

# Wind Effects in the Thermosphere during the Propagation of Atmospheric Waves Generated by a Tropospheric Heat Source

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**Abstract**—The results of a numerical study of the processes of propagation into the thermosphere of internal gravity waves excited by heat sources in the troposphere are presented. The results of numerical experiments have shown that thermospheric disturbances from such sources arise ~30 min after the onset of their action. The reason for the appearance of a fast reaction of the thermosphere is the infrasonic waves excited during the generation of internal gravity waves. It is shown that the thermospheric wind significantly affects the spatiotemporal structure of wave disturbances in the upper atmosphere. This influence manifests itself in an increase in the amplitudes and a decrease in the spatial scales of waves that propagate against the thermospheric wind. For waves that propagate in the direction of the thermospheric wind, a decrease in amplitudes and an increase in spatial scales are noted.

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## 1. INTRODUCTION

The influence of tropospheric processes on the perturbation of the parameters of the thermosphere and ionosphere has been reliably established in experimental studies (Borchevkina and Karpov, 2017; Martinis and Manzano, 1999; Boška and Sauli, 2001; Polyakova and Perevalova, 2013; Li et al., 2017). Acoustic and internal gravity waves (IGW) excited at the heights of the troposphere are among the important causes of disturbances in the upper atmosphere. The sources of excitation of such waves are diverse, but the most regular and energetically powerful are convective disturbances that determine the meteorological situation (Lindzen, 1981; Fritts and Alexander, 2003; fritts, 1989; Blanc et al., 2014), mesoscale turbulence, for example, (Holton, 2004), as well as the interaction of atmospheric motions with inhomogeneities in the topography of the earth's surface (Gavrilov and Koval, 2013).

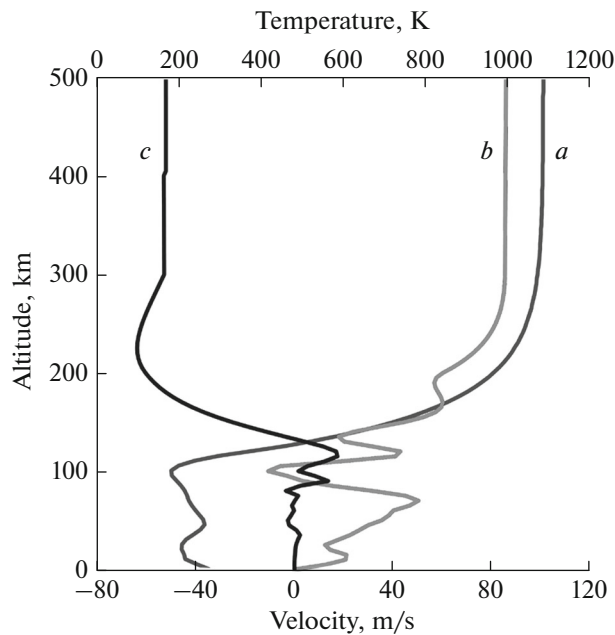
Interpretation of experimental results of studies of the parameters of the atmosphere and ionosphere is often complicated by disturbances caused by fluctuations in solar and geomagnetic activity, which leads to difficulties in identifying the contributions of tropospheric sources to the observed variations in atmospheric parameters.

To understand the features of the relationship between processes in the troposphere and processes in the upper atmosphere it is important to conduct theo-

retical studies that consider the processes that accompany the propagation of atmospheric waves, taking nonlinear and dissipative processes into account.

The improvement of methods for the numerical integration of hydrodynamic equations has made it possible to create atmospheric models that properly take nonlinear and dissipative processes into account, as well as the processes of generation and propagation of infrasonic waves and IGWs in the atmosphere, taking its real stratification into account, for example, (Kshevetski, 2001a; Hickey et al., 2001; Fritts and Alexander, 2003; Akhmedov and Kunitsyn, 2004). The propagation of waves from the troposphere to the thermosphere, in addition to stratification, is significantly affected by winds. It was noted in (Waldock and Jones, 1986) that atmospheric winds in the lower atmosphere can have a great influence on wave parameters at thermospheric heights, which leads to significant effects observed in the experimental study of medium-scale traveling ionospheric disturbances (TIDs). Possible changes in the properties of atmospheric waves at different heights, associated with the influence of wind should be taken into account when they are parameterized in global numerical models of the atmosphere.

The purpose of this work was to study the features of the effect of atmospheric wind on the vertical propagation of IGWs generated by model tropospheric sources.



**Fig. 1.** The background temperature values (*a*) obtained by the empirical model NRLMSISE-00, and zonal (*b*) and meridional (*c*) velocity component obtained from the empirical model HWM14. The zonal wind component is directed from west to east, the meridional wind component is directed from south to north.

## 2. NUMERICAL EXPERIMENTS

In the numerical experiments the “AtmoSym” model of the neutral atmosphere of high spatial and temporal resolution was used. The model is based on solving nonlinear and nonhydrostatic hydrodynamic equations, which allows one to describe the processes of propagation in the atmosphere of both acoustic and internal gravity waves. The numerical methods used in the model, the integration of equations, and the study of the convergence of solutions were described in detail in (Kshevetskii, 2001a, 2001b, 2001c). A number of theoretical studies of the influence of atmospheric waves excited in the troposphere on disturbances in the upper atmosphere were carried out using this model (Kshevetsky and Kulichkov, 2015).

This paper presents the results of numerical experiments on modeling disturbances in the upper atmosphere caused by the propagation of atmospheric waves from the troposphere, taking wind motions in the atmosphere into account.

In the calculations, the dimensions of the region of integration of the equations were 2000 km in the horizontal direction and 500 km in the vertical direction. In the calculations, the OX axis is not tied to longitude and latitude. The spatial distributions of atmospheric parameters and the wind in the initial condition were set according to the NRLMSISE-00 (Picone et al., 2002) and HWM14 (Drob et al., 2015) empirical models for the mid-latitude winter atmosphere. Figure 1

shows the vertical profiles of the temperature and horizontal wind components under the initial conditions.

In numerical calculations, a model tropospheric heat source that reflects convective processes in the troposphere is approximated by a Gaussian function:

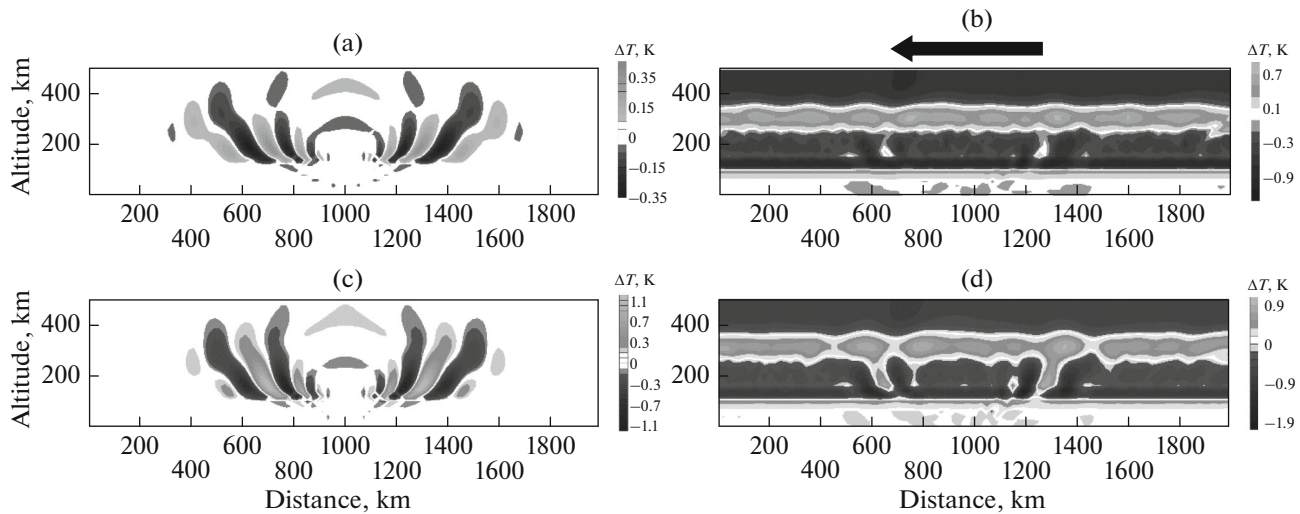
$$f(x, z, t) = A \exp \left( - \left( \frac{x - x_0}{L_x} \right)^2 - \left( \frac{z - z_0}{L_z} \right)^2 \right) \times (1 - e^{t/\tau}) \sin(\omega t), \quad (1)$$

where the parameters  $x_0$  and  $z_0$  determine the vertical and horizontal coordinates of the source center in the computational domain. Options  $L_x$  and  $L_z$  determine the horizontal and vertical scales of the source. In the calculations we performed, the source is located in the center of the computational domain,  $x_0 = 1000$  km at an altitude of  $z_0 = 6$  km. The horizontal and vertical scales of the source are set to 8 km and 3 km, which correspond to the typical size and location of a small cloud.

The source amplitude is small and equal to  $A = 0.001$  K/s. The choice of small amplitudes of the disturbance source is determined by the need to ensure stable vertical propagation of waves up to the heights of the upper atmosphere. It was shown in (Kshevetsky and Gavrilov, 2003) that small-amplitude waves are stable, while their vertical propagation can lead to the formation of jet streams and gas heating. When waves of moderate amplitudes propagate at heights of  $\sim 110$  km, the formation of an unstable turbulent patch is possible, while at large amplitudes the nonlinear decay of the wave occurs very quickly. The parameter  $\tau = 300$  s determines the slow nature of switching the source on.

In observations of the dynamics of atmospheric and ionospheric parameters under the conditions of the development of powerful tropospheric disturbances, an increase in the amplitudes of parameter variations with periods of acoustic-gravity waves was noted. Thus, it was suggested in (Borchevskina et al., 2020) that the observed increase in the amplitudes of total electron content (TEC) variations with periods of 10–16 min is associated with the propagation and dissipation of IGWs coming from the meteorological storm area. The comparative analysis of variations in the TEC ionospheric parameter obtained in observations of signals from GPS navigation satellites and meteorological situation reanalysis data performed in (Polyakova and Perevalova, 2013) showed that during the passage of a tropical cyclone the amplitudes of TEC variations increase with periods of 2–20 and 20–60 min.

In the numerical experiments we carried out, the calculations of disturbances of atmospheric parameters caused by the propagation of internal gravity waves from the troposphere were performed in the absence of wind in the atmosphere and taking the influence of wind on atmospheric disturbances into account. In



**Fig. 2.** The distribution wave addition to temperature under the action of a tropospheric heat source with periods  $T = 30$  min (a, b) or  $T = 15$  min (c, d) 30 min after the start of the calculation. The left panel corresponds to a calm atmosphere, the right panel corresponds to the calculations taking into account the neutral wind. The center of the source along the  $Ox$  axis is at the point  $x = 1000$  km. The arrow indicates the direction of the wind.

these experiments, tropospheric IGWs were excited by local monochromatic tropospheric heat sources (1), with oscillation periods  $\omega = 2\pi/900$  s or  $\omega = 2\pi/1800$  s. The duration of the action of tropospheric sources was 1 hour.

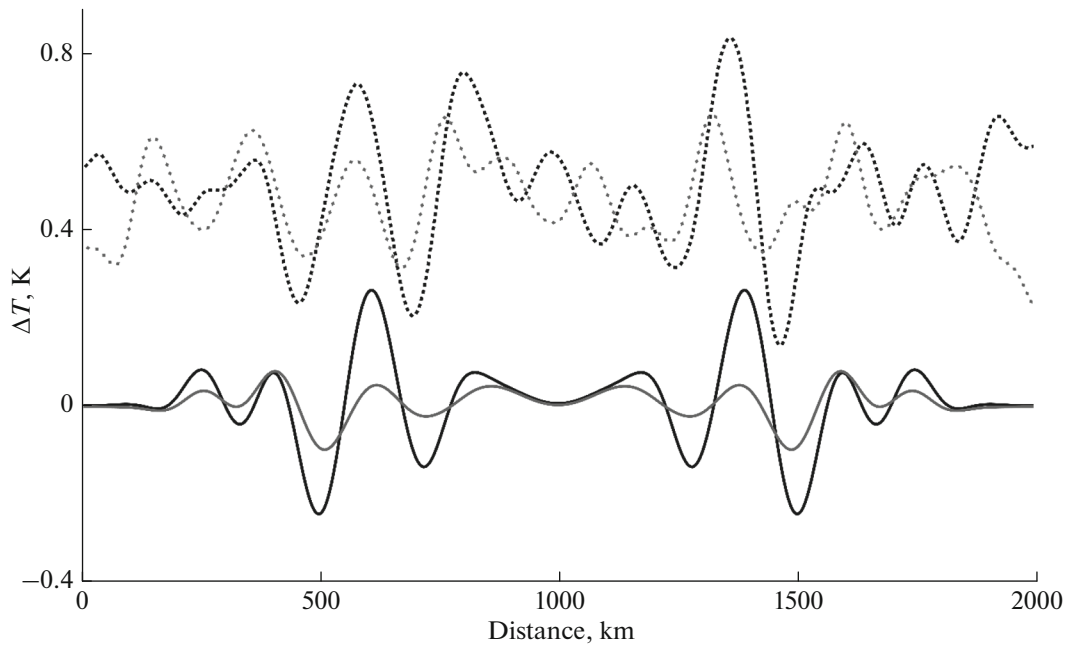
The choice of periods for waves generated by a model tropospheric source was determined on the basis of experimental studies in which perturbations in the parameters of the atmosphere and ionosphere were noted directly above the epicenter of a tropospheric meteorological disturbance. Moreover, as shown in (Kshevetsky and Gavrilov, 2003; Karpov and Kshevetskii, 2017; Kurdyaeva and Kshevetskii, 2021), IGW dissipation processes with periods, close to the Väisälä–Brent period lead to heating of the thermosphere and the formation of local areas of increased atmospheric heating. Such changes in the state of the thermosphere affect the propagation of IGWs.

### 3. DISCUSSION

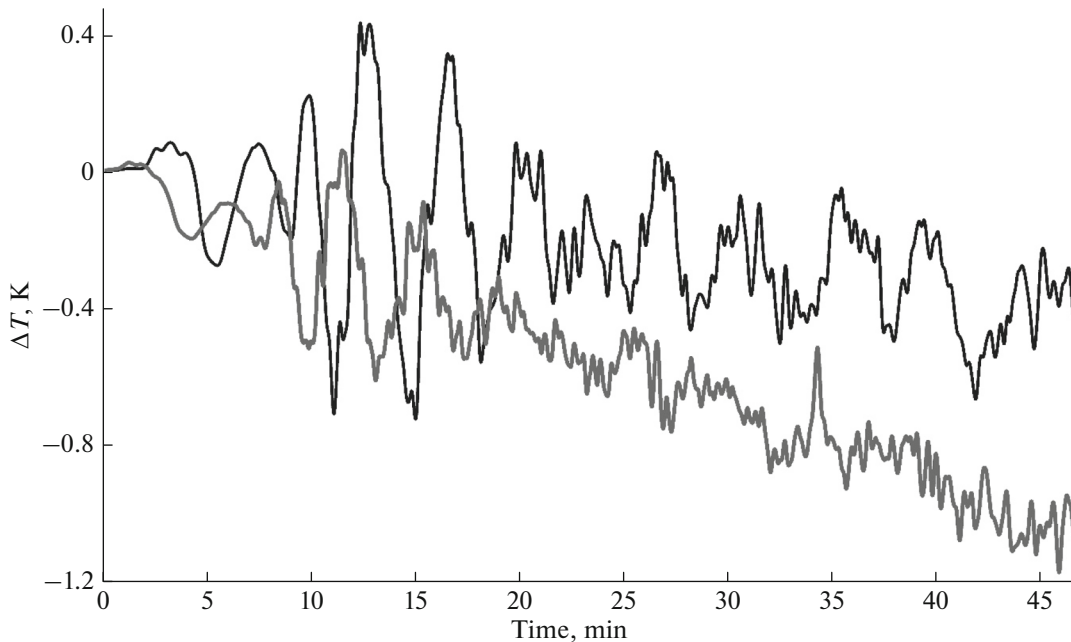
Calculation results for thermospheric disturbances generated by a tropospheric heat source with oscillation periods of 15 min and 30 min after  $t = 0.5$  h after the start of work, in an atmosphere without wind are shown in Fig. 2. As can be seen from the figure, at the initial stage of the calculation, thermospheric disturbances reflect transient processes associated with the action of tropospheric sources (Figs. 2a, 2c) and turning on the wind (Figs. 2b, 2d). In the absence of wind in the atmosphere, the spatial structure of disturbances in the upper atmosphere is symmetrical with respect to the epicenter of disturbances in the troposphere (Figs. 2a, 2c). Differences in perturbations in the thermosphere caused by different sources are

determined only in amplitudes. Turning on the wind (Figs. 2b, 2d) leads to small temperature perturbations in a localized region of heights at a height of 150–300 km in the entire region of integration of the model equations. Figure 3 temperature perturbations are shown at a fixed altitude of 350 km. As can be seen from the figure, in the absence of a thermospheric wind, the disturbances are symmetrical with respect to the epicenter of the tropospheric source. In this case, the horizontal scale of disturbances does not depend on the period of disturbances generated by a tropospheric source. Turning on the wind leads to a significant complication of the pattern of disturbances. However, the spatial scale of disturbances changes insignificantly.

As follows from Figs. 2 and 3, disturbances in the thermosphere occur within 30 min after the onset of the sources, which is a relatively short propagation time for the waves of the studied periods. Such a rapid development of disturbances in the thermosphere may be due to the propagation of acoustic waves. In (Kurdyaeva and Kshevetskii, 2021) it was shown that IGW generation by a heat tropospheric source cannot occur without the generation of infrasonic waves. A given heat source locally changes only the temperature. To excite a gravity wave, it is necessary to ensure consistent fluctuations in temperature and density. Generation accompanying acoustic waves during the transient process makes it possible to fulfill this condition. Figure 4 shows the change in the wave addition to temperature over time over the source with a period of 15 min at altitudes of  $\sim 145$  and  $\sim 190$  km. As can be seen from the figure, the wave pattern at the time of the appearance of the first thermospheric disturbances is determined entirely by acoustic waves with



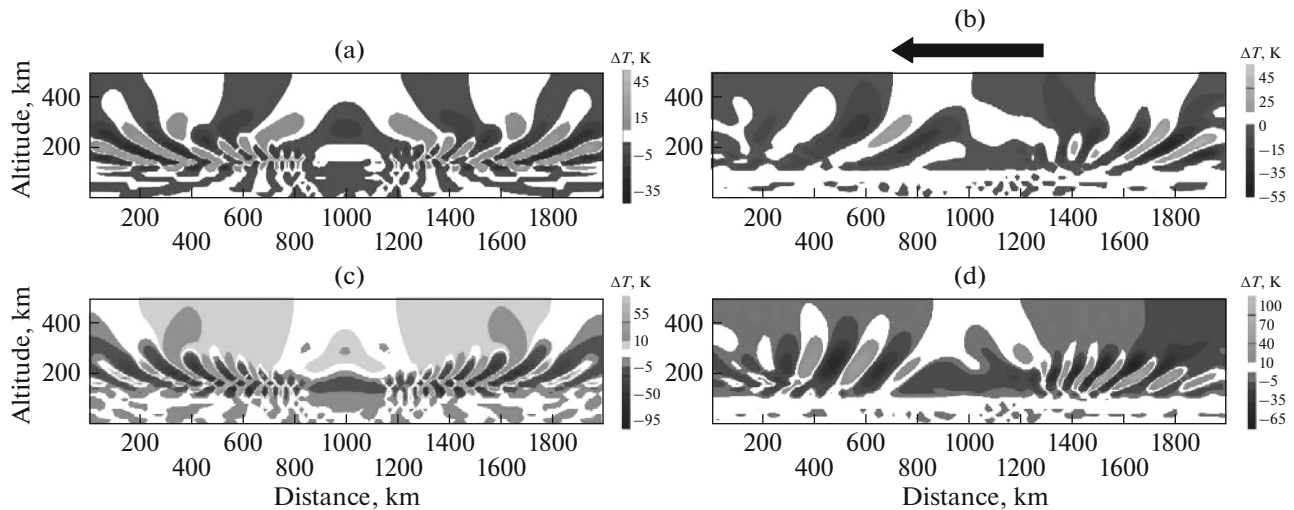
**Fig. 3.** Temperature variations at a height of 350 km along the horizontal axis 30 min after the start of the action of the tropospheric heat source with a period  $T = 15$  min without wind (black curve) and with wind (black dashed curve), and with a period  $T = 30$  min without wind (gray curve) and with wind (gray dashed curve).



**Fig. 4.** The dependence of temperature variations on time over a tropospheric source with a period  $T = 15$  min at altitudes of  $\sim 145$  km (grey line) and  $\sim 190$  km (black line).

characteristic periods of  $\sim 5$  min or less. It was shown in (Karpov and Kshevetsky, 2014; Drobzheva and Krasnov, 2003) that the dissipation of infrasonic waves in the thermosphere leads to a noticeable heating of local regions, which, in turn, affects the nature of wave propagation.

Figure 5 shows the results of calculations of disturbances of the thermosphere 2 hours after the inclusion of the tropospheric source of disturbances. It follows from the figure that the emerging spatial structure of perturbations has a quasi-waveguide character. At the same time, it is obvious that the influence of the ther-



**Fig. 5.** The distribution of the wave addition to the temperature 2 hours after the start of the calculation under the action of a tropospheric heat source for a calm atmosphere and taking into account the neutral wind with a period  $T = 30$  min (a, b) and  $T = 15$  min (c, d) respectively. The center of the source along the OX axis is at the point  $x = 1000$  km. The arrow indicates the direction of the wind.

ospheric wind (Figs. 5b, 5d) is very significant and manifests itself in a decrease in the amplitude and an increase in the spatial scale of waves that propagate in the direction of the thermospheric wind. For waves that propagate against the wind, the amplitude increases and the spatial scale decreases. Such a change in the spatial pattern of wave temperature variations is consistent with the results of (Medvedev et al., 2017). Differences in the structure of disturbances are more clearly manifested in the differences in the results of calculations caused by a tropospheric source in the presence and absence of wind. Figure 6 shows the spatial pattern of the difference in the amplitudes of thermospheric disturbances (Fig. 5) obtained in both variants of calculations after 2 hours after the start of operation of the tropospheric source. As can be seen from Fig. 6, in the lower thermosphere (below 150 km), perturbations with small spatial scales exhibit the character of waveguide propagation. It was shown in (Dong et al., 2021) that at the heights of the lower thermosphere, the influence of the vertical wind structure leads to waveguide propagation of IGWs; the so-called Doppler waveguide is formed. The formation of such a waveguide is due to the thermospheric wind at altitudes of 90–130 km and the absence of wind in the adjacent high-altitude areas. The propagation or attenuation of waves in such a waveguide is determined by the dispersion relation:

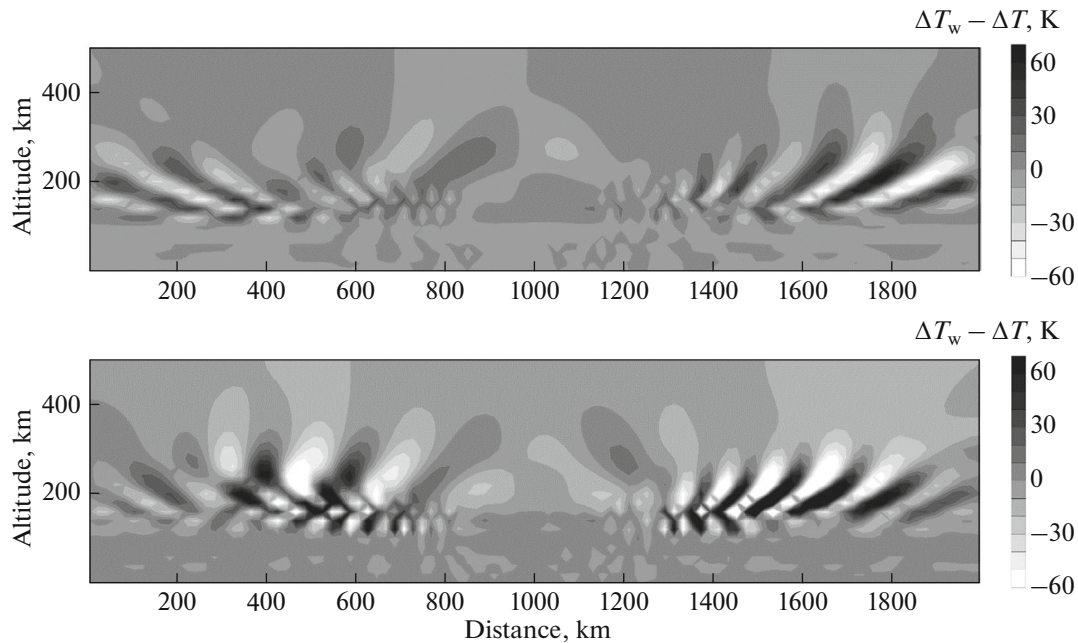
$$m^2 = k^2 \left( \frac{N^2}{(\omega - kU)^2} - 1 \right), \quad (2)$$

where  $m$ ,  $k$  are the vertical and horizontal wave numbers;  $N$  is the Väisälä–Brunt frequency; and  $U$  is the horizontal component of the thermospheric wind. Positive values of  $m^2$  correspond to vertically propa-

gating waves and negative values correspond to damped waves. The frequency characteristics of the waves captured in the Doppler waveguide are determined by the wind speed and the horizontal component of the wave vector. Expression (2), obtained under the assumption that the thermosphere is isothermal and independent of the height where the wind is observed, is used for a qualitative analysis of the results of calculations and interpretation of physical processes.

In Fig. 6, the waveguide character of disturbances manifests itself at altitudes below  $\sim 150$  km and at distances of  $\sim 500$  km from the epicenter of the tropospheric source. We also note that the spatial scales of disturbances in the lower thermosphere are much smaller than the scales of disturbances at heights above 200 km. At high altitudes, the formation of a waveguide region is possible due to the change in temperature with height. The mechanism of formation of such a region and the possibility of changing its scale due to the dissipation of acoustic-gravity waves with periods close to the Väisälä–Brent periods in the thermosphere was considered in (Karpov and Kshevetsky, 2014). The influence of such a waveguide will apparently affect the propagation of IGWs generated by a tropospheric source with an oscillation period of 15 min and will practically not affect the waves generated by an oscillation source with a period of 30 min.

Wave disturbances of the thermosphere at altitudes above 200 km are apparently associated with the propagation of waves along the waveguide due to the vertical temperature structure. The influence of the thermospheric wind in this altitude region is manifested in an increase in the amplitudes of waves that propagate against the wind and a decrease in their horizontal



**Fig. 6.** The difference between temperature variations with wind and without wind 2 hours after the start of the calculation under the action of a tropospheric heat source with a period  $T = 30$  min (top panel) and  $T = 15$  min (bottom panel).

wavelength. The amplitudes of waves that propagate in the direction of the wind decrease and their horizontal length increases. In this case, the asymmetry in the characteristics of disturbances that propagate against the thermospheric wind and in the direction of the wind is qualitatively explained by relation (2). Thus, for waves that propagate against the wind, the value  $m^2$  will decrease and may become negative. This will correspond to the attenuation of the waves in the vertical direction. Estimates of  $m^2$  according to the data in Fig. 4 show that the damping mode is realized for such waves. For waves that propagate in the direction of the wind, the mode of propagation along the vertical is preserved. As can be seen from Fig. 6, the vertical dimension of the region of upwind waves is smaller than the dimension of the region of waves that propagate downwind. It also follows from relation (2) that the thermospheric wind will have a greater effect on the propagation of small- and medium-scale waves with small phase velocities in comparison with the wind speed.

#### 4. CONCLUSIONS

The results of numerical experiments show that IGWs excited by heat sources in the troposphere reach the heights of the thermosphere and significantly affect the spatial and temporal variations of atmospheric parameters. Wave disturbances in the thermosphere arise rather quickly (within 30 min). This is due to the propagation and dissipation in the thermosphere infrasonic waves, which are generated together

with IGW by-heat tropospheric sources. The thermospheric wind has a significant effect on the spatiotemporal structure of wave disturbances in the thermosphere. This influence is shown in the following.

1. The propagation of waves with small spatial scales (less than 100 km) at altitudes less than 150 km is waveguide in nature. The appearance of such a waveguide is determined by the vertical structure of the wind in the lower thermosphere.
2. In the upper thermosphere, there is an increase in amplitudes and a decrease in the spatial scales of waves that propagate against the thermospheric wind. For waves that propagate in the direction of the thermospheric wind, we noted a decrease in amplitudes and an increase in spatial scales.

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