannual variations are added to aid the eye in recognizing them in the plots of satellite data. The wiggles in the theoretical diurnal-variation curve are caused by the rapid variations in latitude of the satellite perigee. MJD is the abscissa in the Modified Julian Day (JD minus 2400000.5).

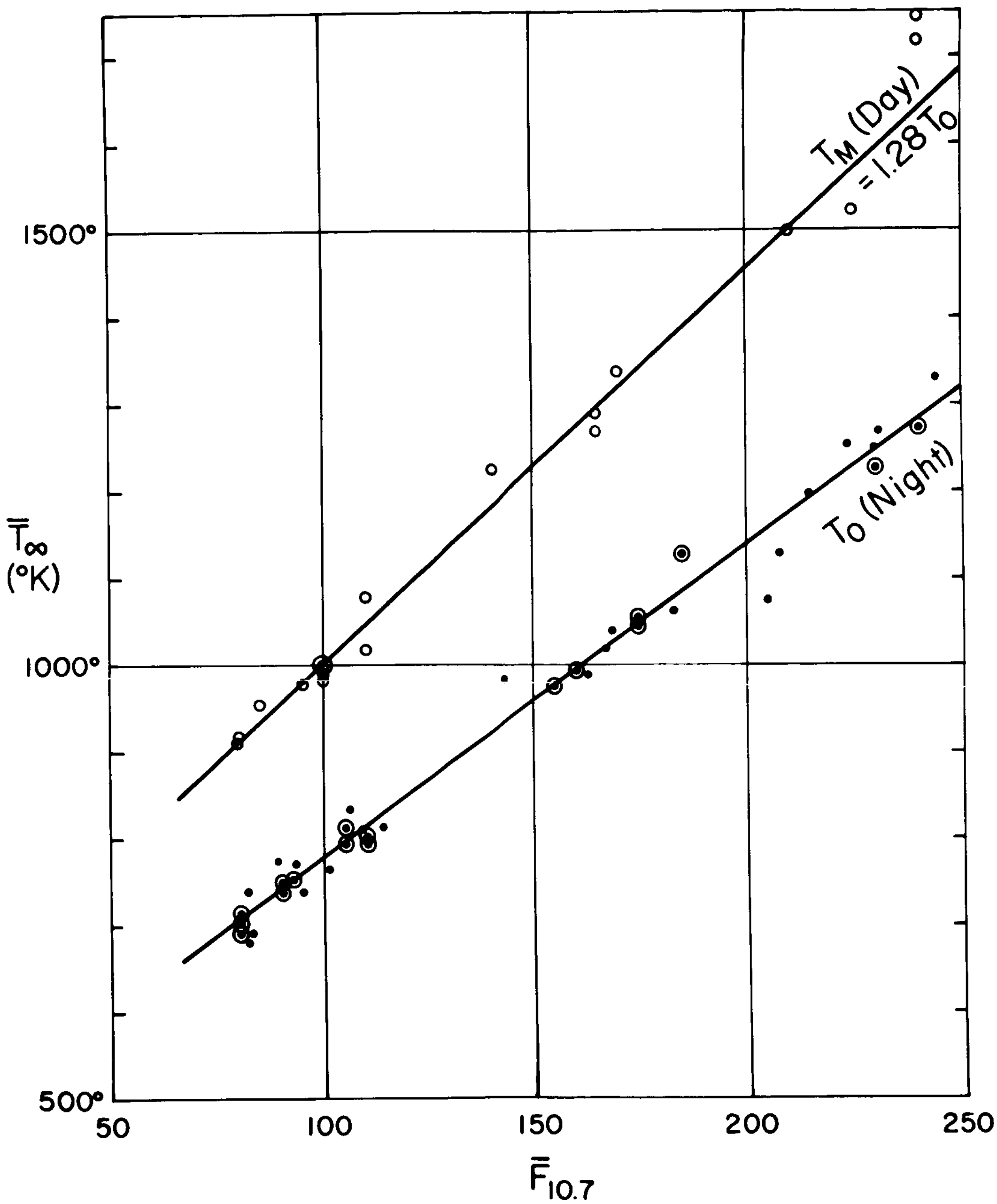

Figure 2. Daytime maximum and nighttime minimum temperatures above the thermopause as a function of the 10.7-cm solar flux, in units of 10^{-22} watts/m^2/cycle/sec bandwidth. Data are averaged over two or three solar rotations. Open circles: individual maxima deduced from satellite drag curves. Dots: temperatures reduced to the nighttime minimum at times when the curve of the semiannual temperature variation was close to the annual average. The temperatures in this diagram must be considered as referred to average quiet geomagnetic conditions (K_p = 2 or a_p = 7).

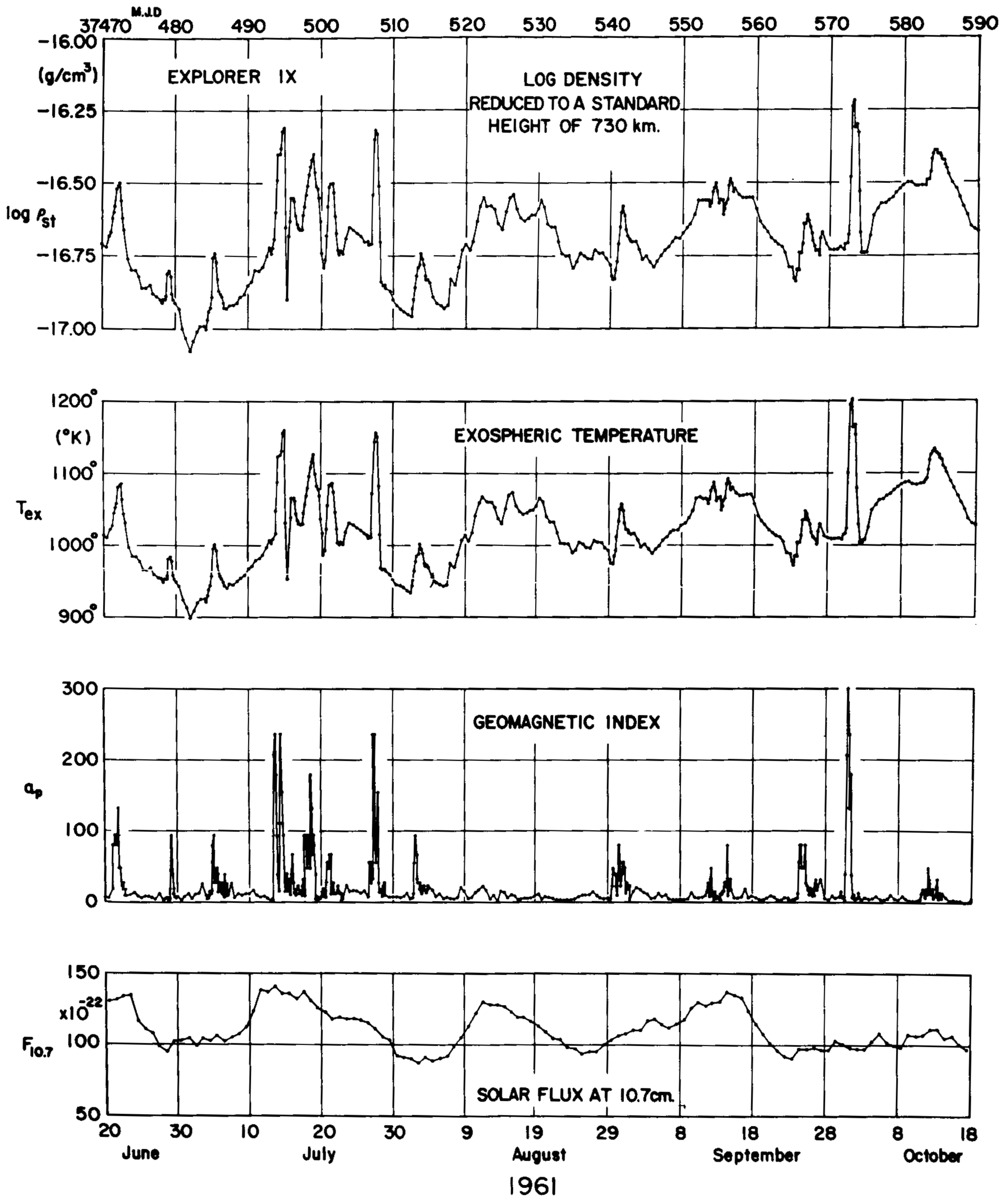

Figure 3. Densities and temperatures derived from the drag of the Explorer IX satellite (1961 δ1), compared with the geomagnetic index a_p and the 10.7-cm solar flux. The drag was determined from precise position measurements on photographs taken with the Baker-Nunn cameras. Notice the 27-day oscillations in phase with the 10.7-cm flux and the perturbations in phase with geomagnetic disturbances. MJD in the abscissa is the Modified Julian Day (JD minus 2400000.5).

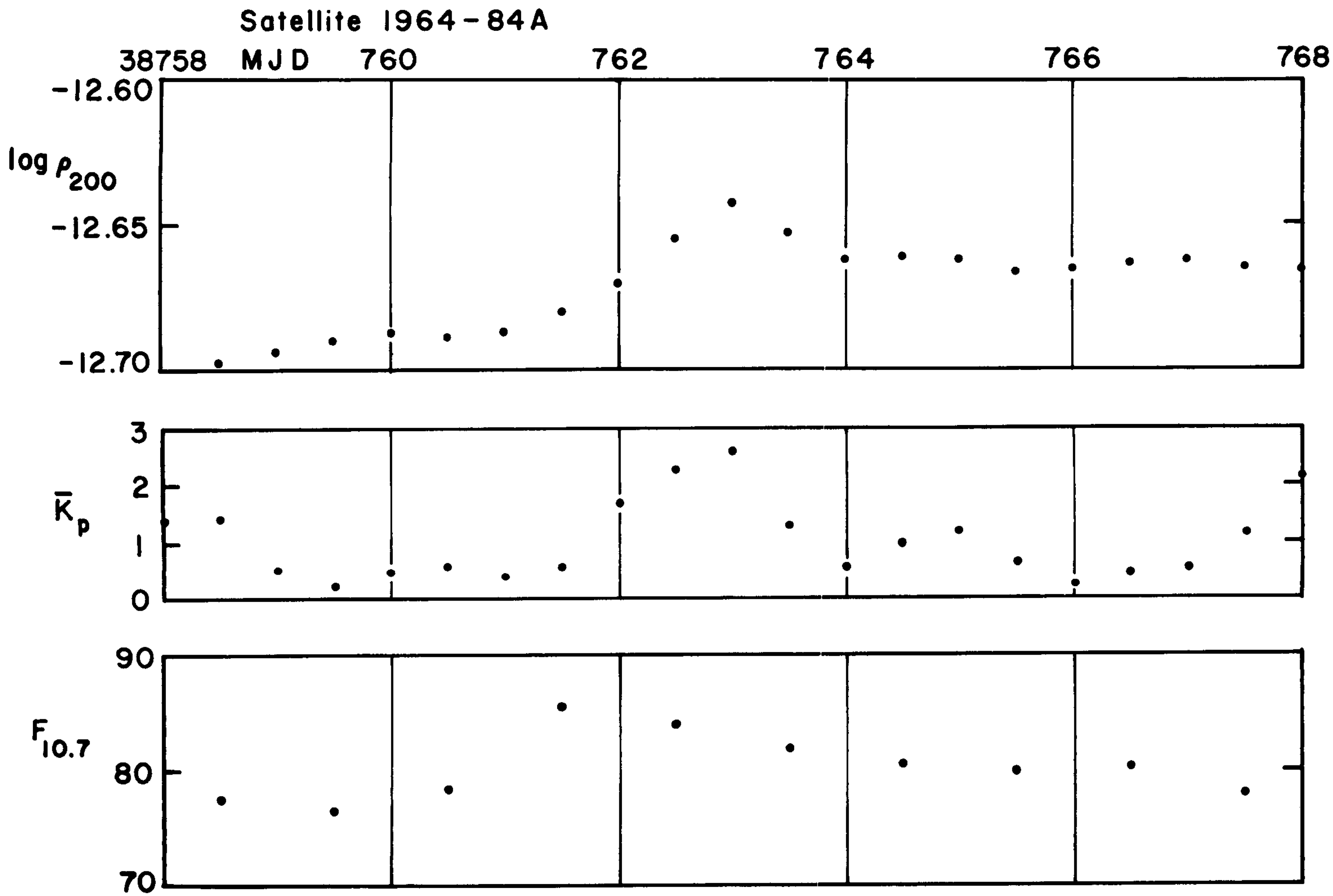

Figure 4. This figure illustrates the error that can be introduced when the time lag between the variations in the 10.7-cm flux and those in the atmospheric densities is derived without first removing from the latter the effect of geomagnetic activity. Densities from the drag of the San Marco satellite (1964 84A) are plotted on top. A sudden increase in the 10.7-cm flux (bottom) is followed by a small magnetic disturbance the following day (center). The maximum in the density curve occurs, as usual, some six hours after the peak of the magnetic disturbance.

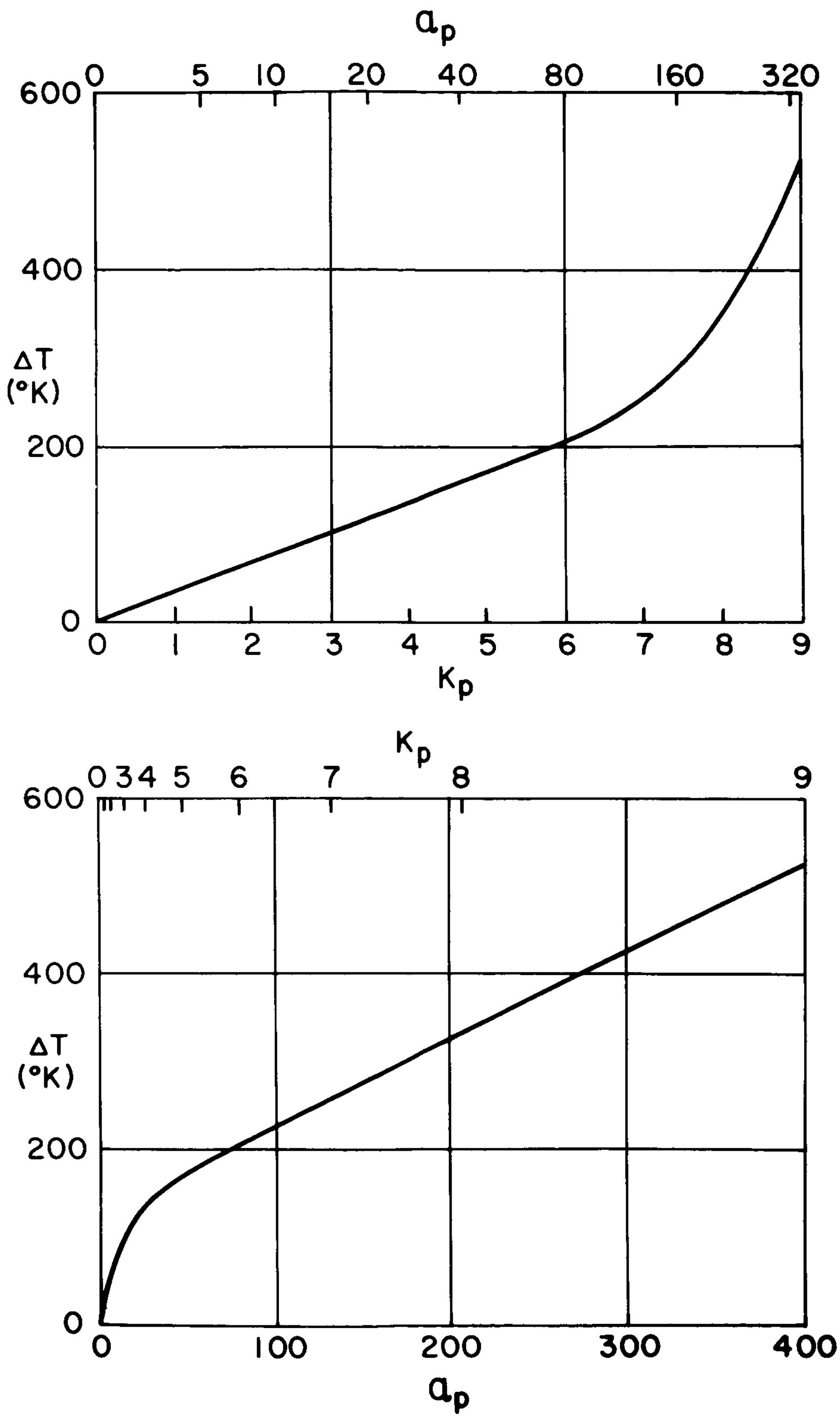

Figure 5. Atmospheric heating ΔT as a function of the three-hour geomagnetic indexes K_p and a_p. The abscissa of the first diagram is K_p; the corresponding a_p values are marked on top. The abscissa of the second diagram is a_p; the corresponding K_p values are marked on top.

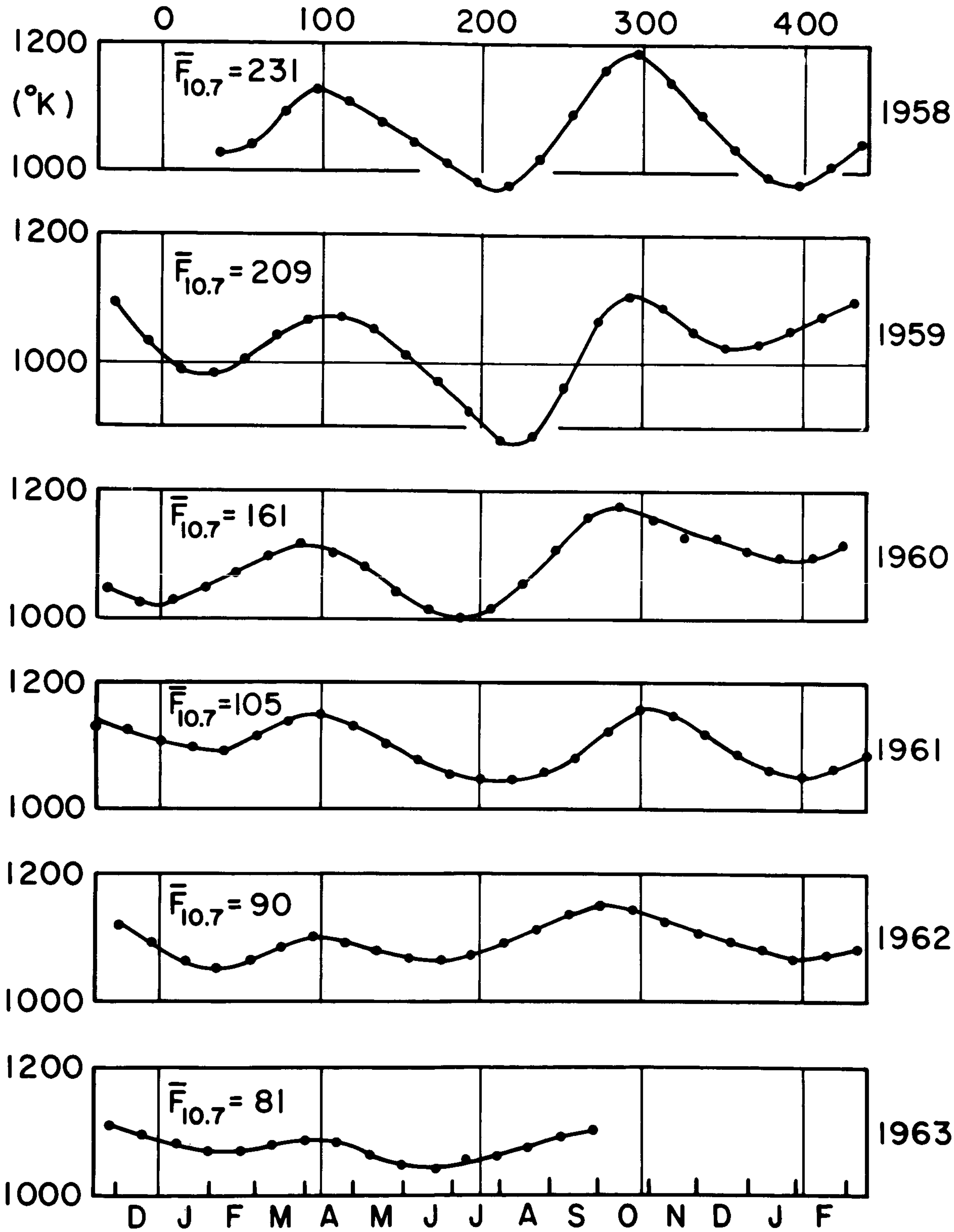

Figure 6. The semiannual variation in the temperature above the thermopause from 1958 to 1963, as derived from the drag of five satellites (Jacchia, 1964). Plotted are nighttime temperatures reduced to a standard 10.7-cm solar flux value of 175. The yearly average of the flux is given for each year.

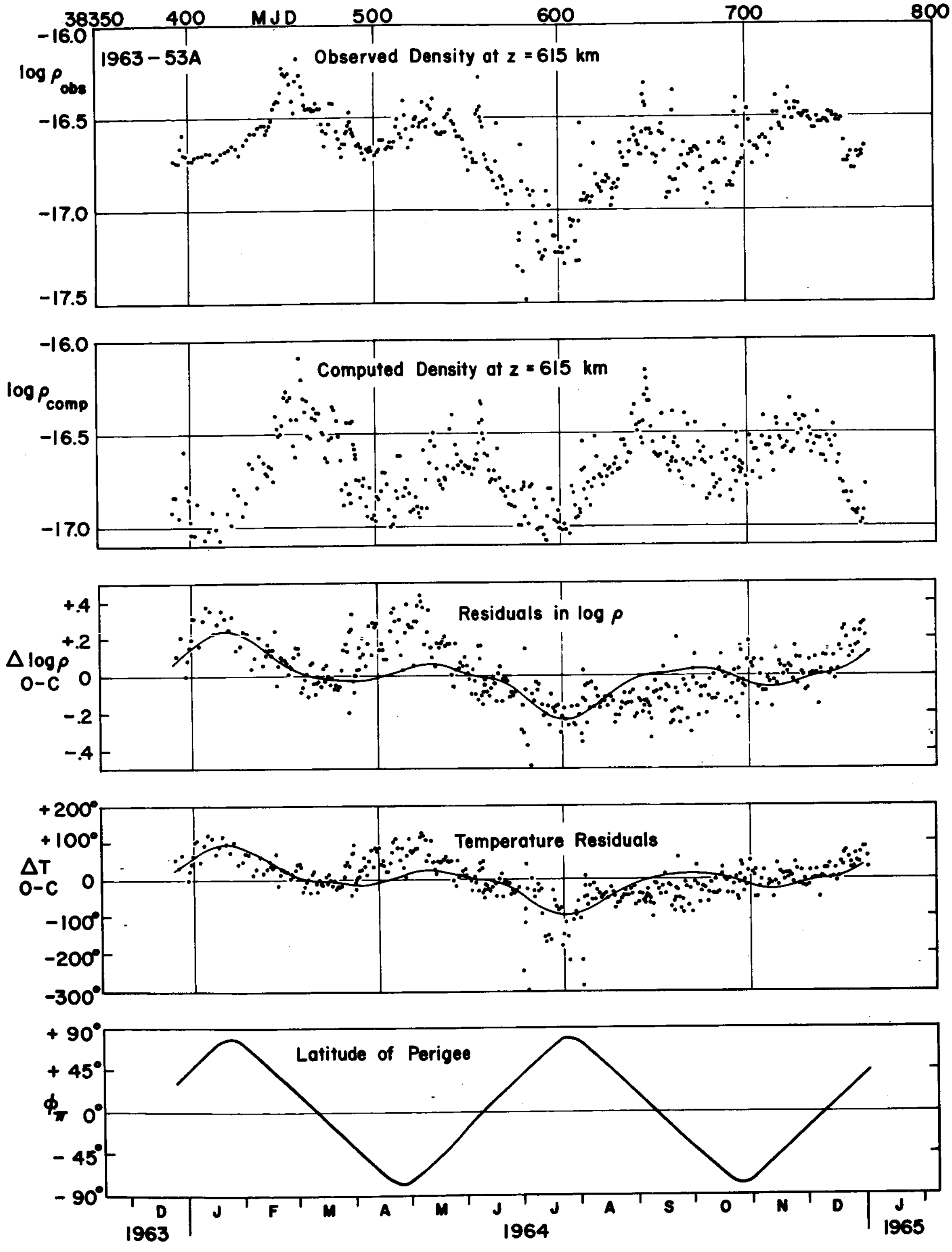

Figure 7. Seasonal variations in the densities derived from the drag of the Explorer 19 satellite (1963 53A). Observed densities as a function of time (top) are compared with densities computed using the formulae and tables given by Jacchia (1964). Residuals in density and the corresponding computed temperature residuals are compared with the curve given by equation (1), when C is made equal to 0.25 for $\Delta \log \rho$ and to 100° for ΔT. The latitude of perigee is indicated in the bottom section.

NOTICE

This series of Special Reports was instituted under the supervision of Dr. F. L. Whipple, Director of the Astrophysical Observatory of the Smithsonian Institution, shortly after the launching of the first artificial earth satellite on October 4, 1957. Contributions usually come from the Staff of the Observatory.

First issued to ensure the immediate dissemination of data for satellite tracking, the Reports have continued to provide a rapid distribution of catalogs of satellite observations, orbital information, and preliminary results of data analysis prior to formal publication in the appropriate journals. The Reports are also used extensively for the rapid publication of preliminary or special results in other fields of astrophysics.

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