

Ionospheric Disturbances due to the Influence of Localized Thermospheric Sources

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Abstract—The paper presents the results of numerical modeling of the ionospheric disturbances from spatially localized, midlatitude, thermospheric sources that simulate the dissipation effect of acoustic–gravity waves generated by phenomena on the Earth’s surface and in the lower atmosphere. The results of numerical calculations have shown that the range of ionospheric effects significantly exceeds the size of the region of sources of thermospheric disturbances and reaches low latitudes. In the spatial distribution of the critical frequency of the ionospheric F_2 layer, it decreases directly above the thermospheric source and increases to the south of it. Negative ionospheric disturbances are due to a decrease in the partial concentration of atomic oxygen in the area of a thermospheric source. The processes of turbulent diffusion, which lead to a decrease in the concentration of atomic oxygen in the lower thermosphere, are most effective in reducing the electron concentration in the ionosphere. The developing large-scale circulation processes in the thermosphere lead to positive ionospheric disturbances, which are observed south of the source region up to low latitudes.

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1. INTRODUCTION

Experimental studies show that various phenomena in the lower atmosphere and on the Earth’s surface can serve as sources of ionospheric disturbances.

Examples of ionospheric disturbances arising during periods of meteorological storms, hurricanes, and typhoons, as well as during the development of stratospheric warming, disturbances of seismic activity, and tsunamis, are presented in the literature (Martini and Manzano, 1999; Pancheva and Mukhtarov, 2011; Chernigovskaya et al., 2015; Yigit et al., 2016; Borchevskina and Karpov, 2017; Li et al., 2017).

The ionospheric disturbances caused by such phenomena are quite diverse. Thus, the ionospheric precursors of earthquakes at midlatitudes are manifested in the form of positive disturbances, and the reaction to meteorological storms is more often manifested in the form of negative disturbances (Pulinets and Boyarchuk, 2004; Borchevskina and Karpov, 2017). The ionospheric response to processes in the lower atmosphere can appear within a few hours after the start of the processes, and the amplitude characteristics of the disturbances of the critical frequency of the F_2 layer (f_oF_2) and the total electron content (TEC) can reach 50% of the background values.

Acoustic–gravity waves (AGWs) are considered a mechanism for this rapid propagation of disturbances

from the lower atmosphere into the ionosphere (Borchevskina and Karpov, 2017). At the same time, much attention is paid to infrasound waves and internal gravitational waves with periods close to the Väisälä–Brunt period. Theoretical studies show that such waves can quickly and almost vertically propagate from the lower layers of the atmosphere and reach ionospheric heights (Petrukhin et al., 2012; Karpov and Kshevetsky, 2014). It was shown that local heating regions of the thermosphere arise due to the dissipation of such waves (Hickey et al., 2011; Karpov and Kshevetsky, 2014). The appearance of thermospheric disturbances, in turn, affects the ionization and recombination processes, which leads to a change in the state of the ionosphere.

Vasilev et al. (2018) studied disturbances of the parameters of the thermosphere and ionosphere created by point sources of thermospheric heating. The results made it possible to explain some features of the ionospheric disturbances that arise; however, the amplitude values of ionospheric effects are much smaller than those observed under meteorological disturbances. This means that the observed ionospheric disturbances are determined by a more complex set of processes that develop in the thermosphere due to disturbances in the lower atmosphere.

The goal of this work was to continue the study of the mechanisms of formation of ionospheric distur-

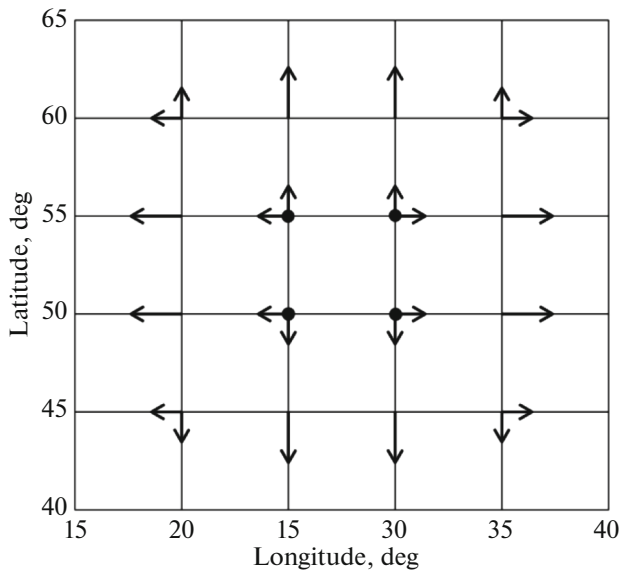


Fig. 1. Location of heat and density sources (black dots) and velocity components (arrows) in grid nodes of the GSM TIP model.

bances caused by local thermospheric sources and to identify the most important factors determining the reaction of the ionosphere.

2. DESCRIPTION OF NUMERICAL EXPERIMENTS

The influence of local disturbances of the thermosphere on the state of the thermosphere and ionosphere was studied with mathematical modeling methods. Numerical experiments were performed with the Global Self-Consistent Model of the Thermosphere, Ionosphere, and Protonosphere (GSM TIP), which enables the study of large-scale processes in the upper atmosphere and ionosphere (Namgaladze et al., 1990).

Disturbances of temperature, wind, and density localized in height in a given latitudinal-longitude region, which simulate the result of dissipation in the upper AGW atmosphere with periods of no more than half an hour (Karpov and Bessarab, 2008; Karpov and Kshevetsky, 2014), are examined as sources of disturbances of the midlatitudinal thermosphere. The model equations include additional sources of heating, density, and wind components, the spatial arrangement of which is presented in Fig. 1.

The value of the addition to a particular parameter was determined with the formula

$$Q = A \exp\left(-\frac{|r - r_0|}{H}\right),$$

where r is the current height; r_0 is the height of the maximum of the source; H is the height of the homo-

geneous atmosphere; A is the amplitude factor; and Q is the power of the source. The vertical profile of the sources and the height of their maxima r_0 were determined based on qualitative estimates of the results of modeling of AGW dissipation from a surface source (Karpov and Kshevetski, 2017).

The amplitude factor A was selected such that the maximum heating of the thermosphere at a height r_0 was ~ 100 K for the heating source; it was 100 m/s for the horizontal components of the wind, which corresponds to the estimates of (Karpov and Kshevetski, 2017). The addition to density $\Delta\rho_d$ was associated with a heat source that added to temperature ΔT_d . It was determined with the polarization relation for large-scale, low-frequency waves (Grigoryev, 1999):

$$\frac{\Delta T_d}{T} = -\frac{\Delta\rho_d}{\rho},$$

where T and ρ are the background values of temperature and density.

In the course of numerical calculations, the amplitudes of the sources increased for 2 h to achieve the specified values of the disturbances of the thermospheric parameters and subsequently ensured their constancy.

In the numerical experiments, a number of source parameters were varied in order to simulate different variants of the effect of thermospheric disturbance on ionospheric parameters. In particular, the amplitude and duration of the source, its maximum height, and its vertical profile were changed. The change in the source height was determined by the dependence on the processes of molecular diffusion and thermal conductivity, as well as on the frequency characteristics of propagating AGWs: the shorter the wave period was, the greater was the height at which they could penetrate the thermosphere. Thus, the height of the source maximum characterizes the frequencies of AGWs participating in the formation of disturbances of the thermosphere and ionosphere.

In addition, the effect of AGWs on the upper atmosphere via the enhancement of turbulent processes at heights of the lower thermosphere was considered. Turbulent diffusion processes lead to a decrease in the relative concentration of the atomic components of the gas composition of the thermosphere in the turbulence region (Karpov and Namgaladze, 1988; Ylugit and Medvedev, 2015). This leads to a change in the conditions of ionization and recombination processes, which may affect the ionospheric state.

In order to study the sensitivity of changes in the gas composition of the thermosphere to the ionosphere reaction, a numerical calculation was performed with the inclusion of a source to reduce the concentration of atomic oxygen in the region of passing AGWs with a maximum at the lower boundary of the simulated space. The amplitude characteristics of the source intensity were estimated according to the

results of calculations (Karpov and Namgaladze, 1988).

The calculations were carried out for the state of the upper atmosphere corresponding to the winter conditions of the Northern Hemisphere. The disturbances of the parameters of the thermosphere and ionosphere were determined in a comparative analysis of the results of calculations of the diurnal dynamics of the unperturbed atmosphere and with calculations that take into account the influence of a local spatial source of disturbances on the thermosphere and ionosphere.

3. RESULTS

Calculations involving only a spatial heating source showed that, as in the case of a point source of thermospheric disturbance (Vasilev et al., 2018), the reaction of the night ionosphere is small and does not exceed several percent of the background values $foF2$ and TEC. The amplitude disturbances of the ionosphere are slightly amplified but do not exceed 0.1 MHz for $foF2$. Moreover, the dynamics of ionospheric effects in the daytime is practically independent of the presence or absence of a heating source at night, which is entirely determined by the parameters of the source during the day.

The maximum amplitude of the daily disturbances of the ionosphere generated by the work of a heat source, in comparison with its background state, was recorded at 1600 UT in most of the calculations. Figure 2a shows the $foF2$ distribution calculated for a heat source with a heating maximum at an altitude of 160 km. As can be seen from the figure, in the spatial structure of the disturbance amplitudes $foF2$, negative ionospheric effects are noted directly above the source, as well as west and northwest of it. A region of positive ionospheric disturbances forms to the south and southeast of the source, which propagates to low latitudes up to equatorial latitudes.

The results of numerical experiments with heights of the maximum of the heating source that vary from 140 to 200 km and various types of its vertical profile have shown that such a spatial structure of the ionospheric response is preserved for any thermospheric heating source. The value of the positive addition to $foF2$ is proportional to the heating value at an altitude above 150 km and is ~ 1 MHz with a maximum heating of 100 K. A negative addition is also associated with the heating value, but it grows more weakly and reaches no more than -0.4 MHz.

The inclusion of additional sources of both horizontal and vertical velocities does not lead to significant changes in the picture of the ionospheric response (Fig. 2b). The characteristic distribution structure of additions to $foF2$ was preserved, and the change in the amplitude values did not exceed 10% in

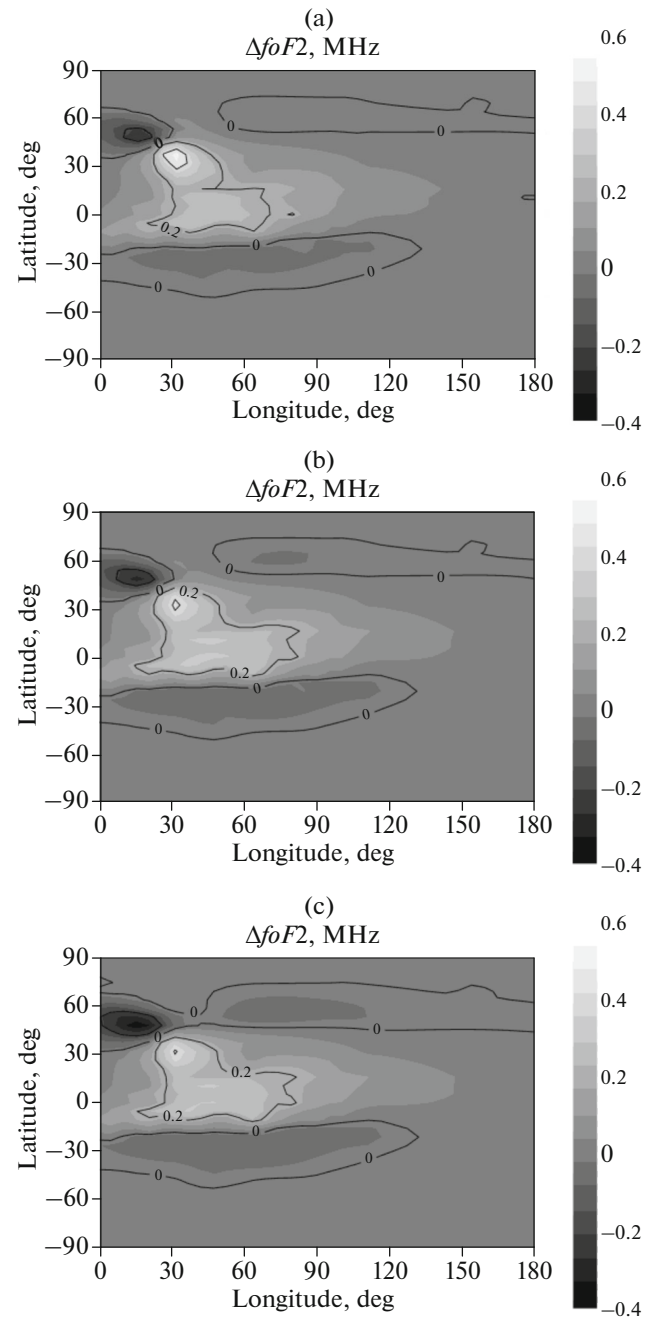


Fig. 2. Distribution of additions to $foF2$ at 1600 UT for sources: thermospheric heating at an altitude of 160 km (a); heating and wind (b); heating, wind, and a reduced concentration of atomic oxygen (c).

comparison with the effects that occur when the heat source is turned on.

On the whole, the inclusion of additional sources of temperature and wind disturbances that affect the dynamic state of the thermosphere leads to the development of circulation processes along the boundary of the disturbance region. An anticyclonic cell forms above the maximum of the source in the upper ther-

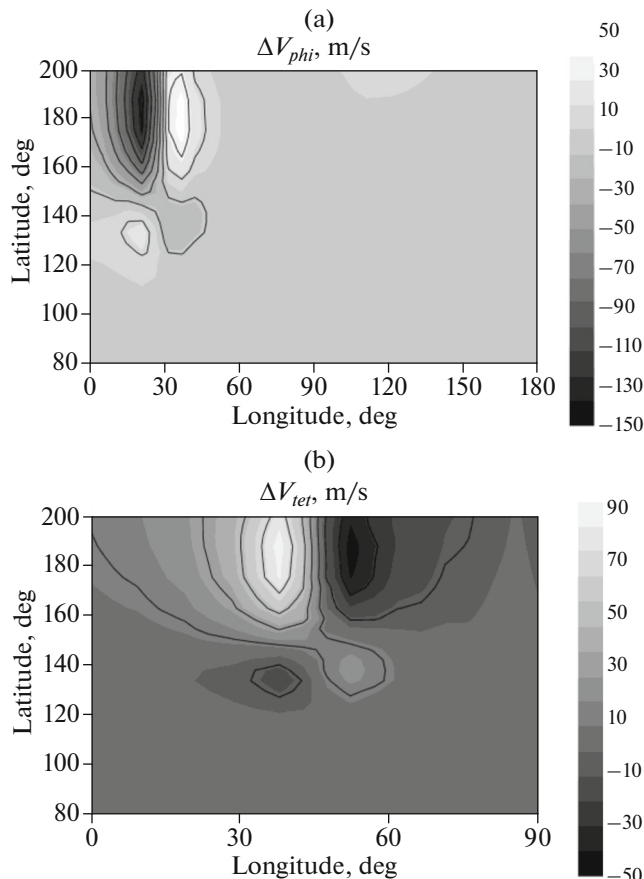


Fig. 3. Additions to horizontal speed components at 1600 UT.

mosphere, and a cyclonic cell forms in the lower thermosphere (Fig. 3). The development of such a large-scale process in the thermosphere, obviously, leads to corresponding changes in the state of the ionosphere and determines the expansion of the region of ionospheric disturbances in comparison with the sizes of the thermospheric region in which additional sources of disturbances act. However, as in the case in which only point thermal sources of thermospheric disturbances are taken into account, the amplitude characteristics of ionospheric disturbances are much smaller than those observed.

The results of calculations with the inclusion of an additional source of a decrease in the concentration of atomic oxygen in the lower thermosphere, which simulates the influence of AGWs on turbulent processes, demonstrate a more significant effect of disturbances of the gas composition of the thermosphere on the ionosphere reaction in comparison with disturbances created by dynamic sources (Fig. 2c)

Figure 4 shows disturbances of the atomic oxygen concentration in the calculation that includes only an additional source of thermospheric heating (Fig. 4a) and in the calculation that takes into account the

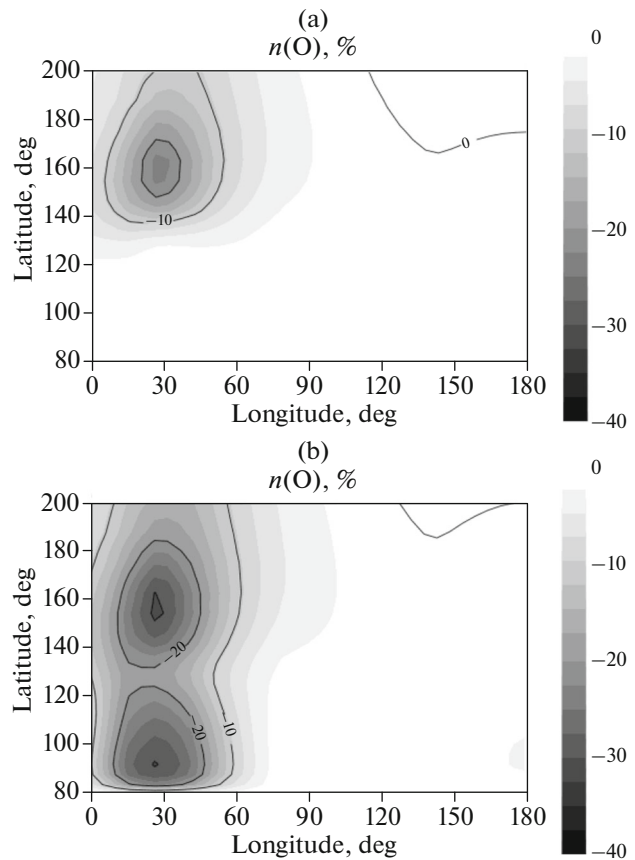


Fig. 4. Disturbance of the concentration of atomic oxygen during the operation of a conventional thermospheric source (a) and with an additional source of a decrease in atomic oxygen in the lower thermosphere (b) at 1600 UT.

decrease in the concentration of atomic oxygen in the lower thermosphere (Fig. 4b). Clearly, a decrease in the concentration of atomic oxygen in the lower thermosphere leads to a decrease in its concentration at all heights above the region of disturbances initiated by the AGW.

A decrease in the concentration of atomic oxygen in the lower thermosphere by 30% as compared to the background unperturbed state leads to significant changes in the ionosphere: the maximum $foF2$ decrease increases by 0.15 MHz in comparison with the amplitudes of negative disturbances created by dynamic sources of disturbances of the thermosphere and reaches -0.5 MHz. The area of the negative effect to the northwest of the source expands, and the value of the positive effect to the southeast of it decreases (Fig. 1c).

Thus, numerical experiments show that the most effective process affecting the decrease in the electron concentration above the AGW source in the lower atmosphere is the amplification of turbulent processes in the lower thermosphere. The observed values of ionospheric disturbances can, in principle, be obtained when the processes that decrease the con-

centration of atomic oxygen in the thermosphere are taken into account.

4. CONCLUSIONS

The purpose of the numerical experiments was to study the mechanisms of the formation of ionospheric disturbances caused by local thermospheric sources. It was assumed that these sources are caused by the processes of propagation and dissipation in the AGW thermosphere, which are excited in the lower atmosphere during periods of meteorological disturbances. Observations of the ionosphere found significant decreases in the ionospheric parameters of the TEC and $foF2$ under such conditions.

The results of numerical calculations with the inclusion of additional thermospheric sources simulating the processes of AGW dissipation from sources in the lower atmosphere showed the following.

1. Thermospheric disturbances caused by such sources lead to a decrease in the electron concentration directly above the AGW source and to an increase to south of it. Ionospheric disturbances weakly depend on changes in the vertical profile of the source and the height of its maximum, preserving the characteristic spatial structure and differing only in the values of positive and negative disturbances.

2. Negative ionospheric disturbances are associated with changes in the gas composition of the thermosphere: a decrease in the concentration of atomic oxygen, which leads to a decrease in the ionization rate. The processes of turbulent diffusion, which lead to a decrease in the concentration of atomic oxygen in the lower thermosphere, are most effective in reducing the electron concentration in the ionosphere.

3. The large-scale circulation processes that developed in the study of the considered sources of disturbances in the thermosphere led to positive ionospheric disturbances, which are observed south of the source region up to low latitudes.

The results show that thermospheric disturbances caused by additional heat and wind sources due to AGW dissipation are not the main factor determining negative ionospheric disturbances above the wave source. A change in the gas composition of the lower thermosphere due to turbulent diffusion more effectively influences the amplitude values of the negative ionospheric reaction. At the same time, due to AGW dissipation, additional thermospheric sources form large-scale disturbances in the source region, which cause positive ionospheric disturbances south of the source up to the equatorial region. Karpov et al. (2019) presented an example of the appearance of a similar ionospheric reaction, in which an analysis of TEC observations showed that a positive disturbance arises in the equatorial region during the period of the development of a meteorological storm at the midlatitudes.

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