Geomagnetism and Aeronomy, Vol. 39, No. 2, 1999, pp. 194–200. Translated from Geomagnetizm i Aeronomiya, Vol. 39, No. 2, 1999, pp. 65–71.

Longitudinal Variations in the Positions of Daytime Winter Ionospheric Troughs

A. T. Karpachev* and V. V. Afonin**

**Institute of Terrestrial Magnetism, Ionosphere, and Radiowave Propagation, Russian Academy of Sciences, Troitsk, 142092 Russia*

***Space Research Institute, Russian Academy of Sciences, ul. Profsoyuznaya 84/32, Moscow, 117810 Russia*

Received November 24, 1997; in final form, June 9, 1998

Abstract—A large set of *Cosmos-900* satellite data obtained at heights 350–550 km in both hemispheres is analyzed statistically. Longitudinal variations in the positions of the minima of daytime main ionospheric trough (MIT) and Muldrew's higher latitude trough are studied for daytime winter conditions. The amplitude of the variations in the position of MIT minimum at daytime and at dawn is shown to be smaller than that at nighttime, but, in general, the longitudinal effect is a stable characteristic of the winter subauroral ionosphere during the entire day. The longitudinal variations in the position of Muldrew's trough, which lies in the auroral oval at near-noon hours, are similar in pattern but are difficult to distinguish, because the effect is weaker and the scatter of data is larger. The causes of longitudinal variations in the ionospheric-trough positions are analyzed. The high-latitude ionosphere for the conditions under consideration has been found to be highly asymmetric.

INTRODUCTION

The position of the main ionospheric trough (MIT) in the nightside subauroral ionosphere can vary dramatically in latitude at fixed local times and magnetic activity [1]. One cause of the scatter of data is the dependence of the trough position on longitude, which was studied in detail using *Intercosmos-19* and *Cosmos-900* satellite data [2, 3]. Under winter conditions, the trough is commonly recorded even at noon (in 70% of cases, at some longitudes [4]); the scatter of data in latitude at daytime is even larger than that at nighttime. An analysis of the *Cosmos-900* data shows that this is mainly associated with the presence of two distinct troughs under daytime conditions [4]. One of them lies equatorward of the auroral oval and is similar in characteristics to the nighttime MIT (see Fig. 1*c*). The other trough at near-noon hours is generally observed inside the auroral oval but equatorward of the dayside cusp and has a characteristic shape with a very steep equatorial wall and an indistinct polar wall (see Fig. 1*a*). The daytime MIT is mainly observed in the shadow region, while the trough of the second type is observed at sunlit longitudes. Since in the northern hemisphere the North America longitudes are sunlit in winter, Muldrew was the first to detect it using data from the Canadian *Alouette* satellite [5]. That is why it was called Muldrew's trough for short [4]. However, even if the daytime troughs are separated into two types, the latitudinal variations in their positions remain large. Consequently, there are also other causes of the scatter of data, in particular, the dependence of the trough positions on longitude. For daytime conditions, this dependence was revealed by *Ariel 3* and *Ariel 4* data [6] but remained unstudied. Here, our goal is to analyze in detail the pattern and causes of the longitudinal variations in the positions of both daytime winter troughs.

RESULTS OF OBSERVATIONS

We used in-situ measurements of electron density N_e and temperature T_e aboard the *Cosmos-900* satellite at heights 350–550 km, i.e., near the *F*2-layer maximum. The data refer to magnetically quiet ($K_p < 4$) daytime (08–16 MLT) conditions of local winter and contain 250 and 350 ionospheric-trough observations in the northern and southern hemispheres, respectively. Variations in the positions of density minima of both troughs with geographic longitude are shown in Fig. 2. They are represented as deviations of the experimental values from the mean trough position for given local time and K_p index. The mean trough position (solid curve) was determined by statistically analyzing the entire data set with allowance for a 2.3° displacement of the trough in latitude per unit K_p and for the dependence on LT revealed previously [4]. Thus, the dependence on local time and geomagnetic activity was eliminated, and Fig. 2 shows the variations of both troughs with longitude. Note, however, that the deviations of the experimental values from the statistically mean trough position are fairly large, implying that there is a dependence on other parameters, whose analysis is beyond the scope of this study.

As has been shown previously [4, 7], the daytime MIT occurs more frequently and is more pronounced at deep-shadow longitudes. The shadow region at noon during winter solstice is bounded by the polar circle,

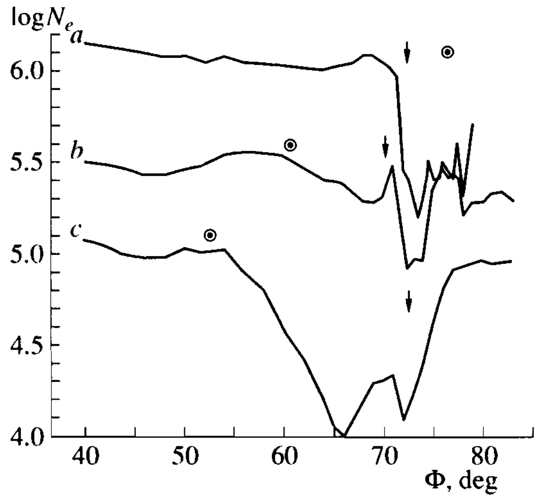

Fig. 1. Typical variations of the electron density with invariant latitude for winter daytime conditions at longitudes where the high-latitude ionosphere is sunlit (*a*), where it lies in a deep shadow (*c*), and at transition longitudes (*b*). Data for the *Cosmos-900* turns are given in the table. The circle and arrow mark, respectively, the terminator position and the position of the equatorial boundary of auroral diffuse particle precipitations [15].

i.e., by geographic latitude 67°. Because of the difference between the positions of the geographic and geomagnetic poles at a fixed invariant latitude near the equatorial edge of the auroral oval, the deepest shadow is observed at longitudes ~120° in the northern hemisphere and at ~270° in the southern hemisphere. Conversely, longitudes ~270° and ~120°–150° in the northern and southern hemispheres, respectively, are sunlit most strongly. The shadow at ionospheric heights is smaller in size, but, as an analysis shows, a fairly large region in which there is no strong ionization (neither solar nor corpuscular) during the entire day remains [8]. This is the region of complete shadow and has the shape of a crescent confined between the terminator and the equatorial edge of the auroral oval. The sizes of this crescent vary as the Earth rotates, i.e., with Universal Time, because of the difference between the pole positions and because of an ~5° displacement of the auroral-oval center along the near-midnight meridian [8]. Since the electron density in the region of complete shadow is maintained only by a weak flow from the plasmaspheric reservoir, it sharply decreases, and a deep trough is formed immediately adjacent to the auroral oval. At unlit longitudes, this trough together with the nighttime trough form a single (for the entire day) branch of the main ionospheric trough. At sunlit longitudes, the daytime MIT is observed much more rarely (and is less distinct) than that in the shadow region. (Variations in the probability of occurrence of daytime troughs with longitude and local time were considered in detail in [7]). Longitudinal variations in the position of daytime MIT minimum in the southern hemisphere (Fig. 2d) are distinguished clearly: the amplitude of the effect A reaches 4.3°, while the rms deviation σ is 1.8°. The correlation coefficient is r = 0.6. Since the difference between the pole positions and the variations in magnetic-field characteristics in the northern hemisphere are smaller than those in the southern hemisphere, all the effects here are less pronounced, which is manifested in our case in the equality of the amplitudes of the longitudinal effect A = 3.0° and 2σ = 3.0° (Fig. 2c). Thus, in the northern hemi-

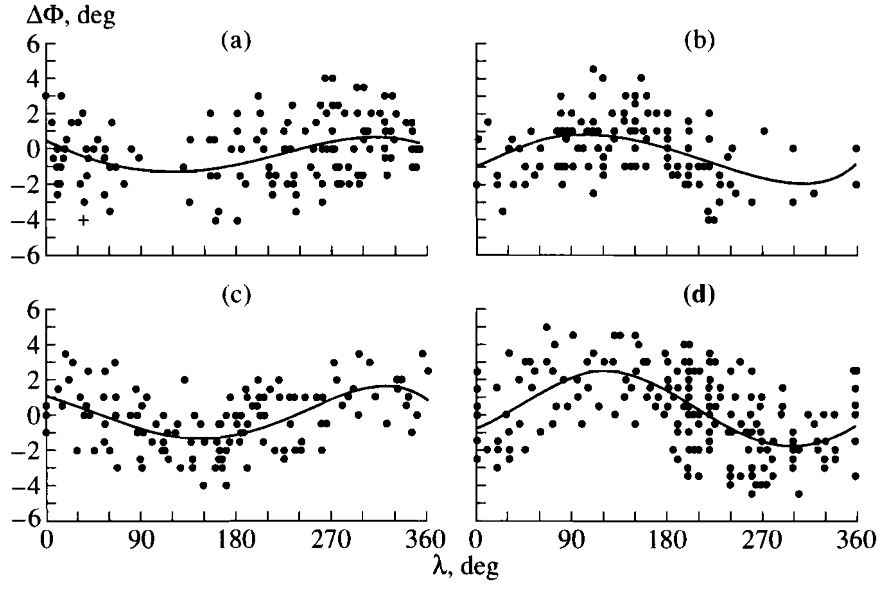

Fig. 2. Variations in the positions of Muldrew's trough (a, b) and daytime MIT (c, d) in the northern (a, c) and southern (b, d) hemispheres with geographic longitude λ. The dots and solid curves represent the *Cosmos-900* data and least-squares fits, respectively.

Data on the *Cosmos-900* orbits (to Fig. 1)

Orbit	Date	UT	MLT	Height, km	Longitude λ, deg	K_p	Hemisphere
10197 (*a*)	Jan. 5, 1979	12:50	13:0	430	340	4–	Northern
9775 (*b*)	Dec. 9, 1978	03:15	13:0	470	200	3–	Northern
12589 (*c*)	June 8, 1979	16:25	12:0	390	300	1–	Southern

sphere, the longitudinal effect is less pronounced and the correlation coefficient is smaller than those in the southern hemisphere.

Muldrew's trough, just as the nighttime MIT, is formed in the stagnation region but in the band of a strong westward drift located in the evening sector at the equatorial edge of the auroral oval. This trough is brought by this drift to the near-noon sector, where it is commonly observed inside the auroral oval [4]. Despite this circumstance, its minimum is clearly distinguished even at sunlit longitudes (see Fig. 1*a*). Muldrew's trough is recorded rarely in the shadow region, because it is masked by a well-developed daytime MIT and can occasionally manifest itself only as a weaker and higher latitude N_e minimum at the trough bottom, as in Fig. 1*c*. At transition longitudes, both troughs can be observed simultaneously (Fig. 1*b*), but more frequently they merge into a single, common structure with a broad N_e minimum; it is therefore easy to confuse them. Clearly, this is the reason why the scatter of data at transition longitudes (~200°–270° in Figs. 2d and 2b) is largest. The longitudinal effect in the position of Muldrew's trough minimum is difficult to distinguish, because its amplitude is 2.8° in the southern hemisphere and 2.1° in the northern one, while the rms deviation is 1.5° and 1.6° and the correlation coefficient is 0.4 and 0.3, respectively (Figs. 2b and 2a). Consequently, the result is statistically insignificant, and we can speak of the longitudinal effect in the position of Muldrew's trough only as a tendency. Nevertheless, this tendency is fairly clear and similar to the variations in the daytime MIT position. In our view, we can therefore speak of relatively stable variations in the positions of both troughs with longitude for some mean geophysical conditions in the dayside winter ionosphere. Note that the longitudinal effect is also revealed by the data of individual satellite sessions. However, since the geophysical conditions during the day when the satellite passes over all longitudes change, the longitudinal effect may differ markedly in pattern for different series of measurements. This makes it difficult to analyze the causes of the longitudinal effect. For the effect of unknown disturbing factors to be reduced, the longest series of continuous measurements (no fewer than 15 or 16 turns, i.e., 360° in longitude) made under magnetically quiet conditions must be selected. This cannot always be done, especially at high solar activity. It is also desirable to use more effective (than K_p) indices of magnetic activity for the conditions under consideration, for example, the product V_sB_z, where V_s is the solar-wind velocity, and B_z is the vertical interplanetary magnetic field component. However, they are often unavailable for the observing periods under consideration. Thus, the longitudinal variations in the daytime trough positions are difficult to study even on the basis of a fairly large set of *Cosmos-900* satellite data.

DISCUSSION OF RESULTS

Let us discuss the possible causes of the longitudinal effect in the configuration of both troughs. To this end, consider the longitudinal variations in ionospheric and thermospheric parameters near the trough minimum in the southern hemisphere, where all effects show up more clearly than those in the northern hemisphere. Apart from the variations in the position of the trough minimum, Fig. 3a shows the variations in electron density N_e obtained from the *Cosmos-900* data and in thermospheric temperature T_n and composition (O/N_2 ratio) calculated using the *MSIS 90* model [9], as well as in velocity W of the vertical drift produced by the neutral wind calculated using the HWM-90 model [10]. The changes in the trough configuration (shape, depth, width, and position of the density minimum) are determined by the longitudinal–latitudinal electron-density variations at the polar and equatorial walls of the trough. The polar wall of the trough is produced by the precipitations of soft electrons with $E_e \leq 1$ eV: either at the equatorial boundary of auroral diffuse precipitations, as in the case of daytime MIT, or by the precipitations of soft particles in the dayside cusp region, as in the case of Muldrew's trough. These processes are complex in nature (see, e.g., [11]) and have not been studied adequately. However, it can be assumed that the precipitations are more intense and that the density maximum at the polar wall of the trough is formed where the geomagnetic field is weak and the particles penetrate deep into the ionosphere. Longitudinal variations in the geomagnetic-field strength are also shown in Fig. 3a. In the southern hemisphere at the trough latitudes, the geomagnetic-field strength is at a minimum at longitudes near 30°, but in an experiment, the polar wall appears to be most distinct at the background-density minimum, i.e., at longitudes 300°–330°. The *Cosmos-900* data completely confirm these assumptions. As calculations show, the equatorial wall of the trough under daytime winter conditions is produced by the drop in density with latitude as the solar zenith angle χ decreases [7]. The variations in solar zenith angle with longitude also determine the longitudinal variations in electron density, as we see in Fig. 3 from a comparison of the curves for N_e and χ. The value of N_e also depends on the vertical plasma drift velocity and on the O/N_2 ratio. The longitudinal variations in the densities of the major thermospheric components at these heights ([O] and $[N_2]$) are similar to the variations in thermospheric temperature T_n and are also determined by the variations in solar zenith angle (accordingly, by the variations in geographic latitude for a fixed geomagnetic latitude). However, as we see from Fig. 3, N_e and the O/N_2 ratio vary virtually in antiphase. Thus, the effect of thermospheric composition is offset by the stronger dependence on solar ionization. We calculated the vertical-drift variations by using the HWM-90 model [10]. They are given by the relation

$$W = 1/2\sin I(U\sin D + V\cos D),$$

where U and V are the zonal and meridional neutral-wind components; and I and D are the dip angle and declination of the magnetic field, respectively. In our view, the HWM-90 model does not faithfully reproduce the neutral-wind parameters. In particular, we can only talk about the coincidence of the variations in phase for the conditions under consideration: because of the neutral-wind effect, the electron density at longitudes 90°–120° is higher than that in the opposite longitude sector 270°–300°.

So, the N_e variations at the equatorial wall of the trough are determined by solar ionization and, in part, by the neutral wind. At the trough minimum, the density is determined by the more developed equatorial wall at sunlit longitudes (90–180° in Fig. 3) and by the more developed polar wall at shadow longitudes (270–360°); therefore, the trough minimum displaces poleward in the former case and equatorward in the latter case. For Muldrew's trough, the effect is clearly less stable, because its minimum is formed in the auroral-oval region, where the N_e variations are irregular in pattern under the effect of particle precipitations, electric fields, and field-aligned currents. Note that the above qualitative reasoning regarding the formation mechanism of the longitudinal variations in the trough position is based on calculations of the density behavior at the trough minimum (see, e.g., [12]).

The longitudinal variations in the trough position for daytime conditions have been analyzed previously by using *Cosmos-900* data [13]. However, the analysis was performed for a very small data set and without separating the troughs into two types. If the troughs are not classified, then mainly Muldrew's higher latitude trough and the lower latitude daytime MIT will be recorded at sunlit and unlit longitudes, respectively. When a small data set is used, this causes a distortion of the longitudinal effect and, most importantly, a great overestimation of its amplitude, as was obtained in [13].

Let us analyze the changes in the pattern of the longitudinal effect in the position of MIT minimum with

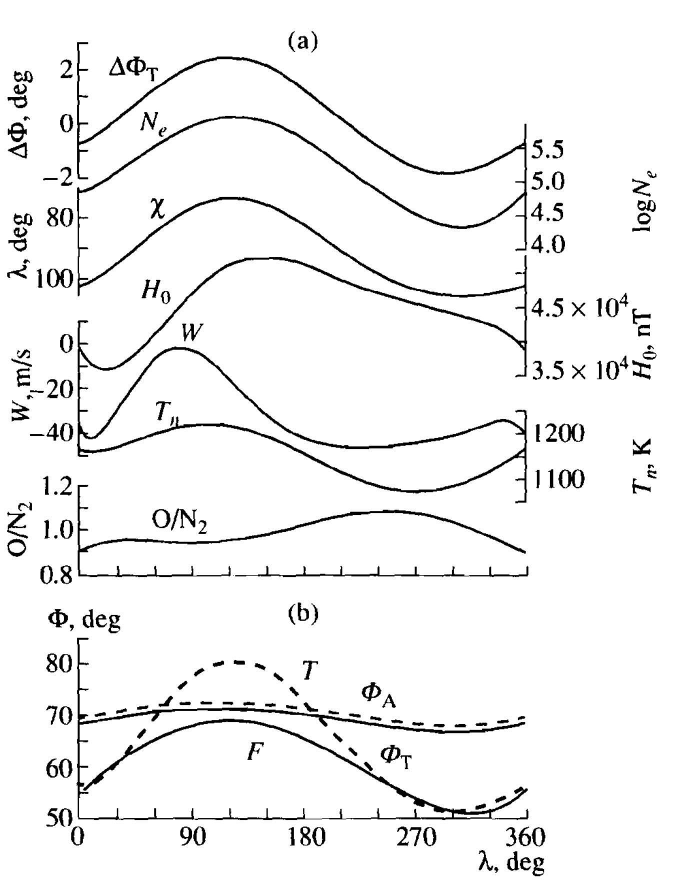

Fig. 3. Longitudinal variations of various parameters in the southern hemisphere for daytime winter conditions: (a) position Φ_T of the MIT minimum, electron density N_e, solar zenith angle χ, magnetic-field strength H_0, vertical drift velocity W, thermospheric temperature T_n, and O/N_2 ratio at invariant latitude $\Phi = -65°$; (b) positions of the equatorial boundary of the auroral oval Φ_A [15, 16] and the MIT minimum Φ_T for $K_p = 1$ and 12 LT, as well as the equatorial F-scatter boundary F [12] and the solar terminator T at the ionospheric height for 12 LT on June 22.

local time. Note that, although the reason for the emergence of daytime and nighttime MITs is the same—the stagnation and decay of ionization in the absence of its sources—these are distinctly different troughs. The nighttime ionospheric trough is formed at dusk in the stagnation region and is brought to the morning sector at invariant latitudes ~60°, which is 5°–7° equatorward of the auroral oval for quiet geophysical conditions, as the Earth rotates. The daytime trough is formed in the region of complete shadow and lies at latitudes 70°–72° at noon in the immediate vicinity of the equatorial boundary of the auroral oval. The equatorial walls of the daytime and nighttime MITs are mainly produced by the drop in density with decreasing solar zenith angle and by plasma exchange between the ionosphere and the plasmasphere, respectively. However, despite all the differences between the troughs, the longitudinal variations in their positions appear to be determined by the same factors [2]. Figure 4 shows the variations in

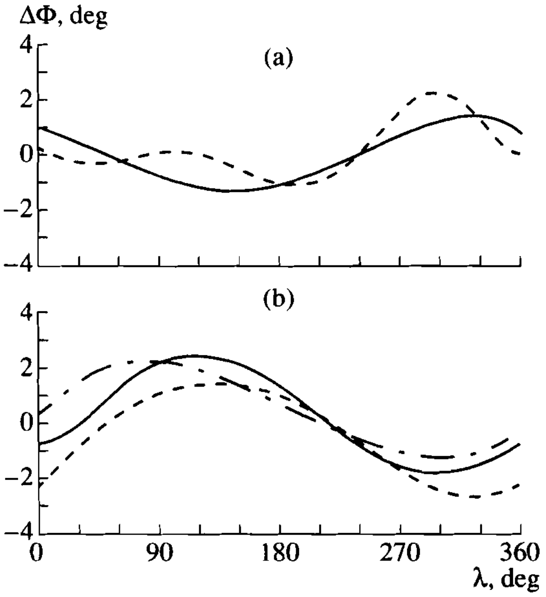

Fig. 4. Longitudinal variations in the MIT position in the near-noon (solid curves), near-midnight (dashed curves), and morning (dashed-dotted curve) sectors of local time in the northern (a) and southern (b) hemispheres.

the MIT position obtained above from the *Cosmos-900* data for daytime conditions and revealed previously for nighttime conditions [2]. Note that, since the deviations of experimental values in the latter case were reckoned from the model values obtained from *ESRO-4* data [4], the mean trough positions slightly differ. As we see from Fig. 4, the longitudinal variations in the MIT position under nighttime and daytime conditions are similar, to a first approximation. However, there are also differences: the longitudinal effect under nighttime conditions is slightly larger in amplitude and has a more complex shape in the northern hemisphere. This, apparently, is because N_e at the equatorial wall of the trough depends more strongly on the zonal neutral-wind component under nighttime conditions. Recall that by nighttime and daytime conditions we mean the intervals 18–06 and 06–18 MLT, respectively. We therefore performed an additional analysis: we separately considered the pre- and post-midnight periods, as well as the dawn hours (05–08 MLT), which cast doubt on the stability of the longitudinal effect. The analysis shows that the pattern of longitudinal variations in the MIT position is virtually unchangeable during the day, and they are also clearly distinguished at the dawn hours (the dash–dotted line in Fig. 4b). As we see from a comparison of all the three curves for the southern hemisphere, they differ mainly in phase, less strongly in amplitude, and only slightly in shape. Note that the curve shape depends somewhat on the degree of the series chosen to fit the experimental data: the higher the degree, the smaller scale variations are reflected on the resulting curve. In our view, however, the harmonics of a series higher than the third or fourth degree for such a large scatter of data reflect only the quality of the sample used. Thus, the accuracy achieved above is the limiting one for our sample, and, within this accuracy, we may conclude that the longitudinal variations in the position of MIT minimum are relatively stable in pattern during the entire day. It is also important to note that, for the first time, this has allowed us to analyze the causes of the longitudinal effect in the daytime trough positions. For a higher accuracy to be achieved, the scatter of data must be reduced, which requires that its causes, which are not yet known, be elucidated. Among them, the effect of IMF B_z, the prehistory of trough dynamics with time, etc., should possibly be taken into account.

Fig. 3b also shows the longitudinal variations in the position of the equatorial *F*-scatter boundary, as revealed for the southern hemisphere by Intercosmos-19 external sounding data for daytime (06–18 LT) magnetically quiet ($\Sigma K_p < 16_+$) conditions very similar to those under consideration [15]. In [15], they were compared with the nighttime MIT position; we can now make a proper comparison, because we know the variations in the MIT position with local time and longitude for the entire day. For this purpose, Fig. 3b shows longitudinal variations in the positions of daytime the MIT minimum and the equatorial boundary of auroral diffuse precipitations [16] for 12 ± 2 LT and $K_p = 1$. The model [16] yields no longitude dependence for the equatorial boundary of auroral diffuse precipitations, but there are both circumstantial and direct evidence [17] for the existence of such a dependence. Figure 3b therefore shows an approximate longitude dependence revealed in the southern hemisphere by satellite particle-precipitation observations [17]. We see from Fig. 3b that the variations in the positions of all the three structures of the dayside high-latitude ionosphere are similar in shape. However, the equatorial *F*-scatter boundary at longitudes 240°–360° is too far from the daytime trough minimum in latitude to discuss any relationship between them. On the other hand, the *F*-scatter intensity is known to reach a maximum within 1 or 2 h after sunset. The terminator position for 12 LT during summer solstice is also shown in Fig. 3b. When the terminator is located equatorward of the auroral oval, the *F*-scatter actually begins after sunset. When, however, the terminator is located poleward of the equatorial edge of the auroral oval, the appearance of scattered trails on external sounding ionograms is determined by the abrupt increase in N_e irregularities caused by particle precipitations at the equatorial edge of the auroral oval. When passing from one dependence to the other, a kink in the resulting curve must be observed, but it appears to be smoothed out when the data are fitted.

As we see from Figs. 2 and 4, the longitudinal effect differs sharply in shape in the northern and southern hemispheres. Thus, there is a strong interhemispheric asymmetry in the parameters of the winter subauroral ionosphere under both daytime and nighttime conditions. The presence of asymmetry implies that the pattern of longitudinal variations in N_e gradually changes when passing from one hemisphere to the other. It would therefore be more precise to speak of longitudinal–latitudinal variations of N_e in the trough region. It is the longitudinal–latitudinal density variations that determine the longitudinal effect in the configuration of the trough as a whole structure, i.e., not only in the position of trough minimum but also in the variations of the trough shape, depth, and width. Under daytime conditions, the asymmetry also manifests itself in different probabilities of occurrence of both troughs at different longitudes of the northern and southern hemispheres [17]. The presence of longitudinal variations in the configuration and probability of occurrence of both daytime troughs implies that the "snapshot" of the high-latitude ionosphere will change with Universal Time (UT) in each hemisphere in different ways. Consequently, we can also talk about an asymmetry in the UT control of the high-latitude ionosphere. The interhemispheric asymmetry in the structure of the topside winter ionosphere is determined by a number of factors. As follows from our analysis, the main factors among them are the difference between the positions of the geomagnetic and geographic poles, as well as the variations in magnetic-field parameters (strength and declination) and thermospheric parameters (composition and neutral wind) with longitude.

CONCLUSIONS

Our statistical analysis of the *Cosmos-900* data shows that the longitudinal effect in the configuration of the main ionospheric trough is a stable characteristic of the high-latitude winter ionosphere under both nighttime and daytime conditions. The longitudinal variations in the position of MIT minimum are different in the northern and southern hemispheres, but their pattern in each of the hemispheres changes only slightly with local time. However, the amplitude of the longitudinal effect at daytime is smaller and the scatter of data is larger than those at nighttime. This is apparently attributable to a reduction of the neutral-wind effect under daytime conditions and to the dependence on other factors which were not taken into account, for example, the IMF B_z. The longitudinal variations in the position of Muldrew's higher latitude (than MIT) trough are similar in shape but smaller in amplitude and are barely distinguishable against the background of the large scatter of *Cosmos-900* data. They can therefore be represented only as a tendency in the behavior of this trough. The longitudinal variations in the positions of both trough minima should be considered in terms of changes in the configuration of the trough as a whole, i.e., the shape, width, and depth of the entire structure, which are determined by the electron-density variations at the polar and equatorial walls of the trough. These variations are determined by many factors and primarily by the variations in solar zenith angles and neutral-wind characteristics. The latter are caused by the difference between the positions of the geomagnetic and geographic poles and by the longitudinal variations in geomagnetic-field parameters (strength, declination, and dip angle). Since all these characteristics vary with longitude differently in the northern and southern hemispheres, this implies the presence of a strong asymmetry in the winter high-latitude ionosphere.

ACKNOWLEDGMENTS

This study was supported by the Russian Foundation for Basic Research (project no. 97-05-64085).

REFERENCES

1. Karpachev, A.T., Deminov, M.G., and Afonin, V.V., Model of the Mid-Latitude Ionospheric Trough on the Basis of *Cosmos-900* and Intercosmos-19 Satellite Data, *Adv. Space Res.*, 1996, vol. 18, no. 6, p. 221.
2. Deminov, M.G. and Karpachev, A.T., Longitudinal Effect in the Main Ionospheric Trough Configuration: 1. The Trough Position, *Geomagn. Aeron.*, 1986, vol. 26, no. 1, p. 63.
3. Deminov, M.G., Karpachev, A.T., Afonin, V.V., *et al.*, Longitudinal Variations in the Main Ionospheric Trough for Nighttime Winter Conditions as Deduced from *Cosmos-900* and Intercosmos-19 Satellite Data, *Geomagn. Aeron.*, 1992, vol. 32, no. 2, p. 75.
4. Karpachev, A.T. and Afonin, V.V., Two Types of Daytime Winter Ionospheric Trough as Revealed by *Cosmos-900* Satellite Data at Altitudes 350–550 km, *Geomagn. Aeron.*, 1998, vol. 38, no. 3, p. 68.
5. Muldrew, D.B., *F*-Layer Ionization Troughs Deduced from Alouette Data, *J. Geophys. Res.*, 1965, vol. 70, no. 11, p. 2635.
6. Tulunay, Y.K. and Grebowsky, J.M., Temporal Variations in the Dawn and Dusk Mid-Latitude Trough Positions—Measured (Ariel 3, Ariel 4) and Modelled, *Ann. Geophys.*, 1978, vol. 31, no. 1, p. 29.
7. Karpachev, A.T. and Afonin, V.V., Dependence of the Probability of Occurrence of Ionospheric Troughs on Season, Local Time, Longitude, and Magnetic Activity, *Geomagn. Aeron.*, 1998, vol. 38, no. 3, p. 79.
8. Kolesnik, A.G., Golikov, I.A., and Chernyshev, V.I., *Matematicheskie modeli ionosfery* (Mathematical Models of the Ionosphere), Tomsk: MGP "Rasko", 1993.
9. Hedin, A.E., Extension of the MSIS Thermosphere Model into the Middle and Lower Atmosphere, *J. Geophys. Res.*, 1991, vol. 96, no. 2, p. 1159.
10. Hedin, A.E., Biondi, M.A., Burnside, R.G., *et al.*, Revised Global Model of Thermospheric Winds Using Satellite and Ground-Based Observations, *J. Geophys. Res.*, 1991, vol. 96, no. A5, p. 7657.
11. Rodger, A.S., Brace, L.H., Hoegy, W.R., and Winnigham, J.D., The Poleward Edge of the Mid-Latitude Trough—Its Formation, Orientation and Dynamics, *J. Atmos. Terr. Phys.*, 1996, vol. 48, no. 8, p. 715.

12. Chernyshev, V.I. and Zabolotskii, M.S., Response of the High-Latitude Ionosphere to a Thermospheric-Wind Change under Disturbed Conditions, *Geomagn. Aeron.*, 1989, vol. 29, no. 6, p. 1025.
13. Afonin, V.V., Benkova, N.P., Besprozvannaya, A.S., *et al.*, The Ionospheric Dynamics in the Northern and Southern Hemispheres: The Longitudinal and IMF Effect, *J. Atmos. Terr. Phys.*, 1996, vol. 57, no. 9, p. 1057.
14. Köhnlein, W. and Raitt, W.J., Position of the Mid-Latitude Trough in the Topside Ionosphere as Deduced from *ESRO-4* Observations, *Planet. Space Sci.*, 1977, vol. 25, no. 3, p. 600.
15. Kochenova, N.A. and Fligel, M.D., Equatorial Boundary of the High-Latitude *F*-Scatter in the Topside Ionosphere, *Geomagn. Aeron.*, 1994, vol. 34, no. 3, p. 166.
16. Hardy, D.A., Gussenhoven, M.S., and Holeman, E., A Statistical Model of Auroral Electron Precipitation, *J. Geophys. Res.*, 1985, vol. 90, no. 5, p. 4229.
17. Meng, C.-I., Diurnal Variation of the Auroral Oval Size, *J. Geophys. Res.*, 1979, vol. 84, no. 9, p. 5319.