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A MODEL STUDY OF THE INFLUENCE OF ARTIFICIAL HEATING OF THE NIGHTTIME HIGH-LATITUDE IONOSPHERE ON THE SPATIAL DISTRIBUTIONS OF THE IONOSPHERIC PARAMETERS

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Abstract. A mathematical model of the high-latitude ionosphere, developed earlier in the Polar Geophysical Institute, is utilized to calculate three-dimensional distributions of ionospheric parameters in the high-latitude F layer, modified by the action of the ionospheric high-frequency heating facility near Tromso, Scandinavia when it is located on the night side of the Earth. The results of the numerical simulation indicate that artificial heating of the ionosphere by powerful HF waves ought to influence noticeably on the large-scale spatial structure of the nighttime high-latitude F-region ionosphere.

Introduction

It is well known that high-power high-frequency radio waves, pumped into the ionosphere, cause the variety of physical processes in the ionospheric plasma. Experiments with high-power, high-frequency radio waves, used for the investigation of the ionospheric plasma's properties during the last four decades, indicated that powerful HF waves can produce significant large-scale variations in the electron temperatures and densities in the F layer [*Utlaut and Violette,* 1974*; Mantas et al.*, 1981*; Duncan et all.*, 1988*; Honary et al., 1995; Gustavsson et al.*, 2001*; Rietveld et al.*, 2003*; Kosch et al.*, 2007*; Pedersen et al.*, 2008]. To investigate the response of the high-latitude F region to a powerful HF wave and the role of specific features of the high-latitude ionosphere, mathematical models may be utilized. One of such mathematical models has been developed in the Polar Geophysical Institute [*Mingaleva and Mingalev*, 1997]. This model has been used to simulate the influence of the power, frequency, and modulation regime of HF waves on the expected response of the height profiles of the ionospheric parameters at F-layer altitudes to HF heating [*Mingaleva and Mingalev,* 2002; 2003*; Mingaleva et al.*, 2003; 2009; 2012]. The purpose of this paper is to examine how high-power high-frequency radio waves, pumped into the high-latitude ionosphere, influence on the three-dimensional distributions of the ionospheric parameters at F-layer altitudes, with the mathematical model developed in the Polar Geophysical Institute being utilized.

Numerical model

To calculate three-dimensional distributions of the ionospheric parameters in the F-region ionosphere the mathematical model of the convecting high-latitude ionosphere, developed earlier [*Mingaleva and Mingalev,* 1996; 1998], is applied. The applied numerical model takes into consideration the strong magnetization of the plasma at F-layer altitudes and the attachment of the charged particles of the F-region ionosphere to the magnetic field lines. As a consequence, the F-layer ionosphere plasma drift in the direction perpendicular to the magnetic field **B** is strongly affected by the electric field **E** and follows **E**×**B** convection paths (or the flow trajectories). In the model calculations, a part of the magnetic field tube of the ionospheric plasma is considered at distances between 100-700 km from the Earth along the magnetic field line. As a consequence of the strong magnetization of plasma at F-layer altitudes, its motion may be separated into two flows: the first, plasma flow, parallel to the magnetic field; the second, plasma drift in the direction perpendicular to the magnetic field. The parallel plasma flow in the considered part of the magnetic field tube is described by the system of transport equations, which consists of the continuity equation, the equation of motion for ion gas, and heat conduction equations for ion and electron gases. The temporal history is traced of the ionospheric plasma included in the part of the magnetic field tube moving along the flow trajectory through a neutral atmosphere. By tracing many field tubes of plasma along a set of flow trajectories, we can construct three-dimensional distributions of ionospheric quantities. Thus, the model produces three-dimensional distributions of the electron density, positive ion velocity, and ion and electron temperatures. It encompasses the ionosphere above 36^0 magnetic latitude and at distances between 100 and 700 km from the Earth along the magnetic field line for one complete day. The numerical method, boundary conditions, neutral atmosphere composition, utilized electric field distribution, thermospheric wind pattern, and input parameters of the model were in detail described in the study by Mingaleva and Mingalev [1998].

The applied mathematical model takes into account the following heating mechanism, caused by the action of the powerful HF radio waves. The absorption of the heater wave energy is supposed to give rise to the formation of field-aligned plasma irregularities on a wide range of spatial scales. In particular, short-scale field-aligned irregularities are excited in the electron hybrid resonance region. These irregularities are responsible for the anomalous absorption of the electromagnetic heating wave (pump) passing through the instability region and cause anomalous heating of the plasma. The rate of this anomalous heating is included in the heat conduction equation for electron gas. The concrete expression to the rate of anomalous heating was taken from the study by Blaunshtein et al. [1992].

Using the given electric field distribution, we calculate the plasma drift velocity along the convection trajectories, which intersect the F-layer volume illuminated by HF heating facility near Tromso, Scandinavia. For these convection trajectories, we obtain variations of profiles against distance from the Earth along the geomagnetic field line of the ionospheric quantities with time (along the trajectory) by solving the system of transport equations described above. These profiles result in two-dimensional distributions of ionospheric quantities along the each flow trajectory. Using these two-dimensional distributions along the each convection trajectory, we can construct three-dimensional distributions of ionospheric quantities, modified by the action of the ionospheric heater.

Simulation results

The utilized mathematical model can describe different combinations of the solar cycle, geomagnetic activity level, and season. In the present study, the calculations are performed for autumn (5 November) and not high solar activity conditions ($F_{10.7}$ =110) under low geomagnetic activity (Kp=0). The spatial configuration of the electron and proton precipitation zones as well as intensities and average energies of the precipitating electrons and protons were chosen as consistent with the statistical model of Hardy et al. [1989].

To examine how high-power high-frequency radio waves, pumped into the high-latitude ionosphere, influence on the ionospheric parameters distributions in the horizontal directions at F-layer altitudes, we made calculations for two distinct cases. For the first case, we obtained the distributions of the ionospheric parameters under natural conditions without a powerful high-frequency wave effect. For the second case, the distributions of the ionospheric parameters were obtained on condition that the ionospheric high-frequency heating facility near Tromso, Scandinavia has been operated.

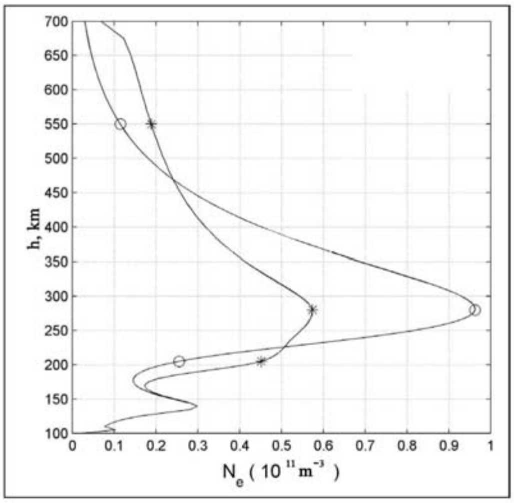

Fig. 1 Profiles of the electron concentration versus distance from the Earth along the geomagnetic field line, situated in the illuminated region, obtained under natural conditions without artificial heating (marked by the symbol ○) and disturbed by the heater at the moment of approximately four minutes after turn on (marked by the symbol *).

For the second case, firstly, we made a series of calculations to choose the wave frequency which provides the maximal effect of HF heating on the electron concentration at the levels near to the F2-layer peak, that is, the most effective frequency for the large-scale F2-layer modification, f_{eff}, [*Mingaleva and Mingalev*, 2003]. It was found that this most effective frequency is 2.6 MHz on condition that the maximal value of the effective absorbed power (EAP) is equal to 30 MW which is quite attainable for the heating facility near Tromso.

Secondly, calculations were carried out, using the pointed out values of the f_{eff} and EAP, to study how the HF radio waves affect the large-scale high-latitude F-layer modification. The ionospheric heater was supposed to operate during the period of five minutes, with the heater being located on the night side of the Earth on the magnetic meridian of 01.20 MLT.

The results of simulations are partly presented in Figs. 1-3. Results of simulation indicate that a great energy input from the powerful HF wave arises at the level, where the wave frequency is close to the frequency of the electron hybrid resonance, when the ionospheric heater is turned on and operates. At this level, pronounced peak arises in the electron temperature profile. At this peak, the electron temperature can increase for some thousands of degrees. The increase in the electron temperature results in a rise in the electron gas pressure. From the level where the electron gas pressure peak is located, the upward and downward electron gas fluxes arise. Due to the electrical neutrality of the ionospheric plasma, the ion gas begins to move, too. Thus, ionospheric plasma fluxes arise from the level where the maximum energy input from the powerful HF wave takes place. Owing to these fluxes, a visible decrease in the electron concentration profile can arise not only near the level of maximum energy absorption from the powerful HF wave, but also near the F2-layer peak (Fig.1). It is seen that powerful HF waves lead to the decrease of more than 40% in electron concentration at the level of the F2-layer peak. After turning off of the heater, the electron temperature decreases due to elastic and inelastic collisions between electrons and other particles of ionospheric plasma, and a period of recovery comes.

The simulation results, obtained on condition that the ionospheric heater has been operated during the period of five minutes, indicate that the electron temperature hot spot is formed on the night side in the vicinity of the location of the ionospheric heater. Inside this hot spot, the electron temperature increases for some thousands of degrees. Moreover, the electron concentration cavity is formed on the night side in the vicinity of the location of the ionospheric heater (Figs. 2 and 3). Inside this cavity, powerful HF waves lead to a decrease of about 40% in the electron concentration at the level of the F2-layer peak.

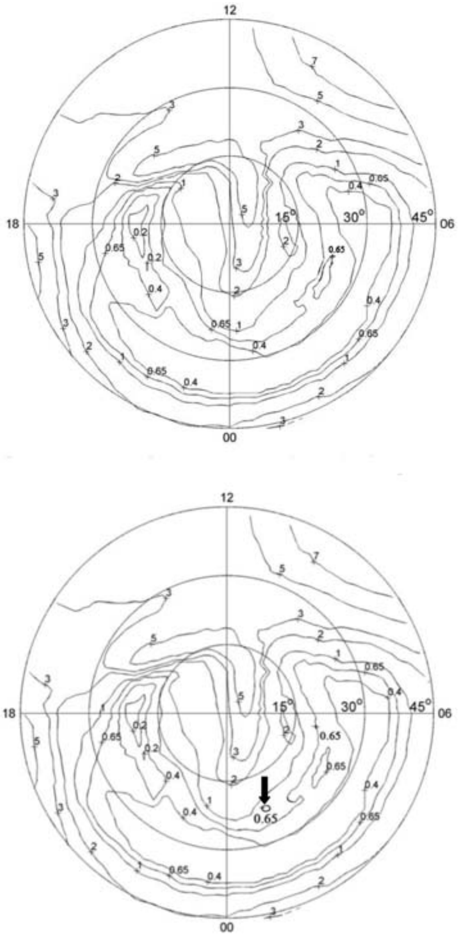

Fig. 2 Simulated distributions of the electron concentration (in units of 10^{11} m^{-3}) at level of 320 km obtained under natural conditions without artificial heating (top panel) and obtained on condition that the ionospheric heater has been operated during the period of five minutes (bottom panel). The electron concentration cavity, created artificially, is indicated by black pointer at the bottom panel.

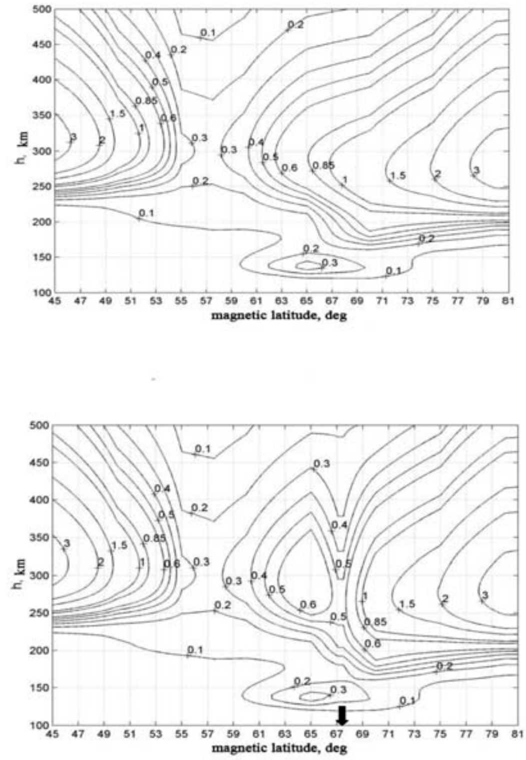

Fig. 3 Simulated distributions of the electron concentration (in units of 10^{11} m^{-3}) in the magnetic meridian plane, lying across the ionospheric heater, obtained under natural conditions without artificial heating (top panel) and obtained on condition that the ionospheric heater has been operated during the period of five minutes (bottom panel). The location of the Tromso heater is indicated by the black pointer at the bottom panel.

The simulation results indicate that the cross sections of the artificial electron temperature hot spot and artificial electron concentration cavity have dimensions of about 100-150 km in the horizontal directions at the levels of the F layer (Figs. 2 and 3). These dimensions are much less than the horizontal sizes of the natural large-scale inhomogeneous structures characteristic for the high-latitude ionosphere, in particular, of the natural electron temperature hot spots and main ionospheric trough. It is seen that the horizontal section of the region, disturbed artificially, at F-layer altitudes is more than the horizontal section of the region, illuminated by the heater, whose diameter is approximately 88 km at 300 km altitude. This peculiarity is conditioned by the convection of the ionospheric plasma. The dimension of the artificial electron concentration cavity in the direction of the magnetic field line is about some hundreds of kilometers (Fig. 3).

Conclusion

The mathematical model of the high-latitude ionosphere, developed earlier in the Polar Geophysical Institute, was utilized to calculate three-dimensional distributions of ionospheric parameters in the high-latitude F layer, modified by the action of the ionospheric high-frequency heating facility near Tromso, Scandinavia. The calculations were made for two cases. Firstly, we obtained the distributions of the ionospheric parameters under natural conditions without a powerful high-frequency wave effect. Secondly, the distributions of the ionospheric parameters were obtained on condition that the ionospheric high-frequency heating facility has been operated during the period of five minutes, with the heater being located on the night side of the Earth on the magnetic meridian of 01.20 MLT. In the second case, powerful high-frequency waves lead to a decrease of about 40% in the electron concentration at the level of the F2-layer peak over the ionospheric heater. The cross sections of the artificial electron concentration cavity have dimensions of about 100-150 km in the horizontal directions at the levels of the F layer. The artificial electron concentration cavity is stretched in the direction of the magnetic field line for some hundreds of kilometers.

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References

Blaunshtein, N.Sh., Vas'kov, V.V., Dimant, Ya.S. Resonance heating of the F region by a powerful radio wave. Geomagnetism and Aeronomy, 32(2), 95-99, 1992 (Russian issue).

Duncan, L.M., Sheerin, J.P., Behnke, R.A. Observations of ionospheric cavities generated by high-power radio waves. Physical Review Letters, 61, 239-242, 1998.

Gustavsson, B., Sergienko, T., Rietveld, M.T., Honary, F., Steen, A., Brandstrom, B.U.E., Leyser, T.B., Aruliah, A.L., Aso, T., Ejiri, M., Marple, S. First tomographic estimate of volume distribution of HF-pump enhanced airglow emission. Journal of Geophysical Research, 106, 29105-29124, 2001.

Hardy, D.A., Gussenhoven, M.S., Brautigam, D. A statistical model of auroral ion precipitation, Journal of Geophysical Research, 94, 370-392, 1989.

Honary, F., Stocker, A.J., Robinson, T.R., Jones, T.B., Stubbe, P. Ionospheric plasma Response to HF radio waves operating at frequencies close to the third harmonic of the electron gyrofrequency. Journal of Geophysical Research 100, 21489-21501, 1995.

Kosch, M.J., Pedersen, T., Rietveld, M.T., Gustavsson, B., Grach, S.M., and Hagfors,T. Artificial optical emissions in the high-latitude thermosphere induced by powerful radio waves: An observational review. Adv. Space Res., 40, 365-376, 2007.

Mantas, G.P., Carlson, H.C., La Hoz, C.H. Thermal response of F-region ionosphere in artificial modification experiments by HF radio waves. Journal of Geophysical Research, 86, 561-574, 1981.

Mingaleva, G.I., Mingalev, V.S. The formation of electron temperature hot spots in the main ionospheric trough by the internal processes, Ann. Geophys., 14, 816-825, 1996.

Mingaleva, G.I., Mingalev, V.S. Response of the convecting high-latitude F layer to a powerful HF wave. Annales de Geophysique 15, 1291-1300, 1997.

Mingaleva, G.I., Mingalev, V.S. Three-dimensional mathematical model of the polar and subauroral ionosphere, pp.251-265, in *Modeling of the upper polar atmosphere processes*, eds. V.E. Ivanov, Ya.A. Sakharov, and N.V.Golubtsova, PGI, Murmansk, 1998, (in Russian).

Mingaleva, G.I., Mingalev, V.S. Modeling the modification of the nighttime high-latitude F-region by powerful HF radio waves, Cosmic Research, 40(1), 55-61, 2002.

Mingaleva, G.I., Mingalev, V.S. Simulation of the modification of the nocturnal high-latitude F layer by powerful HF radio waves. Geomagnetism and Aeronomy, 43(6), 816-825, 2003, (Russian issue).

Mingaleva, G.I., Mingalev, V.S., Mingalev, I.V. Simulation study of the high-latitude F-layer modification by powerful HF waves with different frequencies for autumn conditions. Annales de Geophysique 21, 1827-1838, 2003.

Mingaleva, G.I., Mingalev, V.S., Mingalev, I.V. Model simulation of the large-scale high-latitude F-layer modification by powerful HF waves with different modulation, J. Atmos. Sol.-Terr. Phys., 71, 559-568, 2009.

Mingaleva, G.I., Mingalev, V.S., Mingalev, O.V. Simulation study of the large-scale modification of the mid-latitude F-layer by HF radio waves with different powers // Ann. Geophysicae, 30, 1213–1222, doi:10.5194/angeo-30-1213-2012, 2012.

Pedersen, T., Esposito, R., Kendall, E., Sentman, D., Kosch, M., Mishin, E., Marshall, R. Observations of artificial and natural optical emissions at the HAARP facility. Ann. Geophysicae, 26, 1089-1099, 2008.

Rietveld, M.T., Kosch, M.J., Blagoveshchenskaya, N.F., Kornienko, V.A., Leyser, T.B., Yeoman, T.K. Ionospheric electron heating, optical emissions, and striations induced by powerful HF radio waves at high latitudes: Aspect angle dependence. J. Geophys. Res., 108 (A4), 1141, doi:10.1029/2002JA009543, 2003.

Utlaut, W.F., Violette, E.J. A summary of vertical incidence radio observations of ionospheric modification. Radio Science 9, 895-903, 1974.