CHANGES IN THE LOWER EXOSPHERE SINCE SOLAR MINIMUM

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ABSTRACT

Measurements of atmospheric densities between 500 km and 750 km and between ±80° latitude have been made by means of the Explorer XIX (1963-53A) and Explorer XXIV (1964-76A) satellites during the period of increasing solar activity (1964-1967). During this period the atmosphere has expanded due to increased solar heating to such an extent that near 700 km recent measurements indicate densities 30 times greater than were measured at minimum solar activity. Latitudinal-seasonal variations have changed during this period of increased solar heating. It was found that peak densities near 650 km have shifted from high latitudes in the winter hemisphere to low latitudes in the summer hemisphere. This change in latitudinal-seasonal variations confirms the prediction of Keating and Prior that at these altitudes with an increase in solar activity, the winter helium bulge would be dwarfed by an expanding summer atomic oxygen bulge. It is apparent that atomic oxygen has now replaced helium as the principal constituent near 650 km. After accounting for latitudinal-seasonal variations, a global semiannual and annual variation of atmospheric densities nearly as large as has been observed in the past becomes evident throughout the period of increasing solar activity. Unexpectedly low densities were observed in September of 1964, 1965, and 1966. A comparison is made of the semiannual effect near 650 km with recently reported measurements near 190 km with Secor 6 (1966-51B). There is a striking agreement between the monthly rise and fall of densities at the two widely separated altitudes even though the measurements were made at different latitudes and local times. A comparative analysis of these measurements indicates that between June 1966 and June 1967 the semiannual variation was characterized by much larger density variations in the lower thermosphere and probably smaller variations in exospheric temperature than have been assumed in the past.

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INTRODUCTION

Since July 1964, solar activity has been increasing and the earth's atmosphere at satellite altitudes has been expanding due to increased solar heating. The last such period of increasing solar activity started in 1954 before the launching of earth satellites. Consequently, the cycle beginning in 1964 is the first solar cycle during which it has been possible to study changes in the global distribution of the neutral atmosphere at satellite altitudes throughout the period of increasing solar activity. The drag-sensitive low mass-to-area ratio 12-foot-diameter Explorer XIX and XXIV satellites were specifically designed to measure the global distribution of neutral densities in the lower exosphere near 650 km. Both satellites were launched into high inclination orbits, Explorer XIX in December 1963, and Explorer XXIV in November 1964. Using these satellites, properties of the lower exosphere have been studied throughout the period of increasing solar activity.

This paper deals with drag measurements performed with Explorers XIX and XXIV during the present period of increasing solar activity. In particular, results are given on the response of the lower exosphere to solar heating, on recent measurements of latitudinal-seasonal variations, and on the global semiannual variation in the lower exosphere.

DRAG MEASUREMENTS

The Explorer XIX and XXIV satellites were designed at the NASA Langley Research Center specifically for drag measurements of atmospheric density at satellite altitudes (reference 1). Both are rigid spheres 12.0 ft (3.66 m) in diameter. Explorer XIX, with a mass of 8.069 kg, was launched on December 19, 1963, into an orbit of inclination 78.6°, perigee altitude 592 km and apogee altitude 2392 km. Explorer XXIV with a mass of 8.609 kg was launched on November 21, 1964, into an orbit of inclination 81.4°, perigee altitude 526 km and apogee altitude 2495 km. Radiation-force effects raised the perigee height of Explorer XIX relative to Explorer XXIV so that on the average Explorer XIX measured densities 120 km above where Explorer XXIV measured densities.

The methods developed for the determination of densities from the Air Density Explorer satellites have been described in detail by Keating, Mullins, and others (references 2 and 3). The effects of atmospheric drag are deduced by subtracting energy changes due to radiation forces from the total energy decay. Radiation forces were evaluated from reflectance measurements of the satellite material (references 3 and 4). The assumed drag coefficient increased with perigee altitude. The density at perigee was evaluated by matching the observed energy decay due to drag with the energy losses obtained when the satellite was moving through the rotating spring/fall atmosphere of reference 5. This model atmosphere had a different density profile for each exospheric temperature, and was nearly identical with the static diffusion model of reference 6. In order to minimize errors in atmospheric density due to inaccuracies in the assumed atmospheric model, the density was then evaluated at an altitude between

1/2 and $\sqrt{3/4}$ density scale heights above perigee, depending on the value of the density scale height and its rate of variation (reference 3). This is somewhat similar to the method described by King-Hele (reference 7).

INCREASING SOLAR ACTIVITY

During the month of minimum solar activity, July 1964, inferred exospheric temperatures of less than 700° K were measured with Explorer XIX (reference 3). With the rise of solar activity, daytime temperatures in excess of 1300° K have been measured. This corresponds to an increase in density at 700 km of more than a factor of 30.

The response of the lower exosphere to solar heating during the period of increasing solar activity (1964-1967) has been investigated by means of drag measurements of the Explorer XIX and XXIV satellites. Densities were predicted at the times and location of measurements of Explorers XIX and XXIV and the variations of exospheric temperature with solar activity which best fit observations were determined. To predict densities, the effects of the diurnal variation and the winter helium bulge were taken into account using equations (1) and (3) of reference 8, while the temperature variations associated with geomagnetic activity and the semiannual variation were assumed to be given by the expressions in the U.S. Standard Atmosphere Supplements, 1966 (reference 5). The assumed diurnal variation corresponded to the model of reference 5 with two exceptions: the maximum temperatures occurred at the latitude of the subsolar point and the coefficient m was set equal to 1. The Explorer XIX data covered the period July 1964 through December 1967, while Explorer XXIV data covered the period December 1964 through December 1967. All September data were eliminated due to the September anomaly described in the next section. The minimum nighttime temperature, T_o, was assumed to be related to the 10.7-cm index of solar activity by the expression

$$T_o = 362^o + K_1 \bar{F}_{10} + K_2 \left(F_{10} - \bar{F}_{10}\right)$$

where F_{10} represents the 10.7-cm flux from the sun divided by 10^{-22} watts/m^2/cycles/sec and $\bar{F}_{10}$ represents this quantity averaged over three solar rotations. The coefficient K_1 represents the response of the atmosphere to the long-term variation of solar activity in degrees Kelvin, while K_2 represents the response of the atmosphere to short-term variations.

Predicted temperatures were converted to atmospheric densities assuming the spring/fall model of reference 5. In figure 1 the standard deviations σ between $\log_{10}$ of predicted and observed densities for the period July 1964 through December 1967 are shown as a function of the coefficients K_1 and K_2. Lowest standard deviations are obtained for K_1 of approximately 3.4 and K_2 of approximately 1.6. The lowest root-mean-square residuals are obtained for approximately the same values.

If the latitudinal coefficient, m, in the diurnal model is changed from 1.0 to 2.5, as suggested in reference 14, the minimum standard deviation exceeds 0.1, but the same values of K_1 and K_2 are obtained. Thus the $m = 1.0$ model appears to be slightly better in the lower exosphere.

Approximate values of coefficients K_1 and K_2 during decreasing solar activity (reference 5) were, respectively, 3.6 and 1.8. As during the period of decreasing solar activity, the atmosphere responds more strongly to the variation with the solar cycle than the short-term variations within one solar rotation.

Mahajan (reference 10) has reported an increase of 3.4° K per unit increase of $\overline{F}_{10}$ for nighttime ion and electron temperatures derived from backscatter spectra during the current rising phase of solar activity. These measurements, which were made between 250 and 400 km, are in agreement with the value of K_1 calculated for the lower exosphere during the same period.

SEMIANNUAL VARIATION

After accounting for the diurnal temperature variation and winter helium bulge, using equations (1) and (3) of reference 8, and the effects of solar and geomagnetic activity (reference 5), a semiannual and annual variation in atmospheric densities is evident from the measurements of Explorers XIX and XXIV taken between ±80° latitude throughout the period of increasing solar activity. Shown in figure 2 are mean monthly density residuals from July 1964 through December 1967. Between July and November 1964, the data points represent only the measurements of Explorer XIX. Starting in December 1964, the points represent the average of the residuals from the two satellites. Comparing the data for each year, minimum densities occur within a month of February and August while maximum densities occur within a month of April and November. In addition to the semiannual variation, there is evidence of an annual variation. Each year densities are lower near August than near February. It may be seen that the semiannual density variation was much greater during 1967 than during the previous years. This may be due to atomic oxygen replacing helium as the principal constituent at these altitudes with the increase in solar heating.

The dashed line in figure 2 is based on an empirical expression (reference 6) developed by Jacchia to represent the average semiannual variation of exospheric temperature during decreasing solar activity. The principal difference between the predictions and observations occurs in September of 1964, 1965, and 1966. By September 1966, densities were lower by more than a factor of 2 than predicted. The September anomaly does not appear to be associated with latitudinal variations or with variations in 10 cm flux and, as may be seen, similar variations do not occur near the vernal equinox.

If the semiannual effect were produced by the interaction of the earth with thin streams of plasma from sunspot regions (references 23 and 24), and if, in September as the earth approached maximum northerly heliocentric latitudes a marked deficiency of sunspots existed in the sun's northern hemisphere, the observed anomaly might result. A marked north-south asymmetry has been noted in the development of the new cycle (reference 25), the greatest in 100 years, but it is just the reverse of what seems to be required. There were many more spots in the northern hemisphere than the southern hemisphere. It is also interesting to note that by September 1967, both the September anomaly in density and the north-south asymmetry of sunspots disappeared.

The semiannual variation measured by Explorers XIX and XXIV has been compared with Secor 6 data where all significant variations other than the semiannual variation have been removed (reference 9). Secor 6 was launched into a polar orbit in June 1966, and reentered in early July 1967. Shown in figure 3 are monthly mean density residuals which were calculated for the lifetime of the satellite. As may be seen, there is remarkable agreement between the density variations near 190 km measured by Secor 6 and those near 650 km measured by Explorers XIX and XXIV. At both altitudes, densities reach minimums in July, September, and January and maximums in August, November, and April. The agreement between the data increases confidence in methods of data reduction and indicates that the semiannual effect is truly global since simultaneous measurements were made at different latitudes and local times. Also, the September anomaly observed in the Explorer XIX and XXIV data is confirmed.

The predicted variation of Secor 6 data is indicated by the dashed line. As may be seen, the semiannual variation is predicted to be almost nonexistant at 190 km. The predicted variation is small due to the assumed invariance of density and temperature at 120 km in the U.S. Standard Atmosphere Supplements, 1966 (reference 5). If the percentage variation of density observed at 190 km were to also occur at 120 km for all constituents, a much smaller semiannual exospheric temperature variation would be required to account for the observed semiannual density variation at 660 km, but a larger annual variation would be required. On the other hand, the density variations observed at 190 km could result from temperature variations at 120 km.

In light of the large semiannual variation at 190 km, it has been pointed out (reference 9) that perhaps the diurnal variation of 1.7 measured at 155 km with 1966-101G (reference 26), may be partially a disguised semiannual variation. This seems likely when it is considered that the MUMP diurnal survey of the thermosphere (reference 27) consisting of six launches in one day indicated a diurnal variation at 150 km of less than 1.2.

LATITUDINAL-SEASONAL VARIATIONS

A continuation of a study of latitudinal-seasonal variations in the lower exosphere which resulted in the discovery of the winter helium bulge (references 11, 12, and 8) has now been completed for the period of August 1966 to December 1967. As before, the diurnal bulge was assumed to be located at 2 in the afternoon at a latitude of $B\delta_S$, where B is a constant and δ_S is the declination or latitude of the sun. Thus if B were +1 the area of peak densities would remain at the latitude of the sun and therefore migrate between $\pm 23^{\circ}$ latitude. A positive B would indicate a bulge which remains on the sun side of the equator or in the summer hemisphere, but a negative B would indicate peak densities in the winter hemisphere.

For each data group studied, the value of B was chosen which gave the lowest standard deviation between predictions and observations. Densities were predicted assuming the diurnal variation given by equation (1) of reference 8, the semiannual variation and variation with solar and geomagnetic activity given in reference 5, and the relationship between exospheric temperature, altitude, and atmospheric density given by the spring/fall model of reference 5. The results of the analysis are tabulated in table I. The results of analysis on previous data groups (reference 12) are shown in table II. The quantity $\log_{10}$ [n(He)/n(O)] was determined from the average altitude and temperature of each data set using the spring/fall tables of the U.S. Standard Atmosphere Supplements, 1966 (reference 5).

Comparing tables I and II, it may be seen that the average exospheric temperature of the new data sets is significantly higher than the previous data sets which covered the time interval from February 1961 through July 1967.

Figure 4 shows the tabulated values of B as a function of $\log_{10}$ [n(He)/n(O)]. The new data are represented by the closed data points. On the left atomic oxygen is the principal constituent while on the right helium is the principal constituent. As may be seen, negative values of B or, in other words, peak densities in the winter occur in the helium-rich atmosphere while positive values of B indicating peak densities in the summer occur in an oxygen-rich atmosphere. To explain this shift in latitudinal-seasonal variations, Keating and Prior introduced the concept of a winter helium bulge coexisting with a summer atomic oxygen bulge (references 11 and 12).

With the increase of solar activity and exospheric temperatures, atomic oxygen should have replaced helium as the principal constituent at the measurement altitudes of Explorers XIX and XXIV. If the observed latitudinal-seasonal variations were simply dependent on altitude, such a change in composition would have no effect. On the contrary, Keating and Prior (reference 12) predicted that when such a change of composition occurred that peak densities would shift from the winter hemisphere to the summer hemisphere. As may be seen, comparing the new data with previous data, the predicted shift in latitudinal-seasonal variations has indeed occurred. At these altitudes, with the increase in solar heating, the expanding summer atomic oxygen bulge has dwarfed the winter helium bulge. With the coming decrease of solar activity, it is expected that the atmosphere will cool and the winter helium bulge will again predominate at these altitudes.

With increasing altitude, helium replaces atomic oxygen as the primary constituent and the diurnal bulge should shift away from the summer hemisphere. This relation of the latitudinal-seasonal variations with altitude is evident in the new data. The recent Explorer XXIV satellite measurements are approximately 175 km below those of Explorer XIX. As may be seen, at the Explorer XXIV measurement altitudes, where the helium to atomic oxygen ratio is much lower, the measurements indicate that the diurnal bulge migrates much deeper into the summer hemisphere than at Explorer XIX altitudes.

Keating and Prior (references 11 and 12) suggested that the winter helium bulge may be caused by a seasonal variation in the effective altitude at which diffusive separation of helium begins. A similar explanation was offered by Johnson (reference 13) who reasoned that a drop in turbulence in winter would result in lowering of the eddy-mixing coefficient and lowering of the turbopause. This would result in increased helium concentrations and decreased argon concentrations at satellite altitudes. This hypothesis was also offered by Jacchia (reference 14) who confirmed the existence of a winter helium bulge with an independent study of the Explorer XIX and XXIV data. The first experimental confirmation of the drop in turbopause altitude in winter came shortly from Hartmann et al. (reference 15) who made mass spectrometer measurements of the helium and argon content of the lower thermosphere above Fort Churchill, Canada. They found winter helium concentrations higher by a factor of 5 than predicted by CIRA, 1965 (reference 16), and argon concentrations more than a factor of 2 lower than predicted. (The increase in helium and decrease in argon is consistent with a drop in the eddy-mixing coefficient.) They calculated the resulting turbopause altitudes for the two constituents as 90 km for helium and 99 km for argon. These turbopause altitudes were much lower than predicted by CIRA, 1965. Additional confirmation of the winter helium bulge has been obtained from airglow observations by Tinsley (reference 17).

At the 1967 London COSPAR meeting, Keating and Prior gave the following expression for the latitudinal-seasonal variations in the helium concentration above 120 km, assuming peak exospheric temperatures occurred at the latitude of the sun (reference 8):

$$\Delta \log_{10} n(He) = 0.06 - 0.5\ \delta_P\ \delta_S$$

where δ_P is the latitude of the measurement in radians and δ_S is the declination or latitude of the sun. When this variation of boundary conditions is combined with the diurnal variation of exospheric temperature, the distribution of helium in the lower exosphere is obtained. The peak helium concentrations near the winter pole measured by Explorer XIX (references 12 and 14), Explorer XXIV (references 12 and 14), and Echo II (reference 12); the seasonal variation observed with Explorer IX near the equator (references 18 and 12); and the sharp drop of helium densities in the summer hemisphere observed with Explorer XVII (references 19 and 12) and Explorer XXXII (reference 20) all tend to confirm this model.

Johnson (reference 21) now believes that a more powerful means of concentrating helium over the winter pole than the drop in the turbopause or the decrease of the eddy-diffusion coefficient is provided by the meridional circulation required to heat the winter polar region to observed temperatures. He indicates that the winter pole is adiabatically heated by the downward flow of gas and that this gas is replenished by meridional flow into the winter hemisphere. Johnson finds that this mechanism provides an excess in-flow of helium of six-sevenths of the total in-flow, which is ample to maintain the pole-to-pole variation indicated in the above expression after allowing for lateral diffusion away from the bulge.

Besides the winter helium bulge being a natural consequence of such flow, this sort of circulation pattern could also explain the winter warmings in the mesosphere and the semiannual variation in the thermosphere and exosphere (reference 22). The heat transfer to the winter mesosphere may result in a cooler thermosphere and exosphere reducing the observed densities near the solstices, producing a semiannual variation in density.

CONCLUSIONS

The following may be concluded from the study of Explorer XIX and XXIV drag measurements during the present period of increasing solar activity.

1. The nighttime temperature of the lower exosphere has increased approximately 3.4° K per unit decimetric flux averaged over three solar rotations. This response is in general agreement with the nighttime response of ions and electrons below 400 km.
2. The nighttime temperature of the lower exosphere changes approximately 1.6° K per unit decimetric flux for short-term variations in solar activity.
3. A global semiannual and annual variation is observed in the lower exosphere throughout the period of increasing solar activity.
4. Anomalously low densities occurred in September of 1964, 1965, and 1966. By September 1966, densities were lower by more than a factor of 2 than predicted. The September anomaly does not appear to be associated with latitudinal variations and similar variations do not occur in March.
5. There is a remarkable agreement between global-density variations at 190 km measured by Secor 6 and near 650 km measured by Explorers XIX and XXIV. A comparative analysis indicates that

from June 1966 to June 1967, the semiannual variation is characterized by much larger density variations in the lower thermosphere and probably smaller variations in exospheric temperature than have been assumed in the past.

6. Studies of the latitudinal-seasonal variations in the lower exosphere in 1966-1967 indicate that:

   a. With increasing solar activity peak densities near 650 km have shifted from the winter hemisphere to the summer hemisphere.

   b. With increasing altitude peak densities shift back toward the winter hemisphere.

These results are consistent with the prediction of Keating and Prior that with increasing solar activity the summer atomic oxygen bulge would expand and dwarf the effect of the winter helium bulge.

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TABLE I.- VARIATION OF PARAMETER B WITH ATMOSPHERIC PROPERITES (8/66-12/67)

Satellite	Time interval	Average altitude, km	Average inferred temperature, $^{\circ}K$	B	$\log_{10}\left[\frac{n(He)}{n(O)}\right]$
Explorer XIX	Aug. 21.5, 1966 to Feb. 11.5, 1967	735	1008	-0.1	+0.34
Explorer XIX	Feb. 18.5 to Dec. 25, 1967	773	1122	+.2	+.20
Explorer XXIV	Aug. 15.5, 1966 to Jan. 15.5, 1967	585	921	+1.5	-.19
Explorer XXIV	Jan. 30.5 to Nov. 20.5, 1967	579	1059	+1.1	-.55

TABLE II.- VARIATION OF THE PARAMETER B WITH ATMOSPHERIC PROPERTIES (2/61-7/66)

Satellite	Time interval	Average altitude, km	Average inferred temperature, °K	B	$\log_{10}\left[\frac{n(He)}{n(O)}\right]$
Explorer IX	Feb. 21 to July 19, 1961	744	964	-0.7	+0.53
Explorer IX	July 25 to Dec. 22, 1961	813	996	-1.7	+.74
Explorer IX	Dec. 28, 1961 to May 27, 1962	834	970	-2.5	+.97
Explorer IX	June 2 to Oct. 30, 1962	783	945	-1.1	+.79
Explorer IX	Nov. 5, 1962 to Apr. 4, 1963	672	904	+.7	+.36
Explorer IX	Apr. 10 to Sept. 7, 1963	547	834	+.9	-.14
Explorer IX	Sept. 13, 1963 to Jan. 21, 1964	428	817	+.7	-.88
Explorer XIX	Dec. 24.5, 1963 to Dec. 29, 1964	663	815	-1.1	+.65
Explorer XIX	Jan. 13, 1965 to Jan. 6.5, 1966	692	832	-2.5	+.74
Explorer XIX	Jan. 21, 1966 to July 28.5, 1966	718	911	-.3	+.60
Explorer XXIV	Dec. 9.5, 1964 to Nov. 3, 1965	597	802	+.1	+.30
Explorer XXIV	Nov. 15.5, 1965 to July 26, 1966	638	831	-.5	+.41
Echo II	Feb. 13 to July 14, 1964	1130	848	-2.4	+3.09
Echo II	Jan. 12 to May 25, 1965	1130	780	-2.6	+3.63
Echo II	June 1 to Oct. 19, 1965	1130	823	-3.3	+3.28

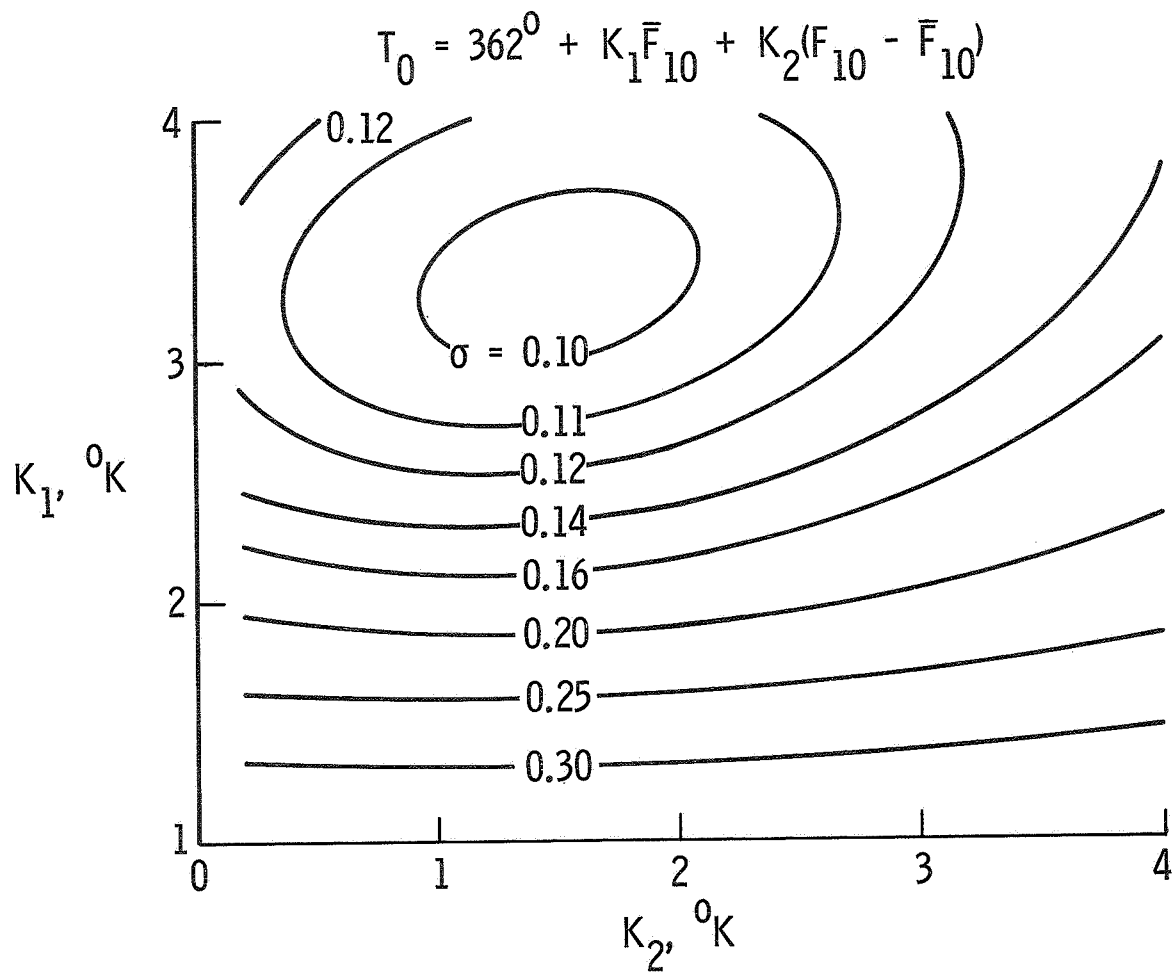

Figure 1.- Standard deviation, σ, of $\log_{10}$ (density, g/cm^3) for coefficients K_1 and K_2 in above expression for minimum exospheric temperature.

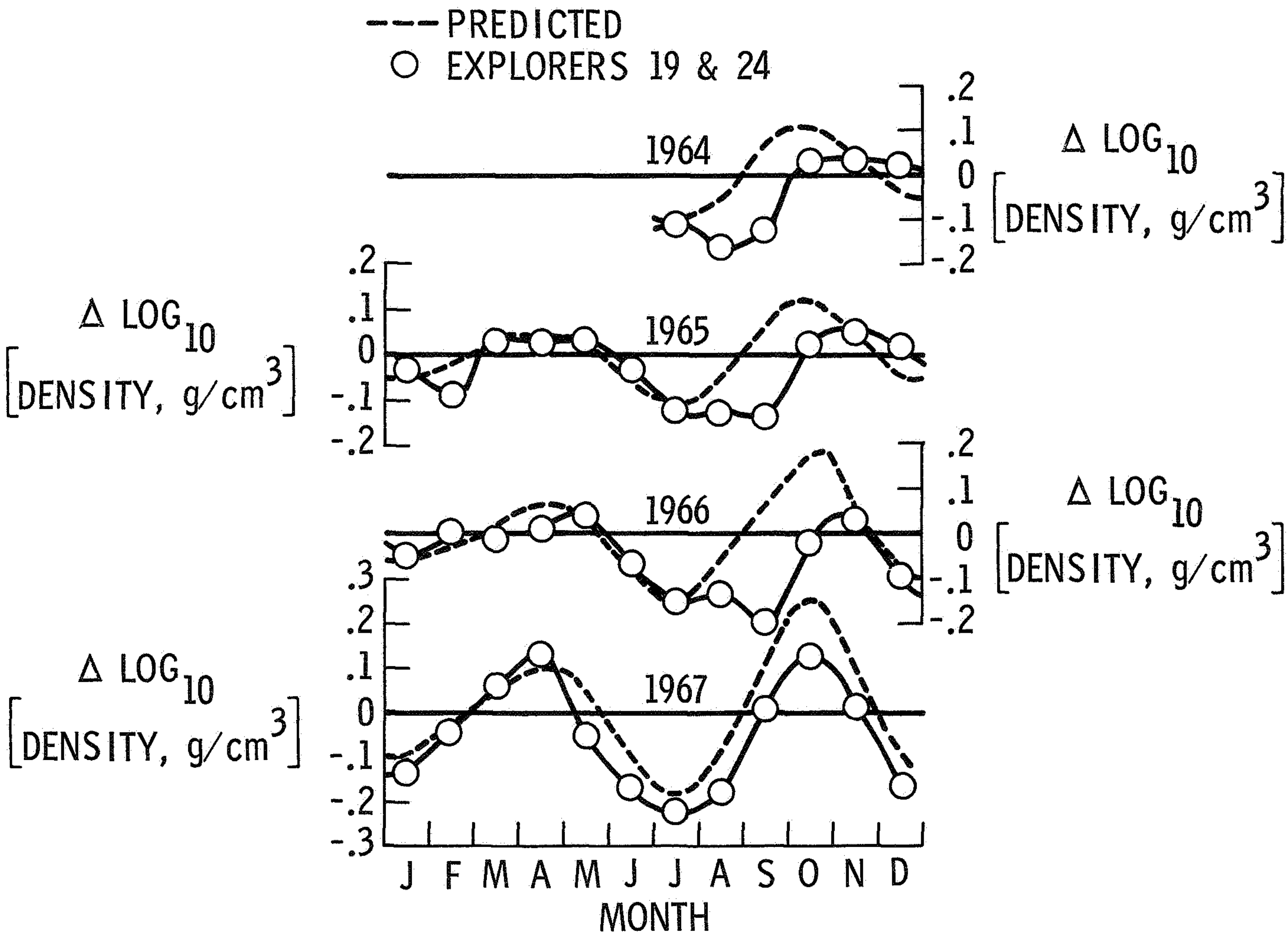

Figure 2.- Monthly means of density residuals of Explorers XIX and XXIV associated with time of year.

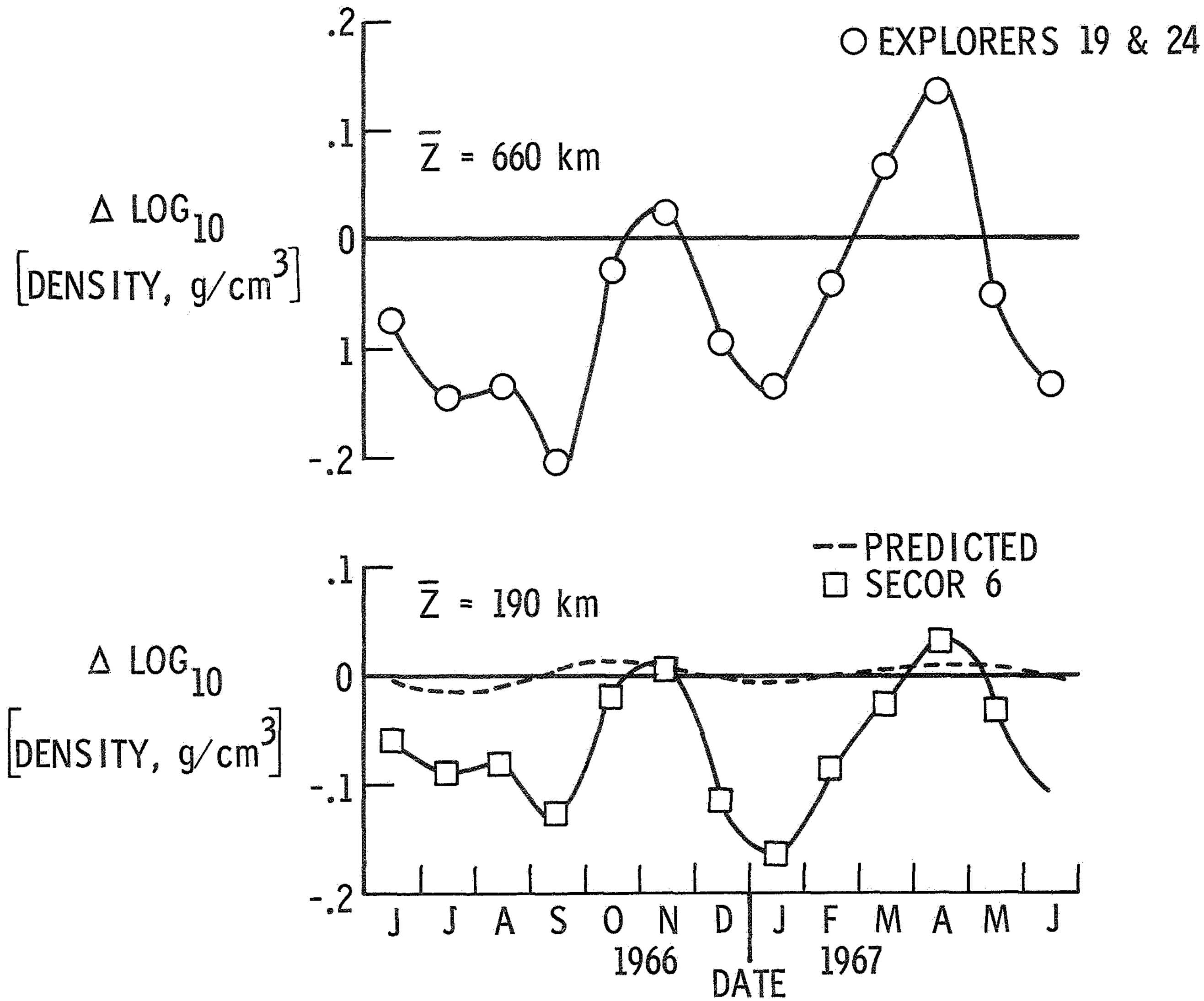

Figure 3.- Global density variation near 190 and 660 km (June 1966-June 1967).

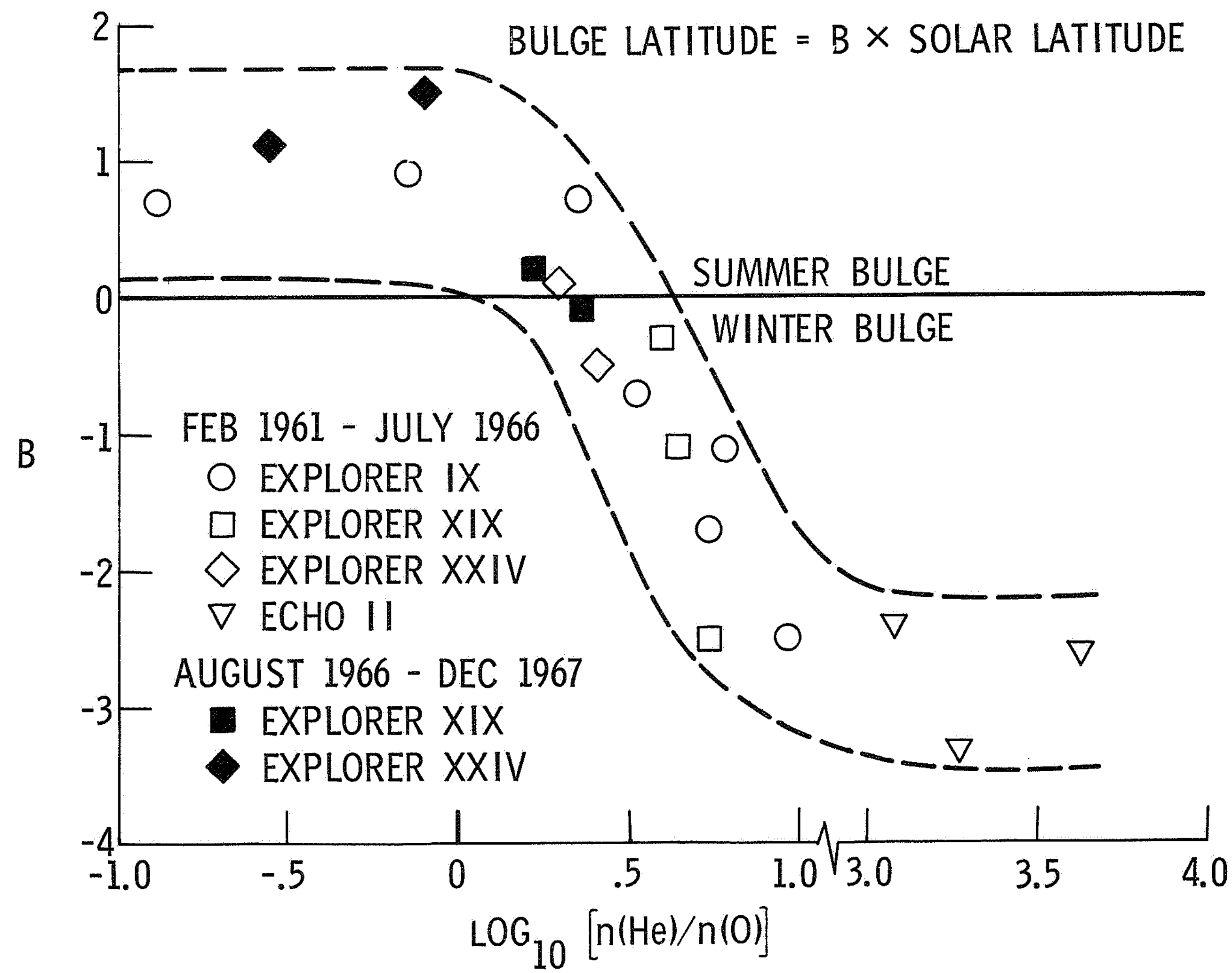

Figure 4.- Relationship between observed values of parameter B, which gives latitudinal-seasonal variation of diurnal bulge position, and relative concentrations of helium to atomic oxygen.

NASA-Langley, 1968