The ionospheric effect of atmospheric gravity waves excited prior to strong earthquake

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Abstract

We have computed perturbations in the nighttime mid-latitude F2 region ionosphere that could be produced by internal atmospheric gravity waves generated before strong earthquakes through ionospheric Joule heating due to the seismogenic electric field of short duration. There is a strong anisotropy of the atmospheric gravity wave effect with respect to the imminent earthquake epicentre, the electron density changes being maximum poleward and equatorward of the epicentre and being minimum eastward and westward of it. It should be noted that the duration of the electron density perturbation in the F2 region ionosphere is much longer than the duration of the primary precursor of an earthquake – the enhancement of the vertical electric field at the Earth’s surface, which initiates the atmospheric gravity wave generation. This fact is important from the practical point of view of predicting catastrophic earthquakes.

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1. Introduction

There are a number of publications discussing a possibility for atmospheric gravity waves (AGW) to occur at ionospheric altitudes before earthquakes (see appropriate papers in Hayakawa (1999) and Hayakawa and Molchanov (2002)). The peculiar variations in the electron density, which have been interpreted as related to atmospheric gravity waves, were observed in the nighttime mid-latitude F2 region ionosphere before some strong earthquakes by Liperovsky et al. (1992). Some observational evidence of the pre-earthquake occurrence of AGW in the D region ionosphere was obtained by Molchanov and Hayakawa (1998), Molchanov et al. (2001) and Shvets et al. (2002). In our preceding paper (Hegai et al., 1997), a possible mechanism has been proposed for the generation of atmospheric gravity waves in the ionosphere before strong earthquakes. According to the proposed mechanism, the AGW generation occurs due to non-stationary Joule heating of a local region of the ionosphere above the epicentral zone of an imminent earthquake. As a primary source of the Joule heating we have adopted a perturbation of the vertical atmospheric electrostatic field on the Earth’s surface in the epicentral zone of the earthquake. The anomalous perturbations of the near-ground vertical electric field were actually observed before earthquakes in the different regions of the Earth (Kondo, 1968; Vershinin et al., 1999; Hao et al., 2000). The physical mechanism responsible for such perturbations of the atmospheric field before earthquake is far from being investigated. Some hypotheses concerning this phenomenon are reviewed in Hayakawa (1999) and by
Pulinets and Boyarchuk (2004). We have also performed calculations of the main parameters of excited AGW and have analyzed their features. AGW have been found to be most effectively generated in conditions of low solar activity.

In this paper, the effect of AGW of seismogenic origin on the electron density $N_e$ in the nighttime mid-latitude F2 region ionosphere is studied. Here, it is worth to be pointed out that AGW themselves are revealed in the F2 region by observations of the variations in the electron density $N_e$, which they produce.

2. Statement of the problem

In our earlier paper (Hegai et al., 1997), we have, on the basis of the formalism developed in Chimonas and Hines (1970) and applying certain assumptions, obtained an analytical expression for the relative perturbation of the pressure of the atmospheric gas, $P_L(r, z, t) = (p - p_0)\rho_0$, caused by the atmospheric gravity wave generated in the ionosphere before strong earthquakes by Joule heating due to the electric field of seismogenic origin (here $p_0$ is the unperturbed pressure). The expression is written in a cylindrical reference system $(r, \varphi, z)$, the origin of which coincides with the epicentre of an imminent earthquake. Here, the horizontal distribution of the electric field in the ionosphere is assumed to be of an azimuthal-symmetric Gaussian form with the characteristic dimension $a$ and maximum field $E_0$ above the epicentre, and the dependence of the field on time is assumed to have the form of a rectangular pulse of length $T$.

The AGW causes the motion of neutral and ionized components of the atmosphere, but the motion of charged particles is restricted because of the presence of the geomagnetic field, and, therefore, their velocity vector differs from the velocity vector of neutral particles. The horizontal ($U_x$) and vertical ($U_z$) components of the vector velocity of motion of neutral particles due to AGW is determined by the relations

$$U_r = -gH \cdot \frac{\partial}{\partial r} \left( \int_0^r P_L(r, z, \tau) d\tau \right) / \partial r,$$

$$U_z = H \cdot \frac{\partial}{\partial z} \left( \frac{1}{\gamma} \frac{\partial g}{\partial H} \right)^{1/2} \frac{\partial P_L}{\partial \gamma} = \frac{\partial P_L}{\partial \gamma},$$

where $g$ is the free-fall acceleration, $H$ is the height of the homogeneous atmosphere, $\gamma$ is the Brunt-Vaisala frequency, and $\gamma$ is the ratio of the specific heat at a constant pressure to the specific heat for a constant volume; in the case of the Earth’s atmosphere $\gamma = 1.4$. The quantity $t_1$ determines the arrival time of the wave from a source at the observation point.

Charged particles can move only along geomagnetic lines of force because of their “magnetization” and, as a consequence, have only vertical ($V_z$) and meridional ($V_x$) velocity components, which can be presented in the form

$$V_z = -U_z \cdot \sin(I) \cdot \cos(I) + U_z \cdot \sin^2(I),$$

$$V_x = U_x \cdot \cos^2(I) - U_z \cdot \sin(I) \cdot \cos(I),$$

where $U_x$ and $U_z$ are the meridional and vertical velocity components of the neutral particles, respectively, $I$ is the magnetic inclination, the $x$-axis is directed toward the pole, and the $z$-axis upward. Here, $U_z = U_z \cos \varphi$, where the azimuth $\varphi$ is read off from the direction toward the pole, and, consequently, the velocity vector of the charged particles, $V$, depends on the azimuthal angle $\varphi$.

As a result of the motion of charged particles, variations in their densities can occur. These variations can be determined from the equation of continuity for these particles. In the F2-region of the ionosphere, $O^+$ ions are the main ones, i.e., $N(O^+) \approx N_e$. The continuity equation for the $O^+$ ions can be written in the case of nighttime conditions in the form

$$\frac{\partial N(O^+)}{\partial t} + \text{div}[N(O^+)[V_d + V]] + \beta \cdot N(O^+) = 0,$$

where $V_d$ is the velocity of diffusion of the $O^+$ ions along the geomagnetic lines of force, $V$ is the velocity of motion of the $O^+$ ions along the geomagnetic lines of force due to AGW, $\beta$ is the linear recombination coefficient. The time $t$ is read off relative to the instant $t_1$ of the arrival of AGW from a source at the observation point. The expression for the diffusion velocity is

$$V_d = -D_k [\nabla(N(O^+))] / N(O^+) - (m_k g_k) / kT_i],$$

where

$$D_k = (kT_i) / (m_i \sum_n v_{in}).$$

Here, $m_i$ and $T_i$ are the mass and temperature of $O^+$ ions, $g_k$ is the geomagnetic field aligned gravity acceleration, $k$ is the Boltzmann constant, and $v_{in}$ is the $O^+$ ion-neutral species collision frequency. The recombination coefficient $\beta$ is given by

$$\beta = k_1 N(N_2) + k_2 N(O_2),$$

where $k_1$ and $k_2$ are the rates of the main ion-molecular reactions which determine the recombination of $O^+$ ions in the F region

$$O^+ + N_2 \rightarrow NO^+ + N : k_1,$$

$$O^+ + O_2 \rightarrow O_3 + O : k_2.$$
We shall assume the initial (unperturbed) distribution of N(O⁺) to be horizontally homogeneous and to be determined by the equation
\[ \text{div}(\nabla N(O^+) + \beta \cdot N(O^+)) = 0. \] (6)

As boundary conditions, we shall consider the downward flux of plasma at the height \( z = 700 \text{ km} \) to be fixed at \( 1.5 \times 10^8 \text{ cm}^{-2} \text{ s}^{-1} \), and the density \( N(O^+) \) at the height \( z = 210 \text{ km} \) not to vary with time and to be equal to its initial value. The former corresponds to the average downward plasma flux observed in the mid-latitude nighttime upper F region during solar minimum (Ivanov-Kholodnyi and Mikhailov, 1973). The latter condition follows from our previous results (Hegai et al., 1997) indicating that the AGW is rather weak at an altitude of 210 km, and so one can neglect its effect on \( N(O^+) \).

We will investigate the influence of AGW on the distribution \( N(O^+) \approx N_e \) for the case when AGW are generated by a short (\( T = 15 \text{ min} \)), but strong, pulse of the electric field (\( E_0 = 20 \text{ mV/m} \), \( a = 200 \text{ km} \)). From our standpoint such a case is especially interesting because owing to the AGW properties one might expect the reaction of the ionosphere to turn out to be much more prolonged than the initial seismic process itself that induced the electric field. Moreover, it is evident that highly active processes within the source of an imminent earthquake should be of a short-term character. Indeed, intense luminescence of the atmosphere, most likely caused by the strong electric field resulting in the breakdown of the atmosphere, has been observed within the epicentral area during short time periods (from 5 to 20 min) before a series of catastrophic earthquakes (e.g., Electric and magnetic precursors of earthquakes, 1983; Zhao and Qian, 1997). The value of the breakdown electric field for the parameters of the near-ground atmosphere is 10–50 kV/m. As it follows from calculations, performed by us in Kim et al. (1994), electric field intensities of 10–50 mV/m at the heights of the ionosphere will correspond to the above values of the field intensity in the epicentral zone of an imminent earthquake at the Earth’s surface.

We shall locate the epicentre of the future earthquake at a point with \( I = 45^\circ \) and perform the concrete calculations of the variations of \( N_e \) at four geographical points situated at a distance \( r = 1000 \text{ km} \) precisely toward the pole (\( \phi = 0 \)), toward the equator (\( \phi = \pi \)), to the west (\( \phi = \pi/2 \)), and to the east (\( \phi = 3\pi/2 \)) of the epicentre (see Fig. 1). Here, the angle of the magnetic dip \( I \approx 56^\circ \) will correspond to the first point, \( I \approx 30^\circ \) to the second point, and \( I \approx 45^\circ \) to the last two points.

### 3. Results and discussion

In Fig. 2(a) it is shown, how the electron density \( N_e \) and its maximum value \( N_{mF2} \) vary with time at different heights, when the epicentre of the imminent earthquake is situated at a distance \( r = 1000 \text{ km} \) strictly toward the equator (\( \phi = \pi \)), i.e., when \( I \approx 30^\circ \), and in Fig. 2(b) the vertical profiles of \( N_e \) are given for the same site at different time instants after the arrival of the atmospheric gravity wave. It is seen that the electron density changes noticeably under the influence of AGW at heights near the main ionospheric maximum of \( N_{mF2} \). The changes in \( N_e \) above the main maximum are of a well-defined

![Fig. 1. A geometry of calculations.](image-url)
A wave-like character, which is manifested especially clearly at the height $z = 400$ km. The period of oscillations is approximately 1 h. A shift in the phase of the oscillations occurs as the height decreases, and their aperiodicity is enhanced. The aperiodic component, upon which small quasiperiodic oscillations are superimposed, is dominant in the time variation of $N_{m}F_2$. On the whole, $N_{m}F_2$ initially decreases after the arrival of AGW, and then it is slowly restored to its unperturbed value, undergoing small oscillations. The maximum decrease of $N_{m}F_2$ is approximately 15% relative to the unperturbed value. The height of the maximum of electron density changes slightly with time. Below the main maximum of the ionosphere $N_{m}F_2$, the electron density increases slightly initially, and then it decreases essentially and is subsequently slowly reduced to the unperturbed value. Here, it is interesting to note the course of change in $N_e$ at the height $z = 270$ km, where the density $N_e$ reaches its minimum and then remains unchanged during almost 1 h. As it follows from Fig. 2(b), the changes in $N_e$ near $N_{m}F_2$ are noticeably revealed during over 2 h.

In Fig. 3 the same is shown as in Fig. 2, but only for the geographical point located at a distance $r = 1000$ km strictly poleward ($\phi = 0$) of the epicentre of the future earthquake and corresponding to the magnetic dip $I \sim 56^\circ$. As it is seen, the electron density $N_e$ varies significantly within the interval of heights near the main maximum $N_{m}F_2$ in this case like in the preceding one, but the character of changes in $N_e$ is substantially different. Within this entire interval of heights $N_e$ experiences positive perturbation of average duration of about 70 min. A quasiwave component with a quasiperiod of the order of 50 min is superimposed on this perturbation at heights above the maximum of $N_{m}F_2$. The electron density below the level of $N_{m}F_2$ decreases slightly during the first 20 min after the arrival of the AGW, and then it increases. The amplitude of the increase of
NmF2 exceeds 20%, and the change in height of the maximum does not exceed 10 km.

Contrary to the two cases considered above, the electron density in the F2-region at a distance \( r = 1000 \) km strictly to the west \((\varphi = \pi/2)\) and to the east \((\varphi = 3\pi/2)\) of the epicentre of an imminent earthquake \((I = 45^\circ)\) is only slightly perturbed under the action of the AGW, which is illustrated by Fig. 4, where the changes of \( N_e \) in time are shown at fixed heights.

Thus, the changes in electron density in the nighttime F2-region of the ionosphere caused by the atmospheric gravity wave induced in the ionosphere before strong earthquakes manifest strong azimuthal anisotropy relative to the epicentre of the future earthquake. The perturbation of \( N_e \) is maximum along the equator–pole direction and is minimum in the west–east direction. Such an anisotropy is caused by the azimuthal dependence of the velocity vector of the motion of charged particles due to AGW. The value of this velocity is maximum when \( \varphi = 0 \) and \( \varphi = \pi \), and it is small when \( \varphi = \pi/2 \) and \( \varphi = 3\pi/2 \). It should be noted that the changes in \( N_e \) are of a clear wave-like character only within the sector located toward the equator from the epicentre, whereas the oscillatory component toward the pole from the epicentre manifests itself insignificantly. Hence, follows the interesting conclusion that the actual presence of AGW of seismogenic origin can be recorded with a sufficient degree of reliability only in the direction toward the equator from the future earthquake and even then only on the basis of the observations of variations of \( N_{mF2} \). On the other hand, in the case of observation of a positive perturbation of \( N_{mF2} \), AGW cannot be also excluded from possible sources causing it.

We emphasize that changes in the electron density are noticeably exhibited within the 250–400 km interval of heights during more than 2 h, i.e., almost by an order of magnitude longer than the pulse length of the electric field \((T = 15 \) min\) initiated by AGW. Consequently, observations of the ionosphere can essentially widen

Fig. 3. As for Fig. 1, but at \( r = 1000 \) km poleward of the epicentre.
the possibilities for revealing the signs of an imminent strong earthquake.

4. Conclusion

In this paper, we have performed calculations of the changes in the electron density $N_e$ in the nighttime mid-latitude F2-region ionosphere, which are caused by the atmospheric gravity waves generated in the ionosphere before strong earthquakes due to the seismogenic electric field penetrating into the ionosphere. We have obtained that the changes in $N_e$ depending on the time of arrival of AGW at a distance $r = 1000 \text{ km}$ from the epicentre of an imminent earthquake reveal a strong azimuthal anisotropy: the changes in $N_e$ are maximum toward the equator and toward the pole from the epicentre and are insignificant to the east and west of it. Here, the variations of $N_e$ are of a clearly defined wave-like character only toward the equator from the epicentrum, while the oscillatory component toward the pole from it is manifested considerably weaker. The electron density at the maximum and at heights immediately under it experiences a positive perturbation toward the pole from the epicentre, whereas a negative perturbation of $N_e$ occurs in the direction toward the pole from the epicentre of the future earthquake.

It is important to note that the duration of the perturbation of the electron density in the F2-region of the ionosphere is much longer than the duration of the primary precursor of an earthquake – the perturbation of the vertical electric field at the Earth’s surface, that initiated the AGW generation. Thus, owing to the ionosphere there exists a “widening” effect of the duration of the manifestation of the sign of an imminent earthquake. This fact is important from the practical point of predicting catastrophic earthquakes.

References


