INTERNATIONAL JOURNAL OF GEOMAGNETISM AND AERONOMY
VOL. 2, NO. 3, PAGES 195–200, DECEMBER 2001

Electron density variations in the polar *D* region from in situ measurements

A. D. Danilov and L. B. Vanina

Institute of Applied Geophysics, Moscow, Russia

Abstract. A dataset of more than 500 in situ (probe method) measurements of the electron concentration in the *D* region on board M100B meteorological rockets at the Molodezhnaya station (Antarctic) and Heiss Island (Arctic) is considered. Dependencies on season, solar zenith angle, and magnetic activity are studied. The results obtained earlier for the 80 km height are now confirmed for 75 and 84 km. On the basis of the vertical profile of the electron concentration in the nonsunlit *D* region a conclusion is drawn that there is a corpuscular ionization source in the auroral oval even in quiet geomagnetic conditions. It is shown that the electron concentration behavior at Heiss Island depends on whether the station is in the auroral oval or polar cap. The electron concentration dependence on the atmospheric temperature is studied.

Introduction

The problem of *D*-region modelling is a rather complicated one. One of the difficulties in the modelling is the presence of many ionization sources. It is especially true for the high-latitude *D* region, where energetic particles (precipitating electrons, solar protons) may create an increased electron concentration during solar-geophysical events.

The principal idea of this study is to carry out comparative studies and obtain information on the electron concentration [*e*] variations depending on conditions (solar zenith angle, season, and geomagnetic activity). We also compare the corresponding dependencies for the Arctic and Antarctic to consider possible differences between the polar ionospheres of both hemispheres.

The first results of this study were published by *Danilov and Vanina* [1999], who considered some dependencies of [*e*] for the fixed height of 80 km. Below we continue analysis of the same data, analyzing two more altitudes (75 and 84 km) and trying to obtain some information on the vertical profile of various effects. The altitude of 84 km was taken because the peak altitude of the M100B rocket flights was around 85 km so at this altitude there are much less measurements than at 84 km.

Paper number GAI99334.
CCC: 1524–4423/2001/0203–0334$18.00

The online version of this paper was published July 6, 2001.
URL: http://ijga.agu.org/v02/gai99334/gai99334.htm
Print companion issued December 2001.

The Initial Data

We use for the analysis the data bank of rocket measurements of the electron concentration in the *D* region [*Knyazev et al.,* 1993]. The MR100B meteorological rockets have been flown by the Central Aerological Observatory in 1979–1992 from two sites: Heiss Island (φ = 80.6°N, λ = 58.0°E, Φ = 72°N) and Molodezhnaya (φ = 67.7°S, λ = 45.9°E, Φ = 69°S). The device of an electrostatic probe type has been used. The instrumentation and data processing were described by *Borisov et al.* [1981] and *Sinel'nikov et al.* [1980].

The databank used contains the results of 326 flights at Heiss Island and 250 flights at the Molodezhnaya station. The vast majority of the flights at Molodezhnaya were performed at 1400 UT which corresponds to about 1700 LT (1500 MLT). The station almost the entire day is situated within the auroral oval, so the data presented below may be considered typical for the dusk sector of the auroral zone.

The Heiss Island flights were conducted at various LT moments. During different periods of the day Heiss Island may be located within the auroral oval, polar cap, and subauroral zone. Since the physics of the *D* region may be different in

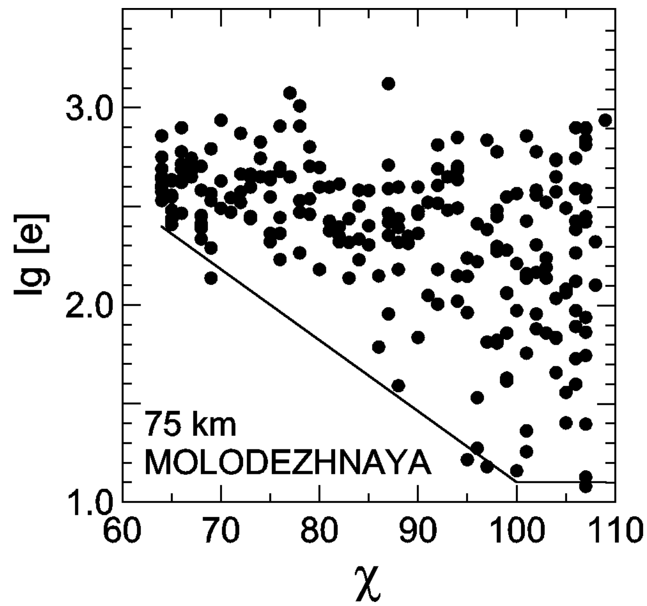

Figure 1. Electron concentration at 75 km versus solar zenith angle χ at the Molodezhnaya station.

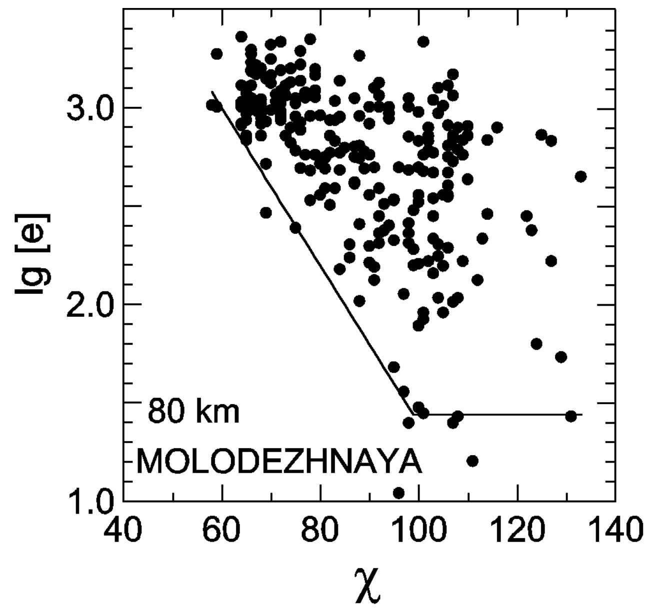

Figure 2. The same as in Figure 1 but at 80 km.

the auroral zone and polar cap, the analysis of the data on $[e]$ should be performed separately for the first two regions. The separation of the Heiss Island data to auroral oval (ao) and polar cap (pc) was done according to the local time of the observations. There are only a few flights corresponding to the Heiss Island location within the subauroral zone, so below we do not consider this region. The Heiss Island (ao) flights were conducted at evening hours, so comparing them with the Molodezhnaya data we compare the dusk sectors of the auroral oval in two hemispheres.

Diurnal Variations of $[e]$

Figures 1, 2 and 3 show typical dependence of the electron concentration on solar zenith angle χ for the Molodezhnaya station at altitudes of 75, 80, and 84 km. The strong scatter of the points is evident, which is quite natural, because in the polar ionosphere there are additional corpuscular sources of ionization which are very changeable. Similar to Figures 1, 2 and 3 pictures were drawn for Heiss Island (separately for the auroral oval and polar cap).

The lines in Figures 1, 2 and 3 show some sort of a lower envelope for each set of data and it seems reasonable to interpret them as a quiet background, that is the level of $[e]$ provided by quiet-time sources of ionization. Certainly, there is an arbitrary element in drawing the lines. Nevertheless, it was shown by *Danilov and Vanina* [1999] that some conclusions may be obtained comparing these lines for various conditions (following that paper we denote the [e] values corresponding to the envelope lines as $[e]^*$).

For example, it was shown that at 80 km the $[e]^*$ values in the nonsunlit period ($\chi > 100°$) at the Molodezhnaya station are higher than at Heiss Island. Now we consider this problem in detail.

Envelope Variations With Height

Figure 4 shows the $[e]^*$ values for three heights and three situations (Molodezhnaya station, Heiss Island (ao), and Heiss Island (pc)). One can see that there are some visual features in the $[e]^*(n)$ behavior in the nonsunlit period ($\chi > 100°$). At 75 km the $[e]^*(n)$ values are close to each other for all three situations: the difference between the highest values corresponding to the Molodezhnaya station and the lowest values corresponding to Heiss Island (pc) is by a factor of 1.6 (0.2 in the logarithmic scale). At 84 km this difference is very high: 1.3 or a factor of 20. At 80 km an intermediate situation is observed: the $[e]^*(n)$ values at

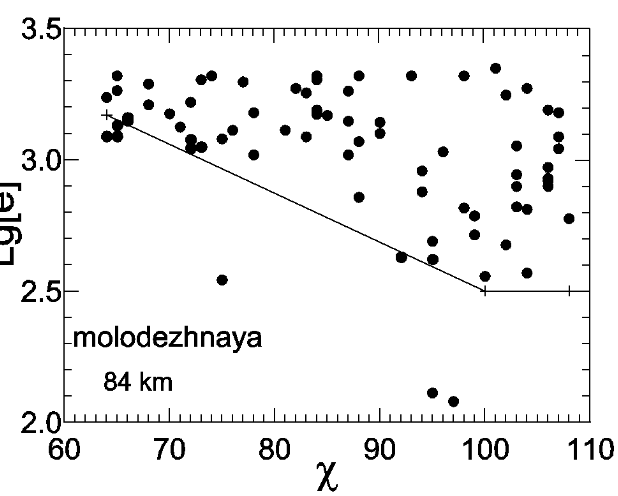

Figure 3. The same as in Figure 1 but at 84 km.

the Molodezhnaya station exceed the values at Heiss Island (pc) by a factor of 4 ($\Delta \lg[e]^*(n) = 0.6$).

Similar picture is seen if we compare the $[e]^*(n)$ values for the two situations at Heiss Island. At 80 km the values of $[e]^*(n)$ for the auroral oval exceed that for the polar cap by a factor of 1.6. At 84 km the difference reaches a factor of 2.5.

We interpret such changes of the relation between the $[e]^*(n)$ values for different situations in the following way. At the 75 km height in quiet geomagnetic conditions there is no additional sources of ionization in the form of precipitating corpuscles. Therefore the equilibrium electron concentration is determined by "normal" (the same as at middle latitudes) ionization sources. It is mainly the ultraviolet radiation (first of all in the Lyman-α line) scattered at the geocorona. The small difference between the $[e]^*(n)$ values for the Molodezhnaya station and Heiss Island (pc) may be of an occasional nature (for example it may be a result of the arbitrary drawing of the lower envelope) or may manifest some interhemisphere changes of aeronomical parameters (the nitric oxide concentration, temperature, etc.) which determine the electron equilibrium concentration, the ionization rate being given.

The $[e]^*(n)$ increase both for the Molodezhnaya station and for Heiss Island (ao) as compared with Heiss Island (pc) shows evidently that even in quiet conditions in the auroral oval there are particle precipitations which are absent (or weak) in the polar cap. The particle energy should be such that they were able to penetrate down to the height of 84 km, partly absorbed above 80 km and were not able to penetrate (completely absorbed) down to 75 km.

Since the flights both at the Molodezhnaya station and Heiss Island (ao) correspond to the dusk sector of the auroral oval, one would expect similar values of $[e]^*(n)$ in both situations. The real difference at 84 km is by an order of magnitude. Such a strong difference manifests a strong difference either in the aeronomical parameters governing $[e]^*(n)$ or in corpuscular fluxes. The former seems very improbable. Actually, to have the difference in the equilibrium electron concentration by a factor of 10 one needs a change in the effective recombination coefficient (due to changes of the aeronomical parameters which determine α_{eff}) by a factor of 100. There is hardly any ground to assume such a strong difference in aeronomical parameters between hemispheres. At the same time, variations of the ionization rate by a factor of 100 due to changes in the fluxes (and/or rigidity) of corpuscles seems quite real. In this case the results obtained most probably indicate to the hemisphere asymmetry (which have been numerously discussed before, see, for example, *Bythrow et al.* [1982], *Newell and Meng* [1988], *Suzuki and Sato* [1987], and *Zanetti et al.* [1982]) in auroral precipitation intensity and spectrum.

Dependence on Geomagnetic Activity

The best parameter to compare the $[e]$ data with would be the geomagnetic AE index, but there are gaps in the data on AE for some period when considerable portion of the flights has been conducted. Neither is it possible to find a bank of precipitating particle measurements adequate to the bank of $[e]$ measurements. Therefore, following the previous paper we compared the electron concentration with the daily sum of the Kp indices ΣKp available in the databank used.

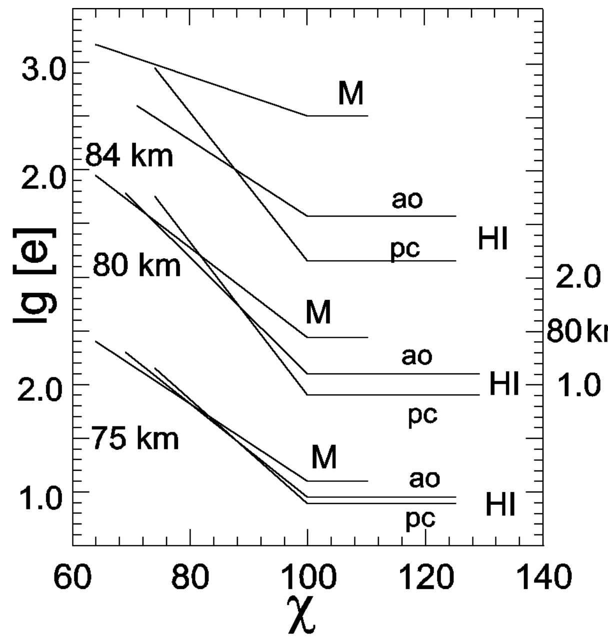

Figure 4. The envelope lines at three heights for the Molodezhnaya station and Heiss Island (auroral oval and polar cap).

Since any rocket flight lasts only a few minutes, it was possible to prescribe to any flight a three-hour Kp index and to make the comparison with Kp instead of ΣKp. We have tried this way for several types of $[e]$ dependence on magnetic activity (analyzed in this paper as well as in other publications) and have found that the statistical characteristics of the results are much worse if Kp is used. Our choice of the ΣKp as a geomagnetic index was also initiated by the fact that the characteristic time of the large-scale magnetospheric processes is about one day. Therefore, one should not expect the particle precipitation to be active only in a particular 3-hour interval with high Kp, but rather depend on the disturbance degree of the total day. It seems that our results mentioned confirm this point of view.

Danilov and Vanina [1999] found some statistically significant correlation of $[e]$ at 80 km with ΣKp for the Molodezhnaya station and for Heiss Island in the auroral oval. It was found that the best pronounced dependence of the electron concentration on ΣKp is seen for the nonsunlit conditions ($\chi > 84°$) at the Molodezhnaya station. It was detected also that there is some sort of a "saturation" effect in the dependence of $[e]$ on ΣKp: a direct relation between $[e]$ and ΣKp is evident and statistically significant (the correlation coefficient $r = 0.49$) for $\Sigma Kp < 30$, whereas it is absent for $\Sigma Kp > 30$ (see Figure 5 in *Danilov and Vanina* [1999]).

Similar comparison for the heights of 75 and 84 km is presented in Figures 5 and 6, respectively. It is seen that

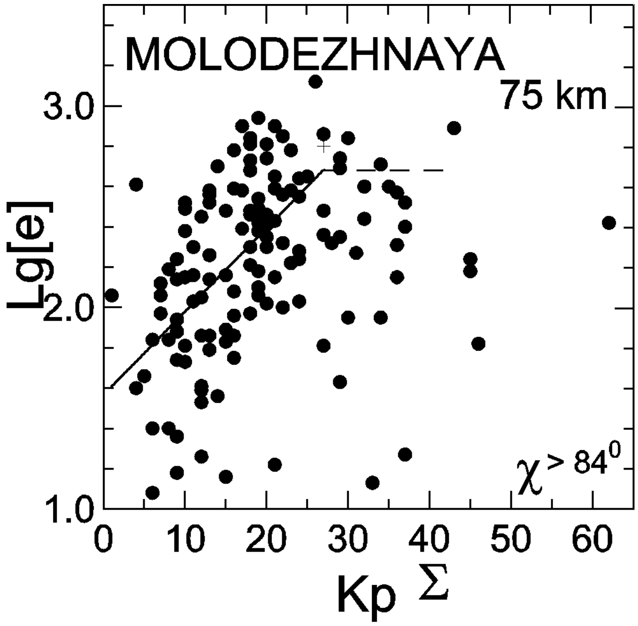

Figure 5. Electron concentration dependence on ΣKp at 75 km at Molodezhnaya station in the nonsunlit conditions.

at 75 km there is an evident increase of $[e]$ with ΣKp up to ΣKp about 25 and then the increase stops. Statistical analysis shows that the highest correlation coefficient ($r = 0.52$) between $[e]$ and ΣKp is obtained if we cut the analysis at $\Sigma Kp = 27$.

At 84 km all the data shown in Figure 6 give $r = 0.53$, but there is only a few points for $\Sigma Kp > 30$. Therefore it is difficult to evaluate the "boundary" value similar to that at 75 and 80 km, we can only believe that the above boundary lies within the $\Sigma Kp = 35 - 40$ interval.

The scatter of individual points makes it difficult to evaluate exactly the slope of the $[e]$ (ΣKp) dependence at $\Sigma Kp < 27$, but visually the dependence at 75 km is much steeper than at 84 km, the data at 80 km showing an intermediate situation. This difference in the slope evidently indicates stronger dependence on magnetic activity level of the electrons (with higher energy) providing ionization at 75 km than of the electrons producing ionization at 84 km.

Thus, the consideration of the altitude profile of the $[e]$ dependence on ΣKp in the nonsunlit conditions at the Molodezhnaya station shows that an increase of the daily mean magnetic activity (the ΣKp index) leads to a significant increase of $[e]$ in the upper D region only under ΣKp below some boundary value, the value increasing with altitude from 75 to 84 km.

The presence of such boundary value may be interpreted in two ways. Either under ΣKp increase above this value there is a "saturation" of the intensity of the precipitating particle fluxes, the boundary value being different for different particle energies, or under high enough magnetic activity there occur some changes of aeronomical parameters which lead to an increase of the effective recombination coefficient and thus compensate the increase of the corpuscular flux intensity and stop further systematic increase of $[e]$ with ΣKp. To decide which of the mechanisms mentioned really determines the observed effect in $[e]$ a special study of dependence of D region aeronomical parameters (first of all, minor constituents such as NO, O, O_3) on geomagnetic activity is required. Currently very little is known about such dependence.

Dependence of $[e]$ on the Temperature

According to the well known equation of photochemical equilibrium

$$q = \alpha_{\text{eff}} [e]^2$$

the electron concentration should depend on two principal parameters, that is on the ionization rate q and effective recombination coefficient α_{eff}. In the majority of cases (except the envelope values $[e]^*$ considered above) the values of q are determined by precipitating particle fluxes. Having no data on such fluxes for every day of rocket launch, we considered above the daily magnetic index ΣKp as an indicator of the intensity of these fluxes. The presence of statistically significant correlation between $[e]$ and ΣKp (see Figures 5 and 6 and also Figure 5 in *Danilov and Vanina* [1999]) demonstrates that the proportionality between $[e]$ and ΣKp does exist. However in all the above figures there is a significant scatter of the points at any fixed value of ΣKp. Part of this scatter may be due to the fact that the ΣKp index is not related unambiguously to precipitating particle fluxes and is not the best index for their description. However, one should not forget that not only q but α_{eff} as well may change in equation (1). Variations of the latter may not be related to changes of geomagnetic activity (and precipitation) but occur due to changes of meteorological parameters (first of all the atmospheric temperature), that is due to the

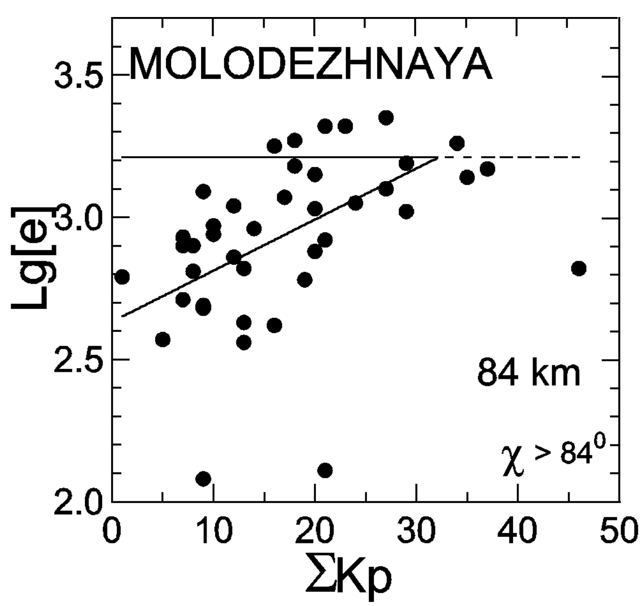

Figure 6. The same as in Figure 5 but for 84 km.

well known meteorological control of the D region [*Danilov,* 1986].

The temperature of the ambient atmosphere T was measured up to a height of 75 km almost in all rocket flights where [e] was measured. Thus it is worth trying to look for [e] dependence on T on the basis of the same databank. However such attempt meets serious difficulties since one has to analyze a multi-dimensional picture of electron concentration variations (with solar zenith angle, magnetic disturbance degree, season, temperature).

Danilov and Vanina [1999] tried to reveal the relation between [e] and T in the following way. The dependence of [e] on ΣKp for the nonsunlit conditions at the Molodezhnaya station (Figure 5 in *Danilov and Vanina* [1999]) was used. Since there was found no systematic seasonal effect, all points were considered with equal significance. A mean dependence of [e] on ΣKp for ΣKp below the boundary value (see above) was calculated, and using this dependence, points for different ΣKp were reduced to a fixed value of ΣKp ($\Sigma Kp = 9$). Then the dependence of the reduced values [e] (9) on the temperature (measured in the same rocket flight at 75 km) was derived. This dependence (see Figure 6 in *Danilov and Vanina* [1999]) was found well pronounced and statistically significant with a correlation coefficient $r = 0.63$.

Since in the procedure described the effect obtained depends strongly on the correct relation between [e] and ΣKp used for the reduction of measured [e] values to a fixed value of ΣKp and since it is difficult to derive an exact dependence [e] = $f(\Sigma Kp)$ because of the data scatter (see, for example, Figure 5), here we made an attempt to reveal the dependence of [e] on T in a different way.

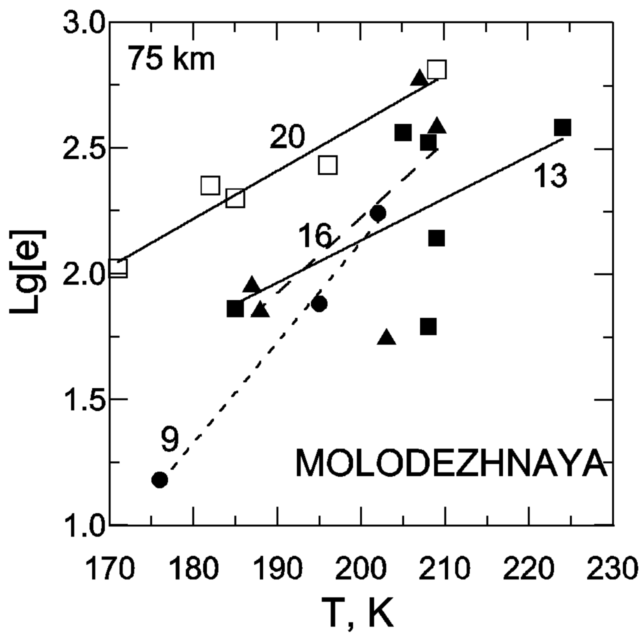

Figure 7. Electron concentration dependence on the temperature T at 75 km for various values of ΣKp (Molodezhnaya station, nonsunlit conditions).

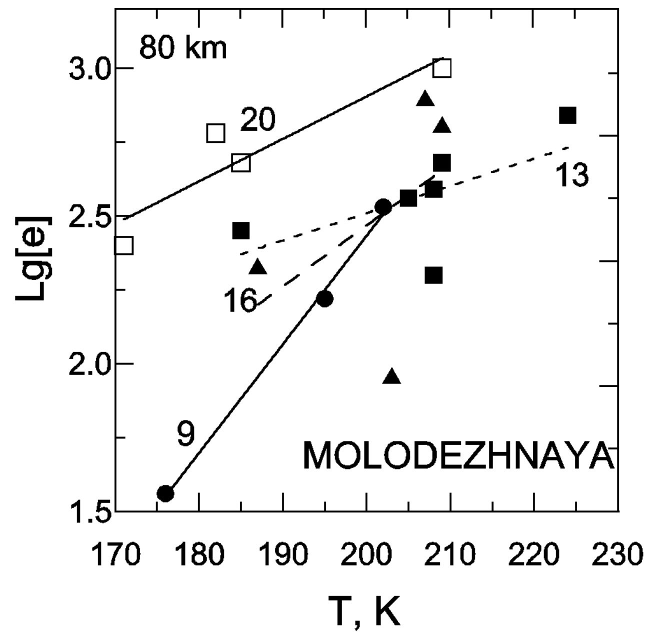

Figure 8. The same as in Figure 7 but for 80 km.

Fixed values of the ΣKp index for which there are several (not less than three) measurements of [e] on different days were considered and a dependence of [e] on T was derived for each value of ΣKp. The number of points for each fixed value of ΣKp in this case is lower than in the method described above, but possible uncertainty in the dependence of [e] on ΣKp used in the previous method to reduce the data to $\Sigma Kp = 9$ is avoided. In fact we thus get rid of one more dependence of the electron concentration and reduce the picture to a two-dimensional one.

The results of the approach described are shown in Figures 7 and 8 for altitudes of 75 and 80 km, respectively. One can see that, though the scatter of the individual points for some values of ΣKp is rather strong, almost in all cases the approximating lines $\lg[e] = A + BT$ (formally calculated by computer) give an increase of [e] with T.

The averaged values of B for all the values of ΣKp considered give $B_{\text{aver}} = 0.023$ and 0.024 for the heights of 75 and 80 km, respectively. Similar analysis for $h = 84$ km was not performed because both there is not enough points in Figure 5 and the real atmospheric temperature at 84 km may differ significantly from that at 75 km.

Thus the results obtained confirm existence of a positive relation between [e] and T found earlier by *Danilov and Vanina* [1999] and make it possible to obtain mean values of the B coefficient in this relation.

Heiss Island Position

Danilov and Vanina [1999] showed that the electron concentration at 80 km over Heiss Island depends on particular polar zone the station is in at the moment of rocket launch.

We have already emphasized above that comparison of each particular rocket flight with geomagnetic and meteoro-

Table 1. Averaged Electron Concentration at Three Altitudes Over Heiss Island

	Auroral oval		Polar cap	
	Sunlit	Dark	Sunlit	Dark
75 km				
χ_{aver}	83.5°		82.8°	
$\lg[e]_{\text{aver}}$	2.17	1.68	2.15	1.44
80 km				
χ_{aver}	83°		83.3°	
$\lg[e]_{\text{aver}}$	2.50	1.94	2.37	1.67
84 km				
χ_{aver}	83.5°		82.8°	
$\lg[e]_{\text{aver}}$	2.64	2.32	2.52	2.06

logical data is limited by the absence of an adequate databanks. Therefore it is worth considering the $[e]$ values averaged over all the flights in this or that situation. In such procedure it is assumed that (due to large number of the flights averaged) the mean values $[e]_{\text{mean}}$ obtained correspond to some mean disturbance level which does not differ significantly for the flight groups in comparison. In other words, we assume that the percents of strong, moderate and weak disturbances is nearly the same among the days when the measurements were conducted in the auroral oval and polar cap. Such approach was used by *Danilov and Vanina* [1999] and *Vanina and Danilov* [1998] to reveal the seasonal behavior of $[e]_{\text{mean}}$ at the Molodezhnaya station and Heiss Island and to compare $[e]_{\text{mean}}$ at 80 km at Heiss Island in the auroral oval and polar cap.

Table 1 shows the $[e]_{\text{mean}}$ values for three altitudes and two situations at Heiss Island. One can see that there is only relatively small difference in the averaged electron concentration in the sunlit period ($\Delta \lg[e] < 0.13$). This difference may be attributed to occasional errors of averaging. However, in the nonsunlit period the difference is higher ($\Delta\lg[e] = 0.24-0.25$) and agrees with the result found earlier at 80 km.

That means that the $[e]_{\text{mean}}$ values over Heiss Island in the nonsunlit conditions are higher by about a factor of 1.8 when the station is in the auroral oval than when it is within the polar cap. That means that the intensity of the precipitating particle fluxes producing ionization in the upper D region are systematically higher by about a factor of 3.5 in the auroral oval than in the polar cap. Stating that, we naturally assume (since we deal with the measurements at the same geographic point) that there is no systematic difference between the auroral oval and polar cap in the values of meteorological and aeronomical parameters. It is worth noting that the effect found (contrary to other effects discussed above) does not show any pronounced altitude behavior.

Conclusion

The analysis of the rocket measurements of the electron concentration in the upper D region performed for three heights (75, 80, and 84 km) confirmed the conclusions drawn earlier [*Danilov and Vanina*, 1999] for a height of 80 km. In particular, the $[e]$ dependence on the daily index of magnetic activity ΣKp and existence of some sort of a "saturation effect" under high ΣKp were confirmed and it was found that the boundary value of ΣKp tends to increase with height. The electron concentration dependence on the atmospheric temperature was also confirmed. This fact demonstrates that the meteorological control of the D region known for midlatitude ionosphere does exist and may be revealed also at high latitudes.

The comparison of the minimum values of $[e]$ in three situations (Molodezhnaya station, Heiss Island (ao), and Heiss Island (pc)) at three altitudes (75, 80, and 84 km) showed that even in quiet geomagnetic conditions there do exist corpuscular precipitations in the auroral oval, the intensity of the precipitations being significantly higher in the southern hemisphere (Molodezhnaya) than in the northern hemisphere (Heiss Island). The characteristics of the corpuscular spectrum should be such that their flux is able to penetrate down to 84 km, is absorbed significantly on its way to 80 km, and does not reach 75 km.

Acknowledgment. The work was supported by the Russian Foundation for Basic Research (project 98-05-65030).

References

Borisov, A. I., V. N. Kikhtenko, and S. V. Pakhomov, The preliminary results of the measurements of the upper atmosphere charged component onboard meteorological rockets, *Proc. Central Aerological Observatory* (in Russian), *144*, 3, Dolgoprudny, Moscow Region, 1981.

Bythrow, P. F., T. A. Potemra, and R. A. Hoffman, Observations of field-aligned currents, particles, and plasma drift in the polar cusps near solstice, *J. Geophys. Res., 87*, 5131, 1982.

Danilov, A. D., Meteorological control of the *D* region, *Ionosfern. Issled.* (in Russian), *39*, 33, 1986.

Danilov, A. D., and L. B. Vanina, Comparison of the polar *D* region behavior in the Arctic and Antarctic, *Adv. Space Res., 24* (12), 1655, 1999.

Knyazev, A. K., L. B. Vanina, L. V. Korneeva, and V. N. Avdeev, Specification of the empirical model of the dependence of the *D* region electron concentration on the solar zenith angle from the rocket measurements, *Geomagn. Aeron.* (in Russian), *33* (5), 145, 1993.

Newell, P. T., and C. I. Meng, Hemispheric asymmetry in cusp precipitation near solstices, *J. Geophys. Res., 93*, 2643, 1988.

Sinel'nikov, V. M., et al., A rocket radiobeacon experiment on the electron density profile measurement in the bottomside ionosphere, in *Proceedings of Satellite Beacon Symposium*, p. 453, Warsaw, Poland, 1980.

Suzuki, H., and N. Sato, Seasonal and diurnal variations of ELF emission occurrences at 750-Hz band observed at geomagnetically conjugate stations, *J. Geophys. Res., 92*, 6153, 1987.

Vanina, L. B., and A. D. Danilov, High-latitude *D* region and the asymmetry of the hemispheres, *Geomagn. Aeron.* (in Russian), *38* (4), 173, 1998.

Zanetti, L. J., et al., Interplanetary magnetic field control of high-latitude activity on July 29, 1977, *J. Geophys. Res., 87,* 5963, 1982.

A. D. Danilov and L. B. Vanina, Institute of Applied Geophysics, 9 Rostokinskaya Str., Moscow 129128, Russia. (danilov@wdcb.ru)

(Received March 15, 1999; revised May 22, 2001;
accepted June 14, 2001)