The Ionospheric response during the passage of seismic trigerred acoustic waves: Non-local analysis

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Abstract

In the context of ionospheric response to the acoustic waves, the non-local analysis of hyromagnetic waves are carried out. For a given wave vector, number of frequencies are allowed to be excited according to the dispersion relations. The wave features are found to be dominant in the F region where they drive large currents. For latitudinal unifrom vertical displacement of Earth's surface, the ionospheric response is found to vary with latitude. The angle between acoustic wave vector and Earth's magnetic field plays the crucial role for the excitation of the hydromagnetic waves. The scalar and vector potentials reveal significant variations in space and give rise to significant amplitude of electric and magnetic field fluctuations.

1 Introduction

Varities of ionospheric perturbations are observed during the seismic activity. They include the fluctuations in the ionospheric density or total electron content (TEC), height of the ionospheric layer and the electromagnetic fields [Chmyrev et al, 1997, Calais and Hasse, 2003]. The dense GPS network has detected the ionospheric TEC perturbations associated with the acoustic-gravity (AGWs), seismic and Tsunami waves [Calais and Minster, 1995, Ducic et al, 2003, Artru et al, 2005]. The low-orbiting satellites have detected the ELF-VLF electromagnetic fluctuations in the ionosphere associated with the earthquakes [Larkina et al, 1989; Molchanov et al, 1993; Hayakwa et al, 1993; Hobara et al, 2005].

These observations indicate the existance of energy flow mechansims from the lithosphere into the atmosphere and to the ionosphere caused by seismic activity. In the literature, electromagnetic and acosutic-gravity waves are discussed as the possible flow channels of the lithosphere-ionosphere coupling [Gokhberg et al, 1995; Molchanov et al, 1995; Kotsarenko et al, 1997]. Among the two, the acoustic channel of coupling is found quite effective [Taeantsev et al, 1973, Koshevaya et al, 2005] due to atmospheric acoustic waves excited by the fluctuations of the terrestrial surface. This channel manifests in different phenomena, for example, the plasma wave excitation in the ionosphere, linear and nonlinear generations of electro-magnetic fluctuations, oscillations of E and F-layers in the ionosphere caused by AGWs. Such phenomena are able to explain the observations [Artru et al, 2001].

The investigations concerning the exciatations of plasma waves by the atmospheric waves are pursued in the framework of local and non-local perturbation analysis [Gorbachev et al, 1973; Pogorel'tsev, 1989; Jacobson and Bernhardt, 1985; Surukov, 1992; Borisov and Moiseyev, 1989; Sorokin et al, 2006]. Most of these investigations are confined to the E region where the large current flows due to the Cowling conductivity. The significant ionospheric response is usually expected in this region. However, the plasma waves should be manifesed more prominantly in the F region where collision frequencies are small. Moreover, the reconstruction of the recent TEC observations [Garcia et al, 2005] indicate the maximum density perturbations to be in the F region. To accomodate the new observational finding such as the TEC and Doppler observations, the F region dynamics is therefore needed to be included as well. In the present investigation, we carry out the linear-non-local response of the E and F region of the ionosphere during the passage of acoustic waves. We solve the closed hydromagnetic equations using the linear perturbation analysis.

2 Non-local Analysis

To study the electromagnetic and density fluctuations of plasma waves caused by the atmospheric waves, following hydromagnetic equations are adopted:

Momentum and continuity Equations:

$$-i\omega\vec{u}_s = \frac{q_s}{m_s}(\vec{E} + \vec{u}_s \times \vec{B}) + \nu_s(\vec{W} - \vec{u}_s) \quad (1)$$

$$-i\omega n + \nabla.(n u_s) = P - L \quad (2)$$

$$J = \sum n_s q_s u_s \quad (3)$$

Wave equation for scalar and vector potentials:

$$\nabla^2\Phi + \frac{\omega^2}{c^2}\Phi = -\frac{\rho}{\epsilon} = -\vec{\nabla}.\vec{E}_{\mathrm{emf}} \quad (4)$$

$$\nabla^2\vec{A} + \frac{\omega^2}{c^2}\vec{A} = -\mu_o\vec{J} \quad (5)$$

Fluctuating fields:

$$\delta\vec{E} = -\vec{\nabla}\Phi - \frac{\partial\vec{A}}{\partial t}; \ \delta\vec{B} = \vec{\nabla}\times\vec{A} \quad (6)$$

where n_s, u_s are the number density and velocity of plasma fluid 's' (s=i,e), ρ, J are the charge and current density and $\vec{E} = E_{\mathrm{emf}} + \delta E$, $\vec{B} = B_o + \delta B$ are the total electric and magnetic fields in the ionosphere. In the ionospheric plasma, electric fields are either static or inductive. Static electric fields ($-\nabla\Phi$) come from distribution of charges and indutive fields, $-\frac{\partial A}{\partial t}$ and E_{emf} , respectively from the time variation of magnetic field and from the electromotive force that results from the motion of plasma across the magnetic field. The free charges are not maintained easiliy in the plasma owing to its large conductivity. the cahrge density ρ appearing in the r.h.s. of (4) is the induced charge maintained by the $\mathcal{EMF}$ force.

3 Results and discussion

In the present investigation, the ionospheric parameters are determined from the IRI (Bilitza et al, 1996) and SAMI2 (Huba et al, 2003) models. The altitude and latitude coverage of ionosphere is chosen to be 90 km-610 km and -30-30^o respectively. The ionospheric electron density derived from the IRI is plotted in Figure 1a. The amplitude, $\vec{W}$, of AGWs is estimated using the wave-propagtion model [Garcia et al, 2005] and is shown in Figure 1b.

When such acoustic wave pierce through the ionosphere, varieties of low-frequency plasma waves are expected to be excited in the ionosphere. The frequency ω appearing in the (1-4) corresponds to the frequency of these plasma waves. At this point, it is crucial to know what kind of plasma waves and frequencies are excited in the ionosphere due to the low-frequency acoustic waves. The obvious ionospheric counterparts to the acoustic waves are the ion-acoutic, magnetoacosutic and Alfven waves. In the partially-ionized medium such as ionosphere, the dispersion relations of these waves are greatly modified due to the collisional damping. It is found that, in the presence of collisions, the dispersion relations of ion-acoustic and Alfven waves are modified to following relations:

$$\frac{\omega_s^2}{k^2} = \alpha c_s^2; \ \frac{\omega_A^2}{k^2} = \beta V_A^2 \ \text{ where } \alpha = \left(1 - \frac{\nu_i\nu_e}{\omega_{\mathrm{pe}}^2}\right)^{-1}; \beta = \left(1 - \frac{\nu_i}{\Omega_i}\right)$$

Similarly, the dispersion relations of fast and slow magnetoacoutic waves modify to following relations:

$$\frac{\omega_{\pm}^2}{k^2} = (\alpha c_s^2 + \beta V_A^2)\Big(1 \pm (1 - 4\varsigma^{1/2})\Big); \qquad \varsigma = \frac{\alpha\beta c_s^2 V_A^2}{(\alpha c_s^2 + \beta V_A^2)^2}(\hat{k}.\hat{b})^2$$

Thus α and β are the crucial parameters to determine the propogation of the low-frequency plasma waves in the ionosphere. In case of their negative values, the wave frequency becomes purely imaginary forbidding the corresponding wave to propogate. In Figure 2a-b, these two paramteres are plotted at equatorial latitude. We note that the $\alpha\,(\beta)$ are negative below 90 (130) km. It means that the Alfven and fast magnetosonic waves can only propogate above 130 km while slow magnetoacoutic wave can propoagte above 90 km. For given wavevector k, then the choice ω in (1-4) should be either of $(\omega_s, \omega_A, \omega_{\pm})$ or in general, the sum of all i.e., $\omega = \omega_s + \omega_A + \omega_+ + \omega_-$. In present investigation, we assume the wavelengths and direction of these plasma waves to be same as the acoustic wave i.e. $\vec{k} = \frac{\omega_a}{c_s}\hat{y}$. The wave frequency ω is then derived from the above summation rule and it is plotted in Figure 3a for $\omega_a = 5$mHz. We note that the plasma waves in the 5mHz-6Hz frequency range are excited in the ionosphere.

In (1) the term appearing with frequency ω and ν_s correspond to the wave and dynamo induced accelerations and their comparative role to determine the J is decided by the ratio $\frac{\omega}{\nu_s}$. In Figure 3b-c, this ratio is plotted as a function of altitude for ions and electrons. The ratio is found to be very small in the E and lower F region and increases with the altitude. Thus, the dynamo induced acceleration plays dominant role in E and lower F region in determing the J and as altitude increases, the wave-induced acceleration (WIA) becomes important. In order to understand this aspect more clearly, the three components of current J_r, J_θ, J_ϕ are plotted in Figure 4 without the ω term in upper panel and with ω term in the lower panel. We note that in the E region, all the three components of J are same in the absence and presence of WIA in (1). It is then interesting to note that the J_r and J_θ components reveal different features in the absence and presence of WIA in the F region. The significant amount of currents are noted at higher altitude in the presence of WIA. Such behaviour indicates that the wave features play vital role in determining the current distribution in the F region of ionosphere while the dynamo induced currents are sole effect in the E region. We also note from Figure 5 that the wave-induced currents varies significantly with latitude and vanishes at the geomagnetic equator. Such feature arises due to the nature of wind which is assumed to propogate vertically. It means that obligue propogation of neutral wave w.r.to B_o is needed to realize the wave features in the ionosphere. It is also noted that J_ϕ component is same in the absence and presence of WIA. It implies that only J_r and J_θ components are responsible for any wave features appearing in the ionosphere.

With the distribution of $E_{\rm emf}$ (or ρ) and J, (4-5) are solved for the scalar, Φ, and vector potential $\vec{A}$. In Figure 5, scalar potential and three components, A_r, A_θ, A_ϕ of vector potential are plotted. In figure 6, the perturbed electric and magnetic field components, derived from (6), are plotted. We note that δE_ϕ and δB_θ components solely arise due to the J_ϕ or A_ϕ and thus caused by the dynamo mechanism. The other components of δE and δB carries both wave and dynamo features where wave features are more dominant in the F region. We note that maximum amplitude of electric and magnetic field fluctuations are of order of $1\,\mu V/m$ and 1 nT and correspond to the δE_θ and δB_ϕ components of fields respectively. It is to be further noted that δE_ϕ and δB_θ are more dominant components in the vicinity of geomagnetic equator whereas other comopnents of fields are more dominant away from the equator.

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