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Experimental Investigation of the Effect of Strong Thunderstorms on Parameters of the Middle Latitude Ionospheric D-Region

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Partial reflection measurements at middle latitudes in the vicinity of Kharkiv have been used to study the effect of strong thunderstorms on parameters of the ionospheric D-region. It is shown that during thunderstorms the electron number density N in the lower D region (z<70km) often increases to $N < 8\cdot 10^3$ cm^{-3}; while in the higher part (z> 80 km) no changes occur. Possible variations of the electron-molecule collision frequency are investigated.

1. Introduction. Over the recent years, the studies of strong atmospheric thunderstorms affecting the higher regions of the atmosphere and the ionosphere have attracted considerable interest because of their importance both for fundamental research and a great number of applied problems. Of particular interest are the possible effects of thunderstorm activity in the ionospheric D region which is closest to the source and the least studied. This problem has been dealt with in a number of papers. Nickolaenko [1976]; Kucherov and Nickolaenko [1979], and Sukhorukov et al. [1996] have sown that the electromagnetic radiation of lightning discharges can penetrate into the lower ionosphere, and the electric field strength there can be as high as a few mV m^{-1}. According to the estimates of Kucherov and Nikolaenko [1979], the average horizontal lightning discharge heats electrons in the lower ionosphere nearly twice as Hectivecy as the average vertical discharge. In the case of powerful lightning discharges, the size of the heated region can reach hundreds of kilometers. The ionospheric heating by VLF waves during thunderstorms was investigated by Inan [1990]; Rodriguez et al. [1991], and Inan et al. [1991]. In particular, it has been found that the heating of the D region plasma observed in experiment can be caused by absorption of wave energy as a result of a sharp increase in the electron collision frequencies by ~30% at the altitude z = 85 km.

The satellite [Voss et al., 1984] and rocket [Goldberg et al., 1986] observations of energetic electrons precipitating from the magnetosphere during lightning discharges have stimulated new attention toward mechanisms for the ionosphere-magnetosphere coupling processes and energy transfer, particulary, because such events are observed in the daytime when the ionosphere may adversely affect the propagation of radio waves due to enhanced losses in the ionospheric D region. Precipitating energetic electrons can, under certain conditions, give rise to changes of the background ionization in the D-region and appearance of layers of enhanced ionization [Gokov and Gritchin, 1992].

Electric field measurements [Vale, 1983; Kelley et al., 1985] have revealed electric pulses in the ionosphere that follow lightning strokes and are much longer in duration than predicted by electomagnetic radiation or 'relaxation time' theories. Hale and Baginsky [1987] and Tonev and Velinov [1992] suggested an analytical model for the penetration of the electric field of a thunderstorm cloud into the ionospheric plasma. The model shows that temporal variations of the current induced in the ionosphere and the global circuit, and the corresponding return stroke current to the earth depend on the profile of conductivity at intervening altitudes in the middle atmosphere [Hale and Baginsky, 1987].

Grigoryev and Dokuchaev [1981] have also shown that strong thunderstorms can cause wave disturbances propagating in the ionospheric D region with vertical velocities of V~300 m s^{-1}.

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Studies of variations in the electron-molecule collision frequency in the D region are of importance both for purely scientific purposes and for practical problems. This problem is far from its solution either for quiet conditions in the D region or in the presence of disturbances of natural and anthropogenic origin. The question of possible changes in $\nu(z)$ in the lower D-region due to strong thunderstorms in the atmosphere is extensively discussed in the literature (see, for instance, [Inan, 1990; Inan et al.,1991]).

In this paper, possible changes in the parameters of middle latitude ionospheric D-region are studied using the data of vertical sounding and partial reflection measurements in the vicinity of Kharkiv during 26 thunderstorms.

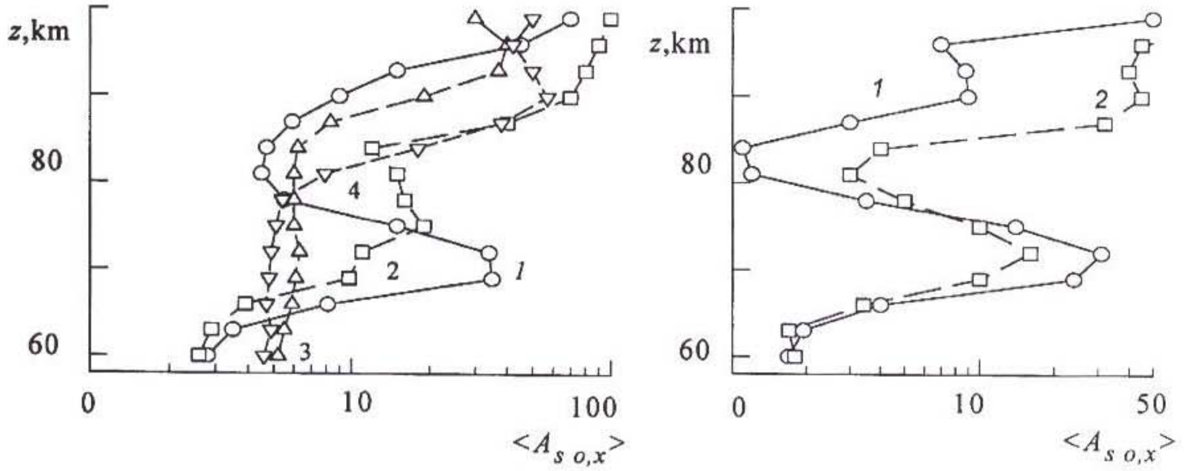
2. Experimental equipment and method of analysis. The measurements of partial reflections and radio noise were made at middle latitudes near Kharkiv in spring and summer periods of 1978-1994 using the partial reflection facility at the Radiophysical Observatory of Kharkiv National University [Tyrnov et al., 1994]. The facility specifications are as follows: the sounding frequencies, f=1.6-4 MHz; sounding pulse length, τ = 25 ms, with the repetition frequency F= 1-10 Hz; and the effective radiated power, PG = 10 MW. Recorded in the experiment were altitude-time dependencies of the amplitudes of a mixture of partially-reflected signals and noise, $A_{o,x}(z,t)$, (where the subscripts "o" and "x" refer to the "ordinary" and "extraordinary" components of the wave, respectively) from 14 altitudes over the 45 km to 60 km range of altitudes in 3-km intervals. To extract the amplitudes of the partially-reflected signals, $A_{s\ o,x}\ (z,t)$, the amplitudes of noise alone, $A_{n\ o,x}\ (t)$, (2 to 6 samples) were recorded at time moments preceding the radiation of sounding pulses. The measurements were made in 10 to 20 min sessions every 40 to 90 min during the day, or continuously over 1 to 10 hour intervals before, during and after thunderstorms. The total number of observations was 26. The data were compared with those obtained with the same equipment under similar helio- and geomagnetic conditions on days free of thunderstorm activity in the region of observations (reference days).

The vertical electron density profiles, $N(z)$, were calculated in the differential absorption method [Belrose and Burke, 1964]; the electron-neutral collision frequency, $\nu(z)$, was obtained either from simultaneous measurements of the differential absorption and correlation coefficients of partially-reflected signal amplitudes (together with $N(z)$) [Benediktov et al., 1972] or using the method of Belrose and Burke [1964] (at z < 70 km where the differential absorption is small and the condition is met $a(z)=\langle A_x^2\rangle/\langle A_o^2\rangle= R_1(\nu)$ (here the averaging is over the time of measurements, ~10 min and $R_1(\nu)$ is the ratio of reflection coefficient for the magnetoionic components). The possible mechanisms responsible for the partial reflections of radio waves were investigated by the methods developed by Misura et al. [1976].

3. Results and discussion. Gokov and Gritchin [1992] noticed that occasionally intense partially-reflected signals (signal to noise ratio of 3 - 10)can be observed from z < 70 km. Analysis of our data on $A_{o,x}(z,t)$ and $A_{n\ o,x}(t)$ obtained during 26 thunderstorms has shown that such events occur approximately in 40% of cases, their duration normally being a few tens of minutes (up to ~90 min). Fig.1 shows examples of the $\langle A_{s\ o,x}(z)\rangle$ obtained during the following thunderstorms (curves 1 and 2, respectively): a) June 3, 1987, 16:11 to 16:21 LT, f = 2.31 MHz; b) March 27, 1987, 12:05 to 12:15 LT, f = 2.31 MHz (curves 3 and 4 were obtained at 11:03 LT before the thunderstorm); (the signal-to-noise ratio is higher than 10). In one case (August 6, 1986), distinct partial reflections from z=63-84 km were recorded before, during and after the thunderstorm. For all such events, electron density profiles have been calculated using the method of Belrose and Burke [1964]. As has been found N increases up to N~ (6-8) 10^2 cm^{-3} at these altitudes. Fig.2 shows sample $N(z)$-profiles in the lower D region obtained during several strong thunderstorms when intense partial reflections from were registered z < 75 km (curves 1-4; curve 5 was obtained on a reference day). Note the characteristic features: normally, at z = 55-68 m a layer of increased values of N ($N < 8\ 10^2 \mathrm{cm}^{-3}$) is observed (under quiet conditions, N is usually $N < 10^2\ \mathrm{cm}^{-3}$ at these altitudes); at z = 68-75 km, there is a valley in the $N(z)$ -profile; at z > 75 km, the behaviour of the $N(z)$-profiles during a thunderstorm does not differ greatly from that under quiet conditions (as for the reference days, see the results below). Using the partial reflection measurements for a series of D-region altitudes, the $N(t)$-dependences were calculated for the thunderstorm periods. Fig.3 shows such dependences for z = 80 km and z = 85 km (curves 1 and 2, respectively) obtained during the thunderstorm of June 25, 1985.

For comparison, the Figure also shows the $N(t)$-dependence for z = 85 km (curve 3) which was obtained under similar helio- and geomagnetic conditions on June 3, 1986 without any thunderstorm activity in the region of observations. As follows from this example and other measurements, there are no sizable (more than 30-40%) changes in N during thunderstorms in the D-region (z = 75-85 km).

We made an attempt to experimentally study possible changes in $v(z)$ in the lower D-region of the ionosphere during a strong thunderstorm. To that end, $A_{o,x}(z,t)$ and $A_{s\ o,x}(z,t)$ were measured during 10-minute intervals every 30 minutes by the partial reflection technique from 09:30 to 16:30 LT on August 6, 1986. In the vicinity of the observation site (distances of a few kilometers), the thunderstorm lasted from about 10:30 to 12:10 LT; at distances greater than a few kilometers, thunderstorm centers were noted during the whole day. As has been noted above, it was characteristic of this experiment that the signal-to-noise ratio over the altitude range 63-84 km was high almost in all cases, except for the records made at 11:00 and 11:30 LT when the level of noise was high. Normally, the signal-to-noise ratio exceeded 2 to 10. (Note that under quiet conditions similar partially-reflected signals are recorded with our equipment roughly in 2-3% of cases). That allowed us to obtain the values of v in the lower D region of the ionosphere by the method of Belrose and Burke [1964] using the relation $a(z) = R_l(v)$. The estimate error was within 50%.



a)

b)

Fig. 1. Sample dependences of $<A_{so}>(z)$ and $<A_{sx}>(z)$ obtained during thunderstorms: curve 1 - $<A_{sx}>(z)$, 2 - $<A_{so}>(z)$; a) June 3, 1987 b) March 27, 1987 (dependences 3 and 4 were obtained before the thunderstorm)

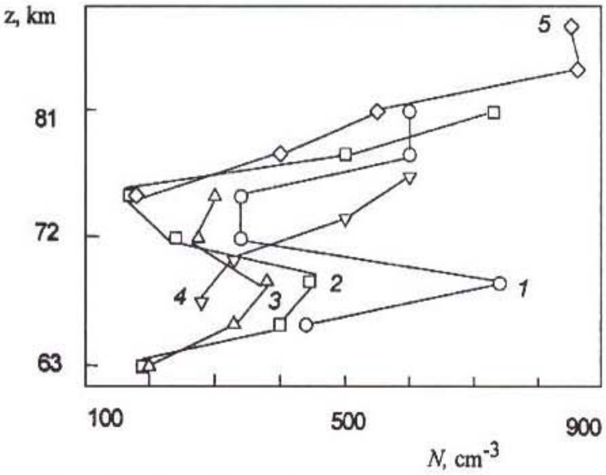


Fig. 2. Sample $N(z)$ profiles for the lower D region obtained during a few strong thunderstorms (curve 1: August 22, 1986; the solar zenith angle 48°; curve 2: August 3, 1988; 35°; curve 3: June 1, 1988, 28°; curve 4: August 6, 1986, 41°) and on August 6, 1988, when there was no thunderstorm (curve 5, 30°).

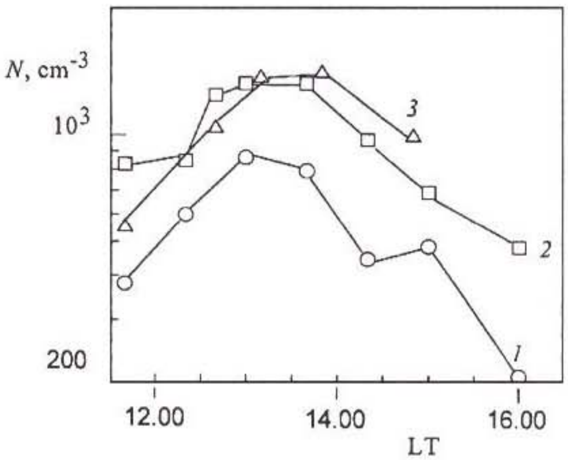


Fig. 3. The $N(t)$ dependences for $z = 80$ km and $z = 85$ km (curves 1 and 2, respectively) obtained during the thunderstorm of June 6, 1985. Dependence 3 was obtained under similar helio- and geomagnetic conditions on June 3, 1986, when there was no thunderstorm

Fig.4 shows the results of calculating for $z = 63$ km (marked as 1). The shaded section marks the thunderstorm period; the data labeled with 2 and 3 represent the values of ν obtained during other thunderstorms. It can be seen from Figure 4 that the values of ν at $z = 63$ km increased during the thunderstorm by a factor of 1.6 to 1.8 . The differences between the values of ν obtained during various thunderstorms seem to be caused by differences in the thunderstorm parameters and different conditions in the ionosphere and the atmosphere over these periods.

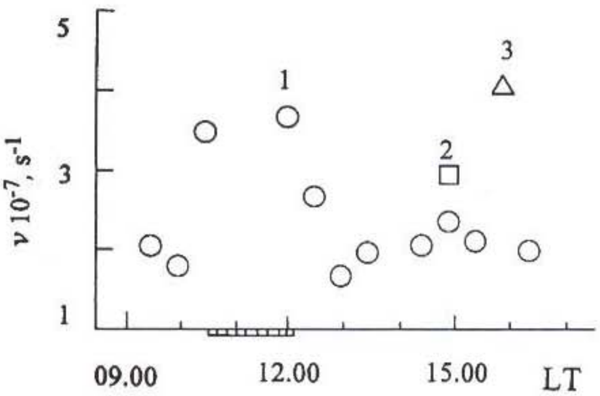


Fig. 4. Variations in the electron-molecule collision frequency at $z = 63$ km in the lower D region during thunderstorms: 1): August 6, 1986, f=2.31 MHz; 2): August 22, 1986, f=2.2 MHz; and 3): June 3, 1987, f=2.2 MHz.

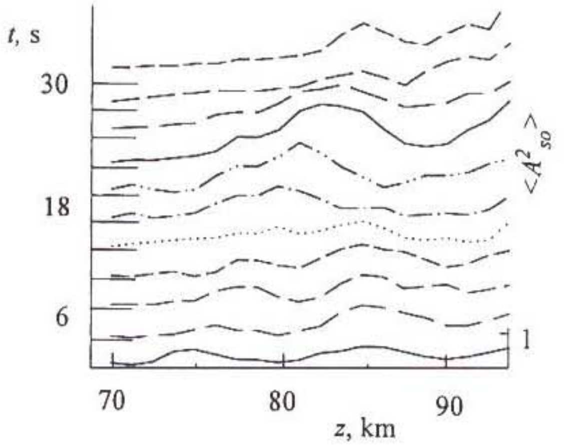


Fig. 5. Height-time profiles of $<A^2_{so}>$- obtained by averaging over 15 sounding pulses (over 3 s).

To investigate the mechanism of partial reflection during thunderstorms (volume scattering or Fresnel reflection) the method of Misyura et al., [1976] was used to separate the scattered component $E_{so,x}$ and the reflected component, $E_{ko,x}$, of the signals. According to the method, the ratio $P_{o,x}=<A^2_{so,x}>/(<A_{so,x}>)^2$ is 1.27 in the case of scattering, while in the presence of both the scattered and reflected component $1<P_{o,x}<1.27$. If the reflected component prevails, than $P_{o,x}=1$. We analyzed the dependences $\beta^2_{o,x}(z,t) = <|E_{ko,x}|^2>/<|E_{so,x}|^2>$ and $P_{o,x}(z,t)$ for those cases when partially reflected signals were recorded from $z < 75$ km during thunderstorms. The analysis of measured data showed that in all the cases considered the values of $E_{so,x}$ were significantly higher than $E_{ko,x}$ Noticeable differences in the $E_{ko,x}$ to $E_{so,x}$ ratios measured during, before and after thunderstorms were not revealed. This indicates that noticeable changes (either increases or decreases) in the size of scattering irregularities in the lower D region of the ionosphere did not occur during thunderstorms.

Analysis of the experimental data on $A_{s\,o,x}(z,t)$, has revealed some differences in their behavior during, before and after the thunderstorm. For instance, the experiment of July 15, 1981, revealed some features in the behavior of $A_{s\,o,x}(z,t)$ during the thunderstorm (the pulse repetition frequency was $F = 5$ Hz) that were not observed before the thunderstorm Fig. 5 shows height-time profiles of $<A^2_{so}>$, each obtained by averaging over 15 sounding pulses (over 3 sec). The maximum value of $<A^2_{so}>$ shifts in height with time (the effect is observed during 30 s), roughly by 10 km; similar behavior is characteristics $<A^2_{sx}>(z,t)$. The vertical velocity of the disturbance is $V \sim 300$ m/s.

The spectral analysis of the dependences $A_{s\,o,x}(z,t)$ that was performed for $z = 78$; 81 and 85 km revealed an increase in the energy of the spectral component at $f = 0.5$ Hz which corresponds to the infrasonic range. It could be suggested that such behavior of $A_{s\,o,x}(z,t)$ during thunderstorms might be caused by the appearance of infrasonic waves propagating from a source in the atmosphere with low losses.

4. Discussion. The results of experimental investigations presented above allow us to come to some conclusions. In particular, the fact that the degree of ionization increases in the lower D-region (z<75km) during a number of thunderstorms seems to confirm the point of some researchers [Voss et al., 1984; Goldberg et al., 1986; Inan and Carpenter, 1987] that a thunderstorm trigger precipitation of energetic particles (electrons) from the magnetosphere, resulting in additional ionization over the range of heights.

The $N(z)$-profiles were calculated with account of the changes in ν during the thunderstorm namely for $z = 63$ km measured values of $\nu(z)$ were taken, white for $z > 63$ km an exponential approximation was used, which is quite admissible for the ionospheric D-region. Nevertheless, we do not think it to be justified. It would be better if electric field variations in the lower ionosphere were taken into account. On the other hand, in the lower D-region during thunderstorms, an increase (by a factor about 1.7 or 1.8) in the electron-molecule collision frequency, $\nu(z)$, has been revealed. This change in v cannot be ascribed to the effects of precipitating energetic particles. We believe that in order to explain this fact, it wooed be necessary to appeal to the mechanism of interaction between the lower atmosphere and the ionosphere through the vertical conduction current (this mechanism was proposed in [Martynenko et al., 1994] to explain the lithosphere-ionosphere interaction). The total resistance of the Earth-ionosphere gap, $R = \int_0^z \rho(z_1)dz_1$, is due mainly to lower layers of the atmosphere to $z < 5$ km, while the resistivity, ρ, is controlled by the level of the Earth's radioactive background. Thunderstorms result in an increased electromagnetic background near the Earth's surface which leads to proportional increases in the conductivity $\sigma = 1/\rho$ of the lower atmosphere, and the discharge current, J. Variations in the electric field strength are often considerable. As a result, one might expect noticeable changes in the electric field of the lower ionosphere as well [Martynenko et al., 1994]. These suggestions are in agreement with rocket and balloon measurements over thunderstorm centres [Kelley et al., 1985; Kelley et al., 1990]. Therefore, we may assume that the thunderstorm produced variations in the ionospheric electric potential are the factor which may result in the changes observed if the ionospheric D-region parameters.

Note also that infrasonic waves similar to those observed during thunderstorms and reported here were also observed earlier in the atmosphere and ionosphere, following orographic forcing, land-sea differential heating, nonlinear interactions with weather systems, volcanic eruptions, sea roughness, and supersonic motions of auroral arcs [Schlegel et al., 1980; Bertel et al., 1978]. The parameters (periods and propagation velocities) of such waves in all cases were of the same order of magnitude. Note also that the mechanism by which partial reflections and scattering from the ionospheric D-region could be explained by the interaction of electromagnetic sounding waves and atmospheric waves was proposed as early as in the paper by Hines [1960].

5. Conclusions. It has been estabeisned in experiments that the background ionization if the lower D-region (at $z < 70$ km) can increase during thunderstorms several times above to quiet level, reaching values up to $N = (5\text{-}8)10^2$ cm^{-3}. Such events took place in about 40% of the cases considered. The electron-molecule collision frequency, ν, at $z = 63$ km increased by a factor of 1.7-1.8 during thunderstorms. Possible reasons for such behavior of $N(z)$ and $\nu(z)$, could be the energetic particles precipitating from the magnetosphere or variations in the ionospheric electric potential due to changes in the conductance of the lower atmosphere produced by strong thunderstorms.

References

1. Belrose J.S. and Burke M.J., Study of the lower ionosphere using partial reflection. 1. Experimental technique and method of analysis, J. Geophys. Res., Vol. 69, pp. 2799-2818, 1964.
2. Бенедиктов Е.А., Гришкевич Л.В., Иванов В.А. Одновременные измерения электронной концентрации и частоты соударений электронов D-области ионосферы методом частичных отражений. (Simultaneous measurements of the electron density and electron collision frequency in the ionospheric D-region using the partial reflection technique.) Известия вузов. Радиофизика, 1972, т.15, сс. 695-702.
3. Bertel L., Bertin F., Vestud V. et. al., Evaluation of the vertical flux of energy into the thermosphere from medium scale gravity waves generated by the jet stream, J. Atmos. Terr. Phys., Vol. 40, pp. 691-696, 1978.
4. Гоков А.М., Гритчин А.И. О возможном влиянии сильных гроз на параметры D-области ионосферы и характеристики зондирующих КВ радиоволн. (On possible effects of strong thunderstorms on parameters of the ionospheric D-region and characteristics of sounding HF-radio waves.) Геомагнетизм и аэрономия, 1992, т. 32, сс. 178-180.
5. Goldberg R.A., Barcus J.R., Hale L.C., Curtis S.A. Direct observation of magnetospheric electron precipitation stimulated by lightning, J. Atmos. Terr. Phys., Vol. 48, pp. 293-300, 1986.
6. Григорьев Т.И., Докучаев В.П., Инфразвук и внутренние гравитационные волны при грозовых разрядах в атмосфере. (Infrasound and internal gravity waves from thunderstorm discharges in the atmosphere.) Известия АН СССР. Физика атмосферы и океана, 1981, т. 17, сс. 690-697
7. Hale L.C. and Baginski M.E., Current to the ionosphere following a lightning stroke, Nature, No. 329, pp. 814-816, 1987.
8. Hines C.O., Internal atmospheric gravity waves at ionospheric heights, Can. J. Phys., Vol. 38, pp. 1441-1481, 1960.

9. Inan U.S., and Carpenter D.L. Lightning-induced electron precipitation events observed at L=2.4 as phase and amplitude perturbations on subionospheric VLF signals, J. Geophys. Res., Vol. 92, pp. 3293-3297, 1987.
10. Inan Umran, S. VLF-heating of the lower ionosphere, Geophys.Res. Lett., Vol. 17, pp. 729-734, 1990.
11. Inan U.S., Bell T.F., and Rodriguez I.V. Heating and ionization of the ionosphere by lightning, Geophys.Res.Lett, No 18, pp. 705-711, 1991.
12. Kelley M.C., Siefring C.L., Pfaff R., and Hale L.S., Electrical measurerements in the atmosphere and the lower ionosphere over an active thunderstorm. 1. Campaign Overview and Individual Results, J. Geophys. Res., Vol. 90, pp. 9815-9823, 1985.
13. Kelley M.C., Ding J.C., and Holzworth R.H. Intence ionospheric electric and magnetic field pulses generated by lightning, Geophys. Res. Lett., Vol. 17, pp. 2221-2224, 1990.
14. Кучеров К.И., Николаенко А.П., О нагреве электронов нижней ионосферы горизонтальными грозовыми разрядами. (On the heating of lower ionospheric electrons by horizontal lightning discharges.) Известия вузов. Радиофизика, 1979, т. 22, сс. 894-896.
15. Мартыненко С.И., Фукс И.М., Шубова Р.С. Отклик нижней ионосферы на изменение проводимости приземной атмосферы. (Response of the lower ionosphere to changing the near-Earth atmospheric conductivity.) Геомагнетизм и аэрономия, 1994, т. 34. С. 121-126.
16. Мисюра В.А., Пивень Л.А., Федоренко Ю.П. О природе частично отраженных сигналов. (On the nature of partially reflected signals, 1976. Particle Acceleration and Effects in Cosmos.) Ускорение частиц и плазменные эффекты в космосе . Киев: Наукова думка, 1976. 14с.
17. Николаенко А.П. О нагреве электронов нижней ионосферы электромагнитным излучением вертикальных грозовых разрядов. (On lower ionospheric electrons heated by the electromagnetic radiation of vertical lighting-discharges.) Геомагнетизм и аэрономия, 1976, т. 16, сс. 260-264.
18. Rodriguez I.V., Inan U.S., and Bell T.S., D-region phenomena due to heating and ionization by lightning radiation, Eos., 72, Suppl., 376, 1991.
19. Schlegel K., Thrane E.V., and Brekke A., Partial reflection results in the auroral D-region explained in terms of acoustic waves, J. Atmos. Terr. Phys., Vol. 42, pp. 809-814, 1980.
20. Sukhorukov A.I., Rudenko E.A., Stubbe P., Simulation of the strong lightning pulse penetration into the lower ionosphere, Geophys. Res. Let., No 23, pp. 2911-2915, 1996.
21. Tonev P.T., and Velinov P.I., Time-dependent model of the initial phase of thundercloud electric field penetration into the ionosphere, Doklady Bolgarskoy AN, No 45, pp. 47-50, 1992.
22. Tyrnov, O.F., Garmash, K.P., Gokov, A.M., Gritchin, A.I., Dorohov, V.L., Kontsevaya, L.G., Kostrov, L.S., Leus, S.G., Martynenko, S.I., Misura, V.A., Podnos, V.A., Pokhilko, S.N., Rozumenko, V.T., Somov, V.G., Tsymbal, A.I., Chernogor, L.F., and Shemet, A.S., The radiophysical observatory for remote sounding of the ionosphere, Turkish J. of Physics, Vol. 18, pp. 1260-1265 ,1994 .
23. Vale L.C. In: Weather and Climate Responses to Solar Variations (ed. McCormac,B.M.). 311-321 (Colorado Associated University Press, 1983).
24. Voss H.D., Imhof W.L., Walt M.E. et al. Lightning-induced electron precipitation, Nature, Vol. 312, pp. 740-742, 1984.