J. Plasma Fusion Res. SERIES, Vol. 8 (2009)

Some Physical Mechanisms of Precursors to Earthquakes

James W. VAN DAM,[1] Wendell HORTON,[1,2] Nodar L. TSINTSADZE,[3] Tamaz D. KALADZE,[4] Trevor W. GARNER,[5] and L. V. TSAMALASHVILI [4]

[1] *Institute for Fusion Studies, The University of Texas at Austin, Austin, Texas 78712, USA*

[2] *Department of Physics, The University of Texas at Austin, Austin, Texas 78712, USA*

[3] *E. Andronikashvili Institute of Physics, Academy of Sciences, 0177, Tbilisi, Georgia*

[4] *I. Vekua Institute of Applied Mathematics of Tbilisi State University, 2 University Str., 0186 Tbilisi, Georgia*

[5] *Center for Ionospheric Research, Space and Geophysics Laboratory, Applied Research Laboratories, The University of Texas at Austin, P. O. Box 8029, Austin, Texas 78713-8029, USA*

(Received: 12 September 2008 / Accepted: 13 November 2008)

The existence of precursors to earthquakes at different heights of the earth's ionosphere is investigated. We analyze a mechanism for the generation of low-frequency large-scale zonal flows by higher frequency, small-scale internal-gravity waves in the electrically neutral troposphere. The nonlinear generation mechanism is based on parametric excitation of convective cells by finite amplitude internal-gravity waves. Measured density perturbations arising due to zonal flow generation may confirm the seismic origin of this mechanism. We also investigate nonlinear propagation of low-frequency seismic-origin internal-gravity perturbations in the stable stratified conductive E-layer. The predicted enhancement of atomic oxygen radiation at wavelength 557.7 nm due to the damping of nonlinear internal-gravity vortices is compared with the observed increase of the night-sky green light intensity before an earthquake. The good agreement suggests that ionospheric internal-gravity vortices can be considered as wave precursors of strong earthquakes. These precursors could be a tool for predicting the occurrence of a massive earthquake or volcano.

Keywords: earthquake precursors, internal gravity waves, zonal flows, night-sky green light

1. Introduction

During the past decade, interest has greatly increased in electromagnetic and ionospheric phenomena caused by lithospheric processes that are related to earthquake precursors. This paper addresses the problem of seismo-ionospheric coupling. Experimental evidence is mounting for the mutual influence of processes in different geophysical media. Consequently a modern understanding of geophysical phenomena requires consideration of the effects in more than one medium. Some of the mutual effects in the system consisting of the lithosphere, atmosphere, ionosphere, and magnetosphere are known and have been extensively studied. Among these effects we focus attention on ionospheric precursors of earthquakes—namely, the influence of seismic-related electromagnetic phenomena on the wide-frequency spectra noise background and on ionospheric parameters [1-4]. The effects of the interaction between different geophysical domains cannot be disregarded. Although some progress in this direction has been made, all these effects should be studied further.

The present paper focuses on two main regions of the atmosphere-ionosphere-magnetosphere system of the Earth: (1) the electrically neutral troposphere at lower heights, and (2) the weakly ionized conductive E-layer. The physical model developed in this paper bridges the traditional precursors of earthquakes and the ionospheric precursors, and demonstrates that the latter belong to the same family.

Theoretical and experimental studies have shown that earthquakes can be sources for acoustic-gravity (AG) waves in the ionosphere [5,6]. The main reason for the importance of studying AG waves, related to their practical application, is that energy and momentum fluxes transported by AG waves from the lower to the upper ionosphere are comparable to or even larger than those coming from the solar wind or other sources. Based on the frequency spectra emitted by earthquakes, we will consider the low-frequency internal gravity (IG) branch of the acoustic gravity (AG) waves [5,7]. Internal gravity waves have typical periods τ of 10^2 sec $\leq \tau \leq$ 1 day, wavelengths of $\lambda \approx$ 10 km, and propagation velocities of $v_p \approx$ 30 m/s.

Generally, the dynamics of the weakly ionized ionosphere is largely determined by its massive neutral particles, since the ion-neutral collision frequency is larger than the mode frequency for the internal gravity

author's e-mail: vandam@physics.utexas.edu

waves. Thus, the low-density ions, with density n, are embedded in a neutral gas with density N, where the density fraction n/N can be as low as 10^{-6}. However, the Lorenz force acting on the ions is about 10^6 larger than the horizontal forces acting on the neutral gas, including the Coriolis force. Hence the horizontal acceleration is mostly due to the ion component of the system. In addition, the ion component makes the gas electrically conducting, and the ionospheric plasma is immersed in the geomagnetic field B. Therefore the interaction of the inductive current with the geomagnetic field must be taken into account.

We use a local Cartesian system of coordinates (x,y,z) with the x-axis directed from the west to the east, the y-axis from the south to the north, and the z-axis along the local vertical. The dynamics of the electrically conducting ionospheric plasma can be described with the help of the standard momentum equation (see, e.g., [8]), in which the collisional drag force between the neutral gas and the ions is replaced with the force balance equation for the ionized gas component, which introduces the $\boldsymbol{j}x\boldsymbol{B}$ acceleration. In order to exclude the high-frequency acoustic branch of the acoustic-gravity waves, we make use of the incompressibility condition. The background mass density ρ_0 is stratified by the gravitational field and is taken to vary as $\rho_0(z) = \rho(0)$ $\exp(-z/H)$, where H is the reduced atmospheric height.

In Sec. 2, zonal flow generation by internal gravity waves in the neutral troposphere is considered. In Sec. 3 we give a theoretical justification for why an increase in the intensity of green radiation of atomic oxygen at the wavelength 557.7 nm is observed at ionospheric E-layer heights before earthquakes. Our results are summarized and discussed in Sec. 4.

2. Zonal Flow Generation by Internal Gravity Waves in the Earth's Troposphere

It is widely thought that nonlinear energy transfer from small- to large-scale-length fluctuations (inverse cascade) is an important mechanism for the spontaneous generation of large, coherent structures both in atmospheres and magnetized plasmas. In this section we describe the main results of our calculation for the generation of sheared flows in the atmosphere and lower ionosphere from the parametric decay of finite amplitude internal gravity (IG) waves. The analysis finds the conditions on the wave number vector and amplitude for small-scale gravity waves to spontaneously excite vertically sheared zonal flows. We develop a modified parametric excitation mechanism for the problem of zonal flow generation by low-frequency IG waves. Internal gravity waves are described by two potential fields (ψ,χ), which produce two driving stresses, the Reynolds stress and the stratification stress. Low-frequency IG waves can be described by a coupled system of differential equations for ψ and χ, which are given, e.g., by Stenflo [9].

The nonlinear Jacobian terms in the system of equations allow us to consider coupling between different modes. We consider three-wave interaction, in which the coupling between the pump IG wave and the sideband modes generates low-frequency large-scale modes, the so-called zonal flows. Since the zonal flow varies on a much longer timescale than the comparatively short timescale IG waves, we can use a multiple-scale expansion, assuming that there is a sufficient spectral gap separating the large-scale and small-scale motions. Following the standard procedure to describe the evolution of the coupled system (IG waves plus zonal flows), we split the perturbations into three components, which respectively describe the spectrum of pump IG modes, the spectrum of sideband modes, and the large-scale zonal flow modes having only one component of velocity along parallels that depend on the vertical z-coordinate. The energy and momentum conservation conditions among the frequencies and wave number vectors of the three components are fulfilled.

Then, following further standard procedure, we obtain the zonal flow growth rate; details are given in our published paper [10]. According to our investigation, the possibility of zonal flow generation by IG modes in the upper atmosphere is rigidly connected with the sign of $v_g' = \partial^2\omega/\partial k_z^2$ for these modes (the dispersion of the group velocity of the primary modes). The necessary condition for instability is $v_g'/\omega_k < 0$, which is similar to the Lighthill criterion for modulational instability in nonlinear optics. Accordingly, a particular feature of this instability is that it appears only for IG waves that are localized in a cone bounded by the caustics for which $v_g' = 0$. This feature can lead to the formation of a so-called caustic shadow in the spectrum of the IG waves. The maximum growth rate occurs when $k_z = 0$; this growth rate describes the initial (linear) stage of zonal flow growth due to the parametric instability of small-scale IG waves.

For tropospheric IG waves, we can estimate that the zonal flow growth rate is approximately 10^{-4} s^{-1}. This estimate is consistent with existing observations. Hence our investigation provides an essential nonlinear mechanism for the transfer of spectral energy from small-scale seismic-origin IG waves to large-scale enhanced zonal flows in the Earth's neutral atmosphere.

3. Intensification of Atomic Oxygen Green Line Emission by Internal Gravity Waves

Much of the data from observations confirms that, before and after earthquakes, there is increased wave activity in the atmosphere and ionosphere. General results from investigations on this subject were presented at conferences in Japan [3,11] and in monographs and reviews [1,4,12]. In particular, the excitation of acoustic gravity (AG) waves has been observed. An analysis of the data on pre-twilight night-sky luminescence shows that, before an earthquake, an increase occurs in the intensity of green radiation of neutral atomic oxygen at a wavelength of 557.7 nm. This emission arises from the $O(^1S\text{-}^1D)$ transition and has a radiating layer at heights of 85-110 km. This increase in radiation begins several hours before an earthquake [13-15] and provides preliminary evidence for the presence of internal gravity waves or acoustic gravity waves.

It is generally accepted that the induced radiation of atomic oxygen at wavelength 557.7 nm is caused by the existence of super-thermal electrons [16,17] in the ionosphere, which excite oxygen molecules and atoms by electron impact. A suggestion has been made [18] that the emission of electromagnetic radiation from seismic epicenters and its subsequent propagation to the ionosphere could possibly enhance the electron temperature. However, the suggestions given in Refs. [16-18] are applicable to the F-region in the ionosphere, whereas the detected atomic oxygen green line emission is situated in the ionospheric E-region. To explain this phenomenon we therefore consider the nonlinear propagation of seismic-origin internal gravity waves.

Although the brighter green line emission could result from a local ionization source, it usually indicates an influx of molecular-rich neutrals into the region. Gravity waves can carry moleculars to higher altitudes, and earthquakes are one mechanism for generating these waves. (Other possible mechanisms for generating gravity waves are thunderstorms, unequal heating of the Earth's surface, lunar tidal forces, and unequal thermospheric and mesospheric heating during magnetic storms.)

On the basis of the data available from observations and experiments that find a relationship between intensity changes of the nighttime green-line emissions and seismic activity, we hypothesize that, prior to an earthquake, the dynamics in the atmosphere develop according to the following scheme. Tectonic processes occurring in the Earth's crust generate Rayleigh waves, which propagate over the Earth's surface from the epicenter at supersonic velocities ($\approx$ 3 km/s). These Rayleigh waves give rise to atmospheric pressure disturbances by vertical pulsed action on the air [6]. Acoustic-gravity (AG) waves propagate vertically, almost undamped, to a height of 100 km (their amplitude increases exponentially as the height increases) and give rise to collective motions in the form of IG vortices. Due to the convective vortex motion, the density of atomic oxygen at these heights increases and, consequently, the intensity of green night-sky radiation in enhanced.

Due to the relatively high frequency of the IG waves, the influence of the Coriolis and Lorentz forces caused by the Hall conductivity is negligibly small, while the Pedersen conductivity arises from inductive (magnetic) inhibition and leads to Joule damping of IG waves. However, in the case of strong seismic-origin IG waves, they may reach nonlinear level of propagation. We investigated the nonlinear propagation of IG waves in the conductive ionospheric E-layer. We obtained a simplified set of two-dimensional equations for the dynamics of IG waves in the conductive stable stratified ionosphere. A major finding of this research was to show how the conductivity of the Earth's ionosphere influences the horizontal vortex rolls, which bring higher densities of the lower atomic oxygen up into the ionosphere. Here they are excited to emit enhanced levels of green light as in an auroral display, not associated with enhanced electron precipitation, but with large energy releases from the surface of the Earth. We considered nonlinear solitary vortex structures that are formed on the IG waves. The nonlinear behavior of the low-frequency IG perturbations is dominated by the presence of the convective derivative, and the corresponding vector-product nonlinearity can thus produce various coherent localized vortex structures for a broad range of background configurations. We further find that the energy of the solitary vortex dipole structure of internal gravity waves is decreasing due to Joule losses.

Next, we consider the increase in the intensity of green night-sky radiation. The additional mixing of neutrals related to IG vortices and the transport of atmospheric components in the vertical direction increase the neutral density in the atmosphere at this height. The increase in the density of oxygen atoms increases the efficiency of their recombination and, consequently, increases the intensity of green (λ = 557.7 nm) night-sky radiation observed prior to strong earthquakes. Estimating the predicted variation of green radiation due to IG vortices, we find consistency with observed data. Hence the increase of the green night-sky radiation can be used as an immediate (24-48 h) sign of earthquakes. Details are given in a longer paper [19].

4. Discussion

A novel mechanism for the generation of low-frequency large-scale zonal flows by higher-frequency, small-scale, finite-amplitude internal gravity (IG) waves is analyzed in the atmosphere from the troposphere to the ionosphere E-layer. The nonlinear generation mechanism is based on the parametric excitation of convective cells by finite-amplitude internal gravity (IG) waves. A set of coupled equations describing the nonlinear interaction of IG waves and zonal flows is derived. The generation of zonal flows is due to the

Reynolds stress and mean stratification forces produced by finite-amplitude IG waves. The onset mechanism for the instability is governed by a generalized Lighthill instability criterion. Explicit expressions for the maximum growth rate as well as for the optimal spatial dimensions of the zonal flows are derived. The growth rates of zonal flow instabilities and the conditions for driving them are determined. A comparison with existing results is carried out. The present theory can be used for some applications of IG waves to the earthquake forecast problem. Appearance of large-scale zonal flow fluctuations may be taken as confirmation of this phenomenon.

Low-frequency IG waves, such as may be generated by seismic activity and nonlinearly propagated through the atmosphere to the E layer of the ionosphere, are shown to cause intensification of atomic oxygen green line emission when their amplitude is sufficiently large. The nonlinear equations for the internal gravity waves are derived with the interaction of the induced currents with the geomagnetic field taken into account. When the source of the IG waves is sufficiently strong, we predict that nonlinear vortex structures are formed in the upper stratosphere and lower ionosphere. These nonlinear vortex structures are damped due to Joule losses. The vortices provide a mechanism for increasing the concentration of atomic oxygen in the E-layer and, hence, the associated intensity of the green light radiation at a wavelength of 557.7 nm. Data is discussed that reports the observation of enhanced green light emission prior to earthquakes; this could lead to a forecasting model if the connection with seismic activity can be established.

5. Acknowledgements

This research was made possible by support from the Georgian Research and Development Foundation (GRDF) under Award GEP2-3340-TB-06, the U.S. Civilian Research and Development Foundation, the U.S. National Science Foundation, and the Office of Fusion Energy Sciences of the U.S. Department of Energy.

6. References

[1] M.B. Gokhberg, V.A. Morgounov, and O.A. Pokhotelov, *Earthquake Prediction: Seismo-Electromagnetic Phenomena (*Gordon and Breach, Reading/Philadelphia, 1995).

[2] O.A. Molchanov, V.A. Rafalsky, and M. Hayakawa, "Penetration characteristics of electromagnetic emissions from an underground seismic source into the atmosphere, ionosphere and magnetosphere," J. Geophys. Res. **100**, 1691-1712 (1995).

[3] M. Hayakawa, editor, *Atmospheric and Ionospheric Electromagnetic Phenomena Associated with Earthquakes* (Terra Science, Tokyo, 1999).

[4] S. Pulinets and K. Boyarchuk, *Ionospheric Precursors of Earthquakes* (Springer, Berlin-London, 2004).

[5] G.I. Grigor'ev, "Acoustic-gravity waves in the Earth's atmosphere (review)," Radio-Phys. Quantum Electron. **42**, 1-21 (1999).

[6] H. Kanamori, "Some fluid-mechanical problems in geophysics-waves in the atmosphere and fault lubrication," Fluid Dyn. Res. **34**, 1-19 (2004).

[7] E. Gossard and W. Hooke, *Waves in the Atmosphere* (Elsevier, New York, 1975).

[8] T.D. Kaladze, G.D. Aburjania, O.A. Kharshiladze, W. Horton, and Y.-H. Kim, "Theory of magnetized Rossby waves in the ionospheric E-layer," J. Geophys. Res. **109**, A05302, doi:10.1029/2003JA010049 (2004).

[9] L. Stenflo, "Nonlinear equations for acoustic gravity waves," Phys. Lett. A 222, 378-380 (1996).

[10] W. Horton, T.D. Kaladze, J.W. Van Dam, and T.W. Garner, "Zonal flow generation by internal gravity waves in the atmosphere," J. Geophys. Res. **113**, A08312, doi:10.1029/2007JA012952 (2008).

[11] M. Hayakawa and Y. Fujinawa, editors, *Electromagnetic Phenomena Related to Earthquake Prediction* (Terra Sci. Pub. Co., Tokyo, 1994).

[12] V.A. Liperovsky, O.A. Pokhotelov, E.V. Liperovskaya, et al., "Modification of sporadic E-layers caused by seismic activity," Surveys in Geophysics **21**, 449-486 (2000).

[13] L.M. Fishkova, M.B. Gokhberg, and V.A. Pilipenko, "Relationship between night airglow and seismic activity," Ann. Geophys. **3**, 689-694 (1985).

[14] T.I. Toroshelidze, and L.M. Fishkova, "Analysis of fluctuations of the nightglow of the middle and upper atmosphere preceding earthquakes," Akademia Nauk SSSR Doklady **302**, 313-316 (1988).

[15] A.V. Mikhalev, M.S. Popov, and E.S. Kazimirovsky, "The manifestation of seismic activity in 557.7 nm emission variations of the Earth's atmosphere," Adv. Space Res. **27**, 1105-1108 (2001).

[16] F. W. Perkins and P. K. Kaw, "On the role of plasma instabilities in ionospheric heating by radio waves," J. Geophys. Res. **76**, 282 (1971).

[17] J. A. Feijer and K. R. Graham, "Electron acceleration by parametrically excited Langmuir waves," Radio Science **9**, 1081 (1974).

[18] D. K. Sharma, M. Israil, R. Chand, J. Rai, P. Subrahmanyam, and S. C. Garg, "Signature of seismic activities in the F2 region ionospheric electron temperature," J. Atmospheric and Solar-Terrestrial Physics **68**, 691-696 (2006).

[19] T. Kaladze, W. Horton, T.W. Garner, J.W. Van Dam, and M.L. Mays, "A method for the intensification of atomic oxygen green line emission by internal gravity waves," accepted for publication in J. Geophys. Res. (2008).