Atmospheric Gravity Waves and their Role in the Lithosphere-troposphere-ionosphere Interaction

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This paper is a review on the properties of atmospheric gravity waves that are responsible for the transfer of tropospheric perturbation to the ionospheric altitudes. The generation mechanism of these waves by means of meteorological sources, earthquakes and by the processes of earthquake preparation (by precursors) is examined. We suggest an experimental program for the investigation of acoustic-gravity channel of a seismic effect upon the ionosphere.

Keywords : atmospheric gravity waves, ionospheric precursors, earthquake preparation, lithosphere-troposphere-ionosphere coupling

1. Introduction

In the present work the ionosphere is considered as a specific layer that covers the Earth and that is sensitive to the influences from above and from below. Influences from above are stimulated usually by the solar activity and they lead to a complex of ionosphere-magnetosphere perturbations. Influences from below are linked with atmospheric oscillations and waves that are generated in a neutral atmosphere at lower level (Hines, 1960). Because the main resource of atmospheric energy is concentrated in the motion of the lowest, the most dense layers, it is natural to expect that dynamic tropospheric processes (motion of weather fronts, cyclones and anticyclones, jet streams, penetrating convection and wind flow around Earth's surface) generate ionospheric plasma inhomogeneities as well as strong tectonic and technogenic sources of atmospheric oscillations (volcano eruptions, earthquakes, tsunamis, mighty explosions, rocket launchings, etc.).

Another side of interest in atmospheric waves as to the energy carrier from the lowest atmospheric layers to above ones is related with the problem of ionospheric earthquake precursors. But, the physical mechanisms and conditions of ionospheric perturbation appearance above the area of earthquake preparations are not clear yet. Though there are numerous observations, there are not enough experimental data that would permit us, at least, to find any physical mechanism which is responsible for the "projection" of lithospheric processes onto the ionosphere.

Influences on the ionosphere "from above" were investigated during the last tens years in the framework of different space programs – programs of Solar-Terrestrial relations before, and space weather today. Influences "from below" are studied less extensively because of significant technical and methodological difficulties in the registration of neutral atmosphere inhomogeneities at ionospheric heights as well as in the identification of their sources.

This paper is devoted to a review of theoretical and experimental data on the atmospheric gravity waves and of the analysis of their

role in troposphere-ionosphere and lithosphere-ionosphere interactions. A hypothesis on the causal relationship between the ionospheric earthquake precursors and the neutral atmosphere oscillations was suggested for the first time by Gokhberg et al. (1994), and we would like to propose a technique for the experimental verification of this hypothesis.

The term "atmospheric gravity wave" (AGW) or "internal gravity wave" indicates one of the dispersion branches in atmospheric waves. The period of AGWs is approximately of 5–10 minutes to 10 hours, and the wavelength varies from tens of meters to a few thousands kilometers. Due to viscous dissipation of the short wave components the minimal wavelength is growing with altitude, this length reaches hundreds of meters in the D region and about ten kilometers in the F2 region. Figure 1 illustrates the frequency scale, where the gravity mode of atmospheric waves is close to the low frequency planetary mode and to the high frequency acoustic one. All these waves – acoustic, gravity, planetary – play their roles in the atmosphere dynamics. Acoustic waves are the fastest ones and they form the upfront of perturbations that reach the ionosphere during earthquakes and explosions (Galperin and Hayakawa, 1996).

But, the influence of acoustic wave energetics into the ionosphere is weak because of its significant sound dissipation. More intensive energy flow onto the ionosphere is expected by means of

Fig. 1. Diagram of atmospheric waves and oscillations (f_g is the Brunt-Vaisala frequency, and f_a is the acoustic cut-off frequency)

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planetary waves which are responsible for the formation of large-scale long-living ionospheric inhomogeneities (Danilov et al., 1987). But because of its low velocity, the energy transport by planetary waves takes weeks and months. Gravity waves are not only an energetically effective tool, but also provide us with "quick" dynamic coupling between the lower atmosphere and ionosphere. AGWs with wavelengths of approximately 100~200 km and phase and group velocities of 100~200 m/s play an important role in this coupling.

The structure of this paper is as follows. In section 2 we give a review of some new data on the AGW parameters at ionospheric heights and discuss the sources of these waves. Section 3 is devoted to AGW theoretical analysis. Hypothetical role of AGW in the lithosphere-ionosphere coupling phenomena is given in section 4.

2. Review of Some Experiments

2.1 General Information Ionized gas gives a little addition to the neutral atmosphere in all ranges of the ionospheric altitudes. That is why the perturbations related with the atmospheric wave propagation cause the generation of plasma inhomogeneities. Regular sources of oscillations in the neutral atmosphere at ionospheric altitudes are solar thermal and lunar gravitational tides as well as terminator motion. Sporadic perturbations appear because of solar and geomagnetic activity due to the heating of neutral atmosphere by ionospheric electrical currents, solar short-wave radiation and precipitating particles. The second non-regular source of perturbations is AGW that penetrates to the thermosphere from below. AGW sources were analyzed by Chernogor (1999), who mentioned that meteorological processes are characterized by the highest energy (for example, the cyclone energy is three orders higher than that evolved during a disastrous earthquake). Table 1 gives the parameters of the strongest natural and technogenic AGWs by using the data by Chernogor (1999).

Though the long-term interest in the questions mentioned (Hines, 1974; Francis, 1975; Mayr et al., 1984; Hocke and Schlegel, 1996) the AGWs at ionospheric altitudes are poorly studied still, and especially insufficiently studied experimentally. This happens due to the fact that the standard techniques of remote ionosphere diagnostics do not provide us with any direct information on the parameters of neutral atmosphere. These methods cannot register AGWs themselves, but their plasma demonstrations – travelling ionospheric disturbances (TIDs). A difference of phase velocities and wavelengths may be a key to the selection of TIDs caused by the AGW and solar activity. According to Georges (1968), Francis (1975), and Hocke and

Schlegel (1996), AGWs are responsible for the generation of middle-scale TIDs with periods from 15 min to 3 hours, velocities from 100 to 250 m/s and horizontal wavelengths of approximately a few hundred kilometers. Large-scale TIDs have the same or a little larger periods, phase velocities from 400 to 1000 m/s and horizontal wavelengths more than 1000 km. According to their nature they are considered as ionospheric waves (following Sorokin and Fedorovich (1986), MHD waves loaded by neutral particles). Usually large-scale TIDs are generated in the auroral regions, and they propagate through the entire globe.

2.2 Satellite Observations of AGWs Satellite experiments allow us to measure directly the parameters of ionized and neutral atmospheric components as well as to study their links. Due to the fact that the orbital satellite velocity is much higher than AGW/TID velocities, the satellite registers the spectrum of wave numbers: $\omega' = \omega - k_x V_{sat} \approx -k_x V_{sat}$ (where k_x is component of the wave vector directed along the satellite orbit, $V_{sat} \approx 8$ km/s is the orbital velocity). Several projects with synchronous registration of the neutral and charged atmospheric components were carried out: "Atmospheric Explorer - A, E, C" and "Dynamic Explorer". We observe some results obtained from the "Atmospheric Explorer - E" data analysis.

The atmospheric disturbance by a strong earthquake at altitude of $z \approx 250$ km is shown in Fig. 2 (Fedorenko et al., 2003). Two upper panels demonstrate the history of oscillation intensity (summarized over the wavelength spectrum) along the satellite trajectory. It is possible to notice the anomalous increase in intensity on the orbit 10272 registered at the time moment of UT = 19.30 under the conditions of very low geomagnetic activity. On this orbit the satellite was close to the earthquake epicenter ($M = 6.5$, UT = 12:10, $\lambda = 117.32^\circ$, $\varphi = -9.95^\circ$) through approximately 5 hours after the main shock. Detailed description of O^+ and N_2 perturbation in the epicenter proximity is shown in panel 3. Finally, panel 4 demonstrates the wave spectrum in this region. AGW/TID parameters were as follows.

- horizontal wavelength was approximately $\lambda_x \sim 500$ km;
- relative AGW amplitude was a few percents;
- relative TID amplitude reached 20%;
- disturbance area was shifted to the east from the epicenter that may be explained as AGW shifting by zonal wind.

Tsunamis are also an effective AGW source because of the high propagating velocity (more than 200 m/s in deep water). It is possible to expect that AGWs form a tsunami projection on the ionosphere altitudes. Really, a TID that follows a tsunami was observed by Artru et al. (2003), and it had the following parameters $\lambda_x \sim 150$ km, $\omega/k_x \sim 100$ m/s (according to the results of TEC-measurements with the use of GPS-signal).

Table 1. Characteristics of natural and artificial AGW sources (according to Chernogor, 1999)

Source	Source parameters	Energy, J	Energy flux/ Power, W
Cyclone	Size scale ~ 3000 km	10^{21}	10^{15}
Jet stream	$3000 \text{ km} \times 300 \text{ km}$	10^{19}	10^{15}
Tornado	500 km	10^{18}	10^{13}
Earthquake	Magnitude $M = 9$	10^{18}	
Volcano eruption	Strongest	10^{20}	
Tsunami	Strongest	10^{16}	
Nuclear explosion	Power 58 MT (USSR, 30.10.1961)	2.4×10^{17}	2×10^{24}
Launch of spacecraft	Spacecraft mass $= 2 \times 10^6$ kg	2.4×10^{14}	10^{12}

Panels 1 and 2 represent the distribution of oscillation intensity along the satellite orbit (in relative units)
 Detailed structure of disturbance in the epicenter proximity is shown in panel 3
 Corresponding spectra of AGW/TID are given in panel 4
 Vertical arrows indicate the epicenter location (the place of minimum distance between the satellite orbit and epicenter)

Fig. 2. Satellite observations of AGW/TID (Fedorenko et al., 2003)

Rice and Sharp (1977) analyzed the measurements of neutral component at altitudes 140–200 km on board the "Atmospheric Explorer - C". There were noticed AGWs with relative amplitude of $A \leq 10\%$, whose frequency of events detecting AGWs was in correlation with satellite orbit over the tropospheric weather systems (considered as probable AGW sources). The correlation with solar and geomagnetic activity was not found.

Here we comment on one of the most serious methodological problems – identification of disturbance sources. During propagation from the troposphere into ionosphere, AGW propagates hundreds and thousands kilometers in the horizontal direction. Finally it appears that the AGW source is shifted far from the observation point – in time as well as in space. Because of loss of information on the ray trajectory, inaccuracy in localization of the source region is so great that one can find there numerous probable generating sources. Only in some cases it is possible to localize the source of AGW surely, for example, if the source was specially prepared (active experiments, explosions), or if the satellite occasionally appeared in an appropriate place (as the event in Fig. 2). But even in these cases, in the strict sense of the word, we are speaking only about the correlation relations. Evidently the cause-and-effect relationships might be found only in a case of simultaneous registration of AGW in the source region (close to the Earth surface) and in the ionosphere.

2.3 Experiments at Ukrainian Antarctic Station The ideas mentioned above were tested on the basis of experiments at the Ukrainian Antarctic station "Academician Vernadsky" (Yampolsky et al., 2003, 2004). Oscillations of atmospheric pressure (AGW) were generated by the weather fronts. Quasi-periodic variations of magnetic field were found on the AGW penetration into the E region. These variations can be explained by the AGW interaction with the ionospheric dynamo-region. During the 7-year period of observations from 1996 to 2002 there were registered 260 events in which AGWs were identified either in the variations of atmospheric pressure or in the Earth's magnetic field perturbations. Fig. 3 demonstrates an example of the cyclonic front passage and the corresponding generation of the wave train of pressure and magnetic field variations. As the result of data processing the AGW parameters were defined:

- the most probable AGW period is $T = 1.3$ hours,
- the scale of atmospheric pressure variations $\delta P|_{z=0} \sim 0.2$ mbar
- the scale of magnetic field component variations $\delta B \sim 1 \sim 20$ nT
- time lag between δP and δB is approximately $\tau = +30$ min.

The last characteristic is rather important for the clarification of cause-and-effect relation – the determination of AGW source location (above or below). In a case of tropospheric source the variations have to be anticipated, and this fact was registered. For the effective altitude of dynamo-layer of $z = 110$ km the vertical group velocity for AGWs is $V_{gz} = z/\tau = 60$ m/s.

As one can see from the data review, AGW/TID parameters that were registered using different methods are in good agreement between themselves and supplement each other. It is possible to subdivide several groups of disturbances:

- AGW turbulence in the range of wavelengths from hundred meters to tenths or a few tenths kilometers (Gossard and

Hook, 1975; Gardner, 1996). At different atmospheric layers these AGWs have no correlation between themselves and, probably, have local sources for excitation and dissipation.

- Large-scale TIDs with wavelengths more than 1000 km and velocities higher than the sound velocity in the troposphere.

These waves have ionospheric origins.

Middle-scale AGW/TID with horizontal wavelengths of approximately a few hundred kilometers are registered synchronously in the troposphere and ionosphere. Phase velocities in this case are comparable with the sound velocity, and vertical group velocity reaches 60 m/s. This group of AGWs may be responsible for the troposphere - ionosphere interaction.

3. AGW Theory

3.1 Physical Nature of Atmospheric Waves Waves in the atmosphere, as in any other elastic medium, are a relaxing process that appears in response to any perturbation of equilibrium state of medium. Atmospheric waves may be corresponded to all theoretical provisions of acoustics of fluids and gases. Together with this, oscillations in the atmosphere are characterized by a set of peculiarities caused by Archimedes and Carioles forces, inhomogeneity of atmospheric parameters (in first order, by the vertical stratification of density and temperature), influence of viscosity and turbulence, presence of ionized gas component, wind shifts, etc. Equation of atmospheric particle motion is too complicated if we write it taking into account all these factors. But the roles of different dynamic terms are different in particular ranges of frequencies and wavelengths. In reality, only two-three terms play the roles in the motion equation simultaneously, and different combinations of these terms cause different types of atmospheric waves. For example, waves of sound range appear as the result of a "game" of pressure and inertia forces, and atmospheric vortexes (cyclones and anticyclones) – as result of pressure and Carioles forces with neglecting the inertia term. Detailed analysis of forces that determine the dynamics of atmospheric waves is given in Hook (1977), and Gossard and Hook (1975).

It is possible to understand easily the physical nature of gravity waves using a comparison with acoustic wave. Taking into account the gravity force, the motion equation for fluid particle is given by,

$$\rho \frac{d\vec{V}}{dt} = -\nabla p + \rho \vec{g} \dots\dots\dots (1)$$

where ρ, p are density and pressure, $\vec{V}$ is particle velocity, and g is gravitation acceleration. We mention that the viscosity term responsible for the short waves dissipation is not taken into account here. The stationary (or background, indicated by the suffix 0) distribution of atmosphere density and pressure is given from Ep.(1):

$$\frac{\partial p_0}{\partial z} = -\rho_0 g \Rightarrow \rho_0(z) = \rho_0|_{z=0} \cdot \exp\left\{-\int_0^z \frac{dz}{H(z)}\right\} \dots\dots\dots (2)$$

where $H = T_n/(Mg)$ (M ; molecular weight, g ; gravity) is effective atmosphere scale height, T_n is the temperature of neutral component, the axis OZ is directed upward, and dependence $H = H(z)$ is caused by altitude profile of gas temperature and molecular content. Barometric distribution (2) is automatic consequence of Eq. (1) that determines also wave dynamics. That is why AGWs according to their nature are the

- 1: Fragment from a series of original data recordings
 2: Signal detrending and selection of the quasi-wave variations
 3: Pressure and magnetic field spectra
 4: Their cross-correlation function

Fig. 3. Interconnection between the variations of surface pressure and geomagnetic field in the experiments at Ukrainian Antarctic station [Yampolsky et al., 2004]

waves of non-uniform atmosphere.

After the linearization of Eq. (1) we can find the following equation for the small perturbations:

$$\rho_0 \frac{\partial \vec{V}}{\partial t} = -\nabla \delta p + \delta \rho \cdot \vec{g} \dots \dots \dots (3)$$

where $\delta\rho \cdot \vec{g}$ is Archimedes force that causes the floating of rarefaction areas $\delta\rho < 0$, and immersion of compression areas $\delta\rho > 0$, which are generated by wave propagation. The ratio of Archimedes and pressure terms on the right side of Eq. (3) depends on the period and wavelength T, λ . One can find the approximate ratio:

$$\left| \frac{\nabla \delta p}{\delta \rho \cdot g} \right| \sim \frac{\lambda_*}{\lambda} \sim \frac{T_*}{T} \dots\dots\dots (4)$$

where $\lambda_* = 4\pi H$, $T_* = \lambda_* / c_s$, $c_s = \sqrt{\gamma T_n / M}$ is the sound velocity, and γ is adiabatic index. At normal conditions $H \approx 8$ km, $\lambda_* \approx 100$ km, $T_* \approx 5$ min.

So, until the length and period of atmospheric wave are enough small $\lambda \ll \lambda_*$, $T \ll T_*$ we have the ordinary acoustic waves (infrasonic, sonic, and ultrasonic), and the Archimedes force practically does not influence their propagation. With the growth of T, λ , the role of Archimedes force increases and at $\lambda > \lambda_*$, $T > T_*$ it become significant. Atmospheric waves, respectively, include the acoustic waves with period $T < T_*$, and gravity ones with larger periods, and observed properties for acoustic and gravity waves are different. For even larger wavelengths that are comparable with the Earth's radius and for wave periods of 12 h and more, AGWs continuously transform into planetary waves that propagate under the essential influence of Carioles force and factor of the globe spherical form (see the diagram in Fig.1).

3.2 Dispersion Relations Basic reviews and monographs (Hines, 1964; Hines, 1974; Hook, 1977; Francis, 1975; Kato, 1980, and others) are devoted to the AGW theory. Without the repetition by other authors let us concentrate on the analysis of AGW properties that are important from the point of view of dynamical connection between the lower and upper layers of atmosphere. Special interest will be middle-scale AGWs with lengths $\lambda \sim \lambda_* \sim 100 \sim 600$ km.

We list the simplifying assumptions:

- Carioles force and non-planar shape of the Earth surface are not taken into account. Our approach is valid under the condition that the AGW period is much less than the period of Earth rotation, the wavelength is small in comparison with the Earth's radius and large in comparison with the dimensions of Earth relief;
- Viscosity and thermal conductivity are not taken into account, which is validated due to the essential exceeding of collision frequency of neutrals over the wave frequency $\nu_{nn} \gg \omega$;
- Friction between the neutral and ionized components in the atmosphere is absent, which is valid for $\omega > \nu_{ni}$ (ν_{ni} is the frequency of collisions of neutrals with ions). At the ionospheric altitudes this limits the period of AGW from

above $T < T_{\max} \sim 3$ hours (Sorokin and Fedorovich, 1982).

- The atmosphere under consideration is isothermal, with homogenous molecular content, without the wind shifts. Wind influences AGW propagation non-essentially until at some altitude z_c where the wind velocity $V_w(z)$ becomes equal to the horizontal phase velocity $V_w(z_c) = \omega / k_x$. In our case $\omega / k_x \sim 200$ m/s that exceeds greatly the wind velocity in the atmosphere until the altitudes of F region.
- AGW is linear. This assumption we will discuss below.

Under these assumptions the solution of the system of linearized equations for the motion, state and continuity is as follows.

$$\left. \begin{aligned} \frac{\delta\rho}{\rho_0(z)} = \frac{u}{U} = \frac{w}{W} = A(z) \exp\{i(\omega t - k_x x - k_z z)\} \\ A(z) \equiv \frac{\delta\rho}{\rho_0} \Big|_{z=0} \exp\left\{+\frac{z}{2H}\right\} \end{aligned} \right\} \dots\dots\dots (5)$$

where $\delta\rho$ is the perturbation of neutral atmosphere density, $A(z)$ is relative AGW amplitude, u, w are horizontal and vertical components of atmospheric particle velocities, $\rho_0(z) \equiv \rho_0|_{z=0} \exp\{-z/H\}$ is barometric distribution of homogenous atmosphere density, $U = U(\omega, \vec{k})$, $W = W(\omega, \vec{k})$ are constants (polarization coefficients), OZ axis in the Cartesian coordination system is directed vertically, horizontal OX axis is picked up in a plane of AGW wave vector $\vec{k} = \{k_x, 0, k_z\}$. Values ω and $\vec{k}$ in Eq. (5) are linked through the following dispersion relation:

$$k_z^2 = \frac{\omega^2 - \omega_a^2}{c_s^2} + \left(\frac{\omega_g^2}{\omega^2} - 1 \right) k_x^2 \dots\dots\dots (6)$$

where $\omega_a = 2\pi / T_* = c_s / (2H)$ is the acoustic cutoff frequency, $\omega_g = \sqrt{\gamma - 1} g / c_s$ is the Brunt-Vaisala frequency (we emphasize that $\omega_g < \omega_a$). Solution of Eq. (6) determines the modes of atmospheric waves:

$$\omega \approx \sqrt{\omega_a^2 + k^2 c_s^2} \quad \omega > \omega_a \quad (\text{acoustic wave}) \dots\dots\dots (7)$$

$$\omega = c_g \frac{k \cos \theta}{\sqrt{1 + (k/k_*)^2}}, \quad \omega < \omega_g \quad (\text{gravity wave}), \dots\dots\dots (8)$$

where $k_* = 2\pi / \lambda_* = (2H)^{-1}$, $c_g = 2[\sqrt{\gamma - 1} / \gamma] c_s$, θ is wave vector direction relative to the horizontal plane. Numerical values of parameters here are given in Table 2.

Dispersion branches Eqs.(7) and (8) are given in Fig. 4. We are interested in the gravity branch, and we will focus special attention to the wave number $k \sim k_*$. In short wave limit of $k \gg k_*$ the AGW phase and group velocities tend to zero; in this

Table 2. Atmospheric parameters influencing the AGW propagation (Parameters meanings are given at the Earth surface (for normal conditions), averaged in the interval of $0 < z < 130$ km, and at an altitude $z = 350$ km)

Conditions	$\gamma = c_p / c_v$ for two-atomic gas (N_2, O_2)	Effective atmosphere height H	Sound velocity c_s	Velocity c_g	Brunt-Vaisala frequency ω_g	Wave length λ_*
Normal	7/5=1.4	8 km	340 m/s	307 m/s	0.01 s ⁻¹	100 km
Averaged $z = 0-130$ km		7 km	300 m/s	270 m/s	0.011 s ⁻¹	90 km
$z = 350$ km		50 km	670 m/s	600 m/s	0.004 s ⁻¹	630 km

Fig. 4. Dispersion curves of atmospheric waves: acoustic wave (above) and gravity wave (below)

Fig. 5. Dispersion relations between the AGW period and wavelength for various directions of wave propagation (from above to below: $\theta = 0^\circ$, $\theta = 45^\circ$, and $\theta = 80^\circ$)

area we see no waves but oscillations of atmospheric inhomogeneities with frequency:

$$\omega = \omega_g \cos \theta, \quad k \gg k_*, \quad \dots \dots \dots (9)$$

Physical nature of oscillations (9) – floating and immersion of atmospheric bubbles ("buoyancy oscillations" (Gossard and Hook, 1975)). In the area of long waves $k \leq k_*$ the phase and group velocities are comparable with the sonic velocity ω/k , $\partial\omega/\partial k \rightarrow c_g$. In this case $\lambda \gg H$, that is why it is possible to make an analogy between the long wave AGWs and waves in shallow water. Physical mechanism of such AGW propagation is similar to the atmospheric gas flow between the wave crests and cavities. Gas compressibility and pressure forces are inessential that justifies the term "gravity wave". Dispersion curves in Fig. 5 give an idea on the real AGW periods and wave lengths.

The difference in propagation mechanisms of acoustic and gravity waves causes essential differences in their polarization and dispersion properties. Particle oscillations in the gravity wave are approximately horizontal $\vec{V} \approx \hat{x} \cdot u$ ($\hat{x}$ is the unit vector in the x direction) and are independent of the direction of propagation that is linked formally with inequality of coefficients $U \gg W$ in Eq. (5) for the dispersion parameters Eq.(8). Let us mention also that the phase and group velocities of AGWs have different directions. In a short wave limit the velocity directions are perpendicular to each other, that is resulted directly from Eq.(9).

Fig. 6. Vertical group velocity (on the left) and horizontal phase velocity of AGW (on the right) depending on wavelength and period (contour lines $V_{gz} = 10, 35, 60$ m/s are selected on the left panel (from outside to inside))

3.3 Velocity of Vertical Energy Transport Dispersion relation (8) determines the following expressions for the AGW vertical group velocity and horizontal phase one:

$$\left. \begin{aligned} V_{gz} &= \frac{\partial \omega}{\partial k_z} = -c_g \frac{(k/k_*)^2 \sin \theta \cos \theta}{(1 + (k/k_*)^2)^{3/2}} \\ \frac{\omega}{k_x} &= \frac{c_g}{\sqrt{1 + (k/k_*)^2}} \end{aligned} \right\} \dots \dots \dots (10)$$

According to Eq. (10) V_{gz} reaches its maximum at $k = \sqrt{2}k_*$, $\theta = \pi/4$ in the area of wavelengths of $\lambda = \lambda_*/\sqrt{2}$, and the maximum V_{gz} , $V_{gz\max}$ is,

$$V_{gz\max} = 3^{-3/2} c_g = \frac{2\sqrt{\gamma-1}}{3^{3/2}\gamma} \cdot c_s \approx 60 \text{ m/s}$$

$$(\text{for normal conditions}) \dots \dots \dots (11)$$

As follows from the wave theory, maximal group velocity is a parameter that determines the propagating velocity of the wave process up-front. This results in the time delay between the variation of the near-surface pressure and atmosphere response in the E region $\tau = z/V_{gz\max} \approx 30$ min (at $z = 110$ km), which is found to coincide well with the experiment (Yampolsky et al., 2004). We mention also that according to Eq.(11) maximal AGW velocity depends only on the sound velocity, and the sound velocity depends only slightly on zonal, seasonal and other variations of atmospheric parameters. These facts permit us to estimate a shift of 0.5 hour as a peculiar time standard for the troposphere-ionosphere connection. The time of disturbance transport to the altitudes of F2 layer is approximately 1 hour.

At the left panel of Fig. 6 one can notice the dependence of V_{gz} on AGW period and wavelength. We pay our attention to the "island" of waves with vertical velocities more than 10 m/s. AGWs outside from this island spend more than 4 hours to "travel" to the thermosphere basement and, according to our point of view, are not effective for the dynamic influence on the ionosphere.

3.4 Atmosphere as Amplitude Amplifier and Filter for

AGWs According to Eq. (5) AGW relative amplitude increases exponentially with altitude:

$$\frac{\delta\rho(z)}{\rho_0(z)} = A(z) = A|_{z=0} \exp\left\{+\frac{z}{2H}\right\} \dots\dots\dots (12)$$

It may seem to us that this result is a formal one and reflects some special properties of initial equations. It is not very clear how solution Eq.(12) would change in the "real" atmosphere conditions. Or, probably the exponent in Eq.(12) is linked with mathematical peculiarities of solutions for differential equations without initial conditions. In reality the amplitude growth Eq.(12) has a deep physical nature.

Fig.7 demonstrates schematically the propagation of AGW wave package with the carrying wavelength $\lambda \sim \lambda_*$. In the absence of dissipation the stream of energy that is carried by AGW is $S(z)V_{gz}(z)\rho_0(z)u^2(z) = const$, from which, if we neglect changes in the cross-section of a ray tube S , we obtain the following.

$$A(z) = A_{z=0} \cdot \sqrt{\frac{V_{gz}|_{z=0} \rho_0|_{z=0}}{V_{gz}(z) \rho_0(z)}} \dots\dots\dots (13)$$

With the condition of $V_{gz} = const$, $\rho_0 \sim e^{-z/H}$ we immediately

Fig. 7. AGW train propagation. Ray trajectories (lines of energy flow) are shown by solid lines, and wave fronts by dashed lines (the cross-section of ray tube $S(z)$ is slightly changing in altitude range comparable with AGW wavelength)

Fig. 8. Dependence of relative AGW amplitude $A = \delta\rho / \rho_0$ on the altitude in linear approximation for various initial (surface) amplitudes (horizontal line $A_{max} = 1$ gives the physical limit for AGW amplitude growing)

obtain Eq. (12).

Dependence of $A(z)$ (calculated for the realistic atmospheric model) is plotted in Fig.8. Slowing down of the AGW growth at altitudes $z = 100 \sim 200$ km is connected with the increase in parameter $H(z)$ and in less degree with the increase in $V_{gz}(z)$. Because the density variation cannot exceed physically 100%, the AGW amplitude $A_{max} = 1$ is the nonlinear limit for the wave growth. Let us emphasize that surface pressure oscillation < 0.1 mbar is able to originate a linear AGW up to the upper limit of the E-region. AGWs at higher altitudes or in E-region with higher initial amplitudes are found to be nonlinear.

AGW non-linearity is connected tightly with the possibility of development of Kelvin-Helmholtz instability (Hines, 1974, Gossard and Hook, 1975). As is known, the Kelvin-Helmholtz instability is an instability of a stream with tangentially inhomogeneous velocity distribution $\partial u / \partial z \neq 0$. The instability is known to develop for the Richardson numbers:

$$Ri = \frac{g}{H} \left(\frac{\partial u}{\partial z} \right)^{-2} < Ri_0 \dots\dots\dots (14)$$

where Ri_0 is a phenomenological threshold, which lies in a range from $Ri_0 = 0.25$ to $Ri_0 = 1$ on the basis of different works.

AGWs may be seen as variable in time and inhomogeneous in altitude for the wind with gradient $\partial u / \partial z = k_z u$. The condition for AGW instability follows from Eq.(14):

$$A(z) > A_c = \sqrt{\frac{2}{Ri_0}} \frac{\lambda}{\lambda_* \sin \theta} \dots\dots\dots (15)$$

Eq. (15) suggests that the short wave harmonics reach an instability threshold first and they decay to shorter waves with velocities $\omega' / k' \sim u$. It is important for us that the last waves are the slow ones which are not effective for the vertical transport of energy. So, short wave harmonics of AGW spectrum disappear with altitude.

The Kelvin-Helmholtz instability seems to play an important role in the generation of atmosphere turbulence (see Roper (1977) and Gardner (1996) and references therein). The scheme of turbulent process looks like as following: energy pumping is going in a long wave area, dissipation in a short wave area, and energy transfer from the long waves to the short ones is carried by a cascade process that is linked, probably, with the Kelvin-Helmholtz instability (although this is not only one possibility). In this case Eq.(15) determines the spectrum of the stationary AGW turbulence with characteristic intensity distribution $I(k) = A_c^2 \sim k^{-2}$.

Because $A(z) < 1$, $\sin \theta < 1$, waves with lengths

$$\lambda > \lambda_c = \sqrt{\frac{Ri_0}{2}} \lambda_* = (0.5 \dots 1) \frac{\lambda_*}{\sqrt{2}} \approx 50 \text{ km} \dots\dots\dots (16)$$

are the stable ones (according to Eq.(15)). Such waves propagate without the dissipation in all altitude range from the Earth's surface to the magnetosphere basement. It is easy to see that for the characteristic AGW amplitudes $A|_{z=0} > 10^{-4}$ which are generated by the tropospheric and surface sources, all the short wave part of spectrum $\lambda < \lambda_c$ dissipates at altitudes lower than E-region.

Let us turn our attention to the anisotropy of AGW-channel of troposphere-ionosphere coupling. From time to time we meet such a point of view that middle-scaled AGWs registered at the Earth's surface have an ionospheric origin. Ionospheric sources of

atmosphere oscillations are found to really generate a wide AGW spectrum including waves propagating downward (e.g. Mayr et al., 1984). We discuss a question whether the AGWs mentioned above are able to generate any noticeable air pressure oscillations near the Earth's surface. Because of the exponential amplitude dependence with altitude, during the disturbance propagation downward leading to the surface variations $A|_{z=0} \sim 10^{-4} \sim 10^{-3}$, perturbations of neutrals in the E-region have to be $A|_{z \sim 100 \text{ km}} \sim 10^{-1} \sim 1$. From our point of view, the unique reasonable source for such perturbations is an atmosphere heating in the auroral electric jet (that is confirmed in the experiments with auroral infrasonic noise registration). TIDs with usual relative amplitudes 1-10 % cannot be an effective source for troposphere oscillations.

4. Seismo-ionospheric Effects

4.1 Hypothetical Mechanisms of Lithosphere-ionospheric Coupling Different groups of phenomena are referred to as seismic effects in the ionosphere. One group includes the phenomena linked with the ionospheric response to the seismic event that already happened (earthquake, tsunami). The mechanism of AGW generation in this case is intuitively understandable – it is a “piston-like” influence of the Earth's surface (or water surface) oscillation upon the atmosphere. Although we pay our attention to the fact of disparity in the source time scale (Earth shock with duration of a few seconds - minutes and atmosphere response, AGW/TID with periods of a few tenths of minutes - hours). As in a case of tropospheric sources the problem is that the source energy is concentrated in unsuitable spectral range. It is easier to explain the generation and influence to the ionosphere of the waves in an infrasonic frequency range (Pokhotelov et al., 1994; Lizunov, 2002). In the work of Artru et al. (2001) they developed the general approach describing the lithosphere and atmosphere as coupled elastic media. Waves in the lithosphere and atmosphere and ionosphere disturbances as plasma manifestations of atmospheric waves are described as a single seismic process that is simulated by a set of “lithosphere-atmosphere” own modes.

Another group is referred to as ionosphere phenomena that are the response to the lithospheric processes of the earthquake preparation – ionospheric earthquake precursors. Causal-investigatory relationship here is as follows: lithospheric earthquake precursor $\rightarrow$ carrying the disturbance upon the ionosphere altitudes $\rightarrow$ ionospheric earthquake precursor. A large number of theoretical and experimental works during the last 20 years are devoted to the investigation of these phenomena (see Liperovsky et al. (1992), Hayakawa and Fujinawa (1994), Hayakawa (1999) and Hayakawa and Molchanov (2002)).

During the stage prior to an earthquake in its focus region the substantial growth and redistribution of the mechanical tensions happen that cause medium brittle cracking and diffusion of fluid (pore liquid with dissolved gases). These processes stimulate electrokinetic mechanisms that are responsible for the generation of microscopic electric currents (apparently the most effective is charge separations during microfracturing (Molchanov and Hayakawa, 1995). When the fluid stream reaches the Earth's surface the effects known as earthquake precursors are generated: penetration of lithospheric gases and aerosols into the atmosphere, change in ground water level, surface temperature and conductivity variation, and others. Several hypothetical

mechanisms to connect the precursors mentioned with ionospheric disturbances were suggested.

The electromagnetic mechanism (Molchanov et al., 1995) is a natural explanation of the satellite observations of ELF/VLF ionospheric emissions correlating with earthquakes. Supposed that the sources are electric currents in the region of earthquake preparation that generates electromagnetic noise with wide frequency spectrum. High frequency part of the spectrum is absorbed by the lithosphere (skin effect), and ELF/VLF noises penetrate into the atmosphere and ionosphere. Theoretical estimations show that electrokinetic mechanisms are not so effective for the explanation of emission amplitudes that are registered in the ionosphere in reality. With the aim to increase emission efficiency factor it is necessary to make a special supposition, for example, on the mutual correlation (coherency) of microcurrents (Molchanov and Hayakawa, 1995). This question is “still” open because of the lack of experimental data about the lithosphere source.

It is impossible to call, as “coupling”, an electromagnetic connection between the lithosphere and ionosphere. Influence upon the ionosphere is energetically miserable and cannot modify the ionospheric parameters. Observation of lithospheric emissions from a satellite is a kind of remote sensing that is absolutely analogous to other earthquake precursors registration, for example, to the registration of thermal Earth anomalies.

The electrostatic mechanism on the coupling to the ionosphere was substantiated in the works by Bliokh (1999) and Alperovich and Fedorov (1999). The source of disturbances in this case is emanation of ionizing substances into the atmosphere (radon, some aerosols) that cause a great increase in atmosphere conductivity. Because of the lack of data on the conductivity distribution $\sigma(z)$ above the earthquake preparation region, these authors tried to perform the qualitative estimations. In the work of Bliokh (1999) he assumed that the atmosphere conductivity increases on the order of magnitude in the layer $\Delta z \sim H$ (that is probably a “superoptimistic” estimation). The main idea is increase in conductivity in the lower atmospheric layer that makes main contribution to the resistance of electrical Earth-ionosphere circuit. A decrease in the total atmospheric resistance (in the work of Bliokh (1999) by two times) causes an increase of the fair weather current j and redistribution of the global electric field $E(z)$ between the Earth's surface and ionospheric D region. Because $j = \sigma(z) E(z) = \text{const}$, field strength decreases near the Earth's surface, and increases in the upper atmosphere. The sense of hypothesis is that this field generates Joule ionospheric heating and plasma inhomogeneities. The scheme mentioned was suggested for the first time for the explanation of the Chernobyl accident influence onto the subionospheric VLF radio wave propagation (Martinenko et al., 1994). In this case an ejection in the radioactive substances as the result of accident played a role of ionized factor.

Numerical estimations have yielded the weakness of this electrostatic mechanism. Exponential increase of conductivity with altitude screens the ionosphere from electrostatic field disturbances from below. It seems that at realistic surface variation amplitudes a noticeable effect may be reached only in the D region (that is essential for ELF waves propagating). Maximal electric field disturbances are concentrated at troposphere altitudes. Hayakawa et al. (2002) and Ondoh and Hayakawa (2002) have investigated experimentally and theoretically the influences of

Fig. 9. Sketch illustrating the electrostatic mechanism of lithosphere-ionosphere coupling (perturbation of the lower atmosphere conductivity modifies fair weather electric current and influences on storm activity)

disturbances mentioned on storm activity. It was shown that seismogenic conductivity variations cause the field redistribution in the systems of "Earth - cloud" and "cloud - ionosphere" that further influences the frequency of lightning discharges and spectral characteristics of lightning radio noises. This permits us to explain, from another point of view, ELF/VLF ionospheric emissions above the region of earthquake preparation (Fig. 9).

The electrostatic mechanism is interpreted in absolutely another way (Kim and Hegai, 1999; Pulinets, 2000). The postulated source is an emanation of lithospheric gases, but its influence on the atmosphere conductivity here is not taken into account. These authors pay their attention to the fact that the local charges separation at the surface layer happen under the influence of chemically active aerosols (Pulinets, 2000), and polarization field may reach significant values. During the earthquakes, volcano eruptions, dust storms, thunderstorms, the fluctuations of electric field up to $E_0 = \pm 1 \sim 10$ kV/m at the Earth's surface were really registered. The projection of these fields on ionosphere was calculated in the work of Kim and Hegai (1999), who solved the electrostatic problem with the model (exponential) profile of conductivity $\sigma(z)$ and initial condition: $E|_{z=0} = E_0$. Although the conductivity increase with altitude leads to the field attenuation with a factor of $\sim 10^{-8} \sim 10^{-6}$ at the level $z = 90$ km, and the influence on the lower ionosphere was essential due to the great surface values E_0 .

Such an approach has not been considered as a correct one. The source field E_0 is concentrated only in the area of charge separation, practically in the thin surface layer with height l about several tenths or hundred meters (may be, kilometers). Here is a suitable analogy with a plane capacitor where the field is concentrated between the capacitor plates. Formal problem statement on the distribution of $E(z)$ has to include additional charges (capacitor plates), or initial condition has to be given at a level of electroneutral atmosphere: $E|_{z=l} = E_1$, where we again deal with the fair weather field $E_1 \sim 100$ V/m.

The AGW mechanism of lithosphere - ionosphere coupling was suggested in the work by Gokhberg et al. (1999). AGW sources are the thermal Earth's surface anomalies caused by the earthquake preparation. Thermal anomalies appear as a result of the heat carried out by lithospheric fluid, as well as the result of heat capacity and heat conductance changes in near-surface layer

due to ground water level changes. The emanation of the lithospheric gases with greenhouse components CO_2 , CH_4 , etc. leads to the heating too. Tronin (1999, 2002) studied the parameters of thermal anomalies of the Earth's surface that were registered before strong earthquakes (according to the satellite registration in infrared emission). We pay our attention to the following results:

- The zone of thermal anomaly corresponds to the projection of the earthquake preparation area to the Earth's surface, and reaches hundreds kilometers for strong earthquakes. So, the size of the heat source is comparable with middle-scale AGW/TID wavelengths;
- Temperature contrast is a few $^\circ\text{K}$. Respective variation of the atmospheric pressure is $A|_{z=0} \sim 10^{-3}$ (that is absolutely enough for the "strong" influence on the ionosphere).
- Lifetime of the thermal anomaly ranges from a few days to several weeks. There are no data on the temperature variations in a range of AGW periods (tenths minutes - hours).

Gokhberg et al. (1999) examined the following model of AGW source:

$$A|_{z=0} = A_0 F(x) \sin(\omega t), \dots\dots\dots (17)$$

according to which the temperature oscillations happen in a coherent manner with the same frequency ω at all source territory (hundreds kilometers). Mareev et al. (2002) have examined a more believable and realistic inhomogeneous source:

$$A|_{z=0} = A_0 F(x, y) \sin(\omega t + \Delta\varphi(x, y)), \dots\dots\dots (18)$$

where $\Delta\varphi(x, y)$ is a stochastic phase shift. The coherency of oscillations in source points (x, y) was described by the model correlation function that allowed our finding the AGW energy stream. Further they have examined particular cases: for absolutely non-coherent, partially coherent ("mosaic") and absolutely coherent sources. Comparison of these cases demonstrated that even non-coherent AGW source is effective for the influence on the ionosphere.

The question about the origin of the fluctuation with frequency ω in Eqs. (17) and (18) is not well understood. Gokhberg et al. (1999) mentioned a hypothetical possibility of the source modulation by the global seismo-gravitation oscillations of the Earth (with periods 1~3 hours). Tronin (2002) has discussed, also hypothetically, the excitation of wide spectrum of Brunt-Vaisala oscillations as a result of destabilization of the thin near surface atmospheric layer above the thermal anomaly.

Different mechanisms of lithosphere-ionosphere coupling are not necessary to contrast one with another. Electromagnetic, electrostatic and AGW connections are "switched on" by different processes in the lithosphere and act independently. Nevertheless, *a priori* the AGW mechanism seems to be most effective. As it was shown above, due to the conductivity increase with altitude an atmosphere "works" as an attenuator for electrostatic and electromagnetic disturbances. Only for sufficiently great surface amplitude such disturbances are able to penetrate into the ionospheric D-region, probably to the lower part of E-region. At the same time an atmosphere plays a role of amplitude AGW amplifier with amplification factor from 10^3 (E region) to 10^5 (F region). Variations of near-surface pressure $A|_{z=0} \sim 10^{-4} \sim 10^{-3}$ (that may be easily caused by any lithosphere sources) generate plasma parameter inhomogeneities $\geq 10\%$ at the ionosphere

altitudes.

4.2 Proposals for the Experimental Verification of AGW Mechanism

Imaginations about the mechanisms of lithosphere-ionosphere coupling belong to the sphere of pure theory. Today we have numerous observations of lithospheric anomalies that are referred to as geophysical earthquake precursors and ionosphere anomalies that may be interpreted hypothetically as earthquakes precursors (Hayakawa and Fujinawa, 1994; Hayakawa, 1999; Hayakawa and Molchanov, 2002). But there is no any experiment with the registration of coupling between the lithosphere and ionosphere precursors, for example, with the registration of electromagnetic emission near the Earth's surface, and, simultaneously, in the ionosphere (or disturbance of surface electrostatic field and ionospheric inhomogeneities, oscillations of atmospheric pressure and TID, etc). Based on the results by Yampolsky et al. (2003,2004), we can suggest an experimental program for the verification of the AGW mechanism. For this purpose we suggest:

- Systematic monitoring of meteorological and ionospheric parameter variations in a seismically active region. Measurements have to be carried out in several remote points (at least in 3 points) that are necessary for the registration of AGW wavelength and velocity near the Earth's surface and AGW/TID in the ionosphere. Requirements to the registration equipment are as follows: resolution of the air pressure variations being more precise than $\delta P|_{z=0} = 0.1 \text{ mbar}$, sampling not less than 1 time per 5 min, distance between the points of observations near 70 km ($\sim \lambda_s$);
- Carrying out cross-correlation analysis for variations of near - surface and ionospheric parameters. Finding their interconnections, determination of AGW characteristics that are responsible for TID generation.

We expect that following new results have to be found in this way:

- The fact of AGW coupling with geophysical earthquake precursors will be confirmed experimentally or such confirmation will be doubted;
- The efficiency of the mechanism for AGW influence on the ionosphere will be determined. We emphasize that only a little part of AGWs generated by the surface sources reaches the ionosphere;
- If AGW will be verified as earthquake precursors, TIDs will be verified as such ones automatically.

5. Conclusion

It is difficult to describe AGW basic provisions better than it was already done in the reviews and monographs in 60s ~ 80s being classical for today (Hines, 1964, 1974; Hook, 1977; Francis, 1975; Kato, 1980, etc.). Without repeating the previous works, in our work we concentrated ourselves on the analysis of such AGW properties that are important for the troposphere-ionosphere and lithosphere-ionosphere coupling. Some of our conclusions are original and, probably, debatable. They are summarized as follows:

- Atmosphere plays a role of a filter that is transparent for the long and quick AGW (with wavelength about 100 km and more, phase velocities of 100~200 m/s, and vertical group velocities up to 60 m/s);
- That is why the troposphere and surface TID sources have to provide AGW generation in the parameter range mentioned.

This problem needs further study because, as is known, the main energy of tropospheric turbulence is concentrated in an "unsuitable" region of the short waves with phase velocities comparable with the wind velocity.

In this paper we consider TIDs as natural manifestation of AGWs. In reality, the mechanism of AGW $\rightarrow$ TID transformation is complicated enough. In the D and E ionospheric regions the ion lifetime is so short that it is possible to neglect the spatial transfer of ions by AGWs. In such conditions AGWs play a role of quasi-stationary and quasi-homogenous background that influences the parameters of ionosphere through the changing the photochemical equilibrium conditions. In the F2 region, conversely, the main role played is ion dragging by neutrals along the magnetic field lines. In the F1 altitudes it is necessary to take into account the influence of both the factors mentioned. The works of Hooke (1968), Hines (1974) and Sorokin and Fedorovich (1986) are devoted to this profound examination of AGW-TID coupling.

(Manuscript received March 12, 2004, revised July 16, 2004)

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