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On the source of plasma density and electric field perturbations in PMSE and PMWE regions

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Abstract

Polar mesospheric summer/winter echoes (PMSE/PMWE) are usually very strong radar echoes produced by ionospheric electron density fluctuations at half the radar wavelength. This paper studies the formation of electron density fluctuations in the PMSE/PMWE source region. Using a computational model, the current paper investigates the coupling of the neutral air turbulence with mesospheric dusty plasma as a generation source of fluctuations in plasma and dust densities as well as electric field. The impact of spectrum of irregularity wavelengths in neutral air turbulence including the presence of charged dust particles is investigated and extension of diffusion timescale for electron density fluctuations in smaller wavelength is studied. A comparison of the numerical results with VHF radar observations and in-situ rocket measurement of plasma density perturbations in the mesopause region is presented. The effect of dust density and dust-neutral collision frequencies on the coupling between neutral turbulence and the dust layer in PMSE source region is studied. The computational results are compared with the past theoretical predictions of impact of heavy charged dust on the wavenumber spectrum of electron irregularities. Formation of fluctuations in plasma and electric field in PMWE is then considered. The required plasma and dust parameters for neutral turbulence coupling in winter mesosphere are also determined.

Keywords: Polar mesospheric Summer/winter echoes, Plasma density perturbations in mesosphere, Numerical simulation.

1. Introduction

Noctilucent Clouds (NLCs), as viewed from the ground, or Polar Mesospheric Clouds (PMCs), if observed from space, are one of the fascinating and important seasonal visual manifestations of dust layers in the upper atmosphere. This region has been studied extensively using rocket in-situ measurements (Gelinas et al., 1998; Lynch et al., 2005; Rapp et al., 2005; Rapp et al., 2012; Friedrich et al., 2012), satellite imagery (Aeronomy of Ice in Mesosphere AIM satellite) (Chandran et al., 2009), radars (Ecklund and Balsley, 1981; Rottger et al., 1988), and Lidars (Baumgarten et al., 2008). Recent rocket experiments have detected both positively and negatively charged dust particles in the PMC source region (Robertson et al., 2007).

During summer months in high latitude regions, strong radar echoes in a wide frequency range from HF to UHF are observed to be associated with NLC particles at mesopause altitudes 83-88 km (e.g. Rapp and Lubken, 2004 and references therein). According to observations over the past few decades, gravity waves (GW) may penetrate to very high altitudes up to 500 km. Klostermeyer (1990) showed that internal gravity waves (GW) and the resulted parametric instability can explain the properties of tropospheric UHF radar echoes as well as mesospheric VHF radar observations. Fritts et al. (2014) presented the first 3D numerical simulation of gravity wave breaking in the mesopause environment. This study showed a good agreement between the computational results and the structures observed within NLC. Dissipation of GW at low altitudes, environmental condition for the propagation of GW to high latitudes, and structures associated with GW has been investigated extensively (Fritts and Alexander, 2003 and references therein). Recently, Fritts et al.

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(2014) have studied the modulation of Kelvin-Helmholtz instability (KHI) by small-scale spatial gravity waves as the generation source of spatial structures in NLC near polar summer mesopause. Their model shows a reasonable agreement with small-scale dynamics observed in NLC.

So-called Polar Mesospheric Summer Echoes PMSEs are very strong radar echoes produced by electron density fluctuations at half the radar wavelength (Bragg scatter condition) at altitudes above NLC regions (80-90 km). While polar mesospheric echoes have been observed in the absence of neutral air turbulence in some cases (Lubken et al., 1993; 2002), theoretical studies by Hill et al. (1999) and Rapp and Lubken (2003) have shown that coupling of the neutral air turbulence with the dusty plasma is the main deriving source for PMSE and the electron density fluctuations in the mesopause region without including dust particles, the small-scale fluctuations produced through coupling of neutral air turbulence with electron density fluctuations, diffuse out very fast due to high viscosity effect. Schmidt number Sc defines as a ratio of viscosity ν to electron diffusion coefficient D ($Sc = \nu/D$). Schmidt number is unity if dust particles are excluded. In other word, spectrum of electron density fluctuation will have the same cut-off as the neutral air density fluctuations when no dust particle exists. The spectrum of velocity fluctuations in a turbulent medium is scaled with of $k^{-5/3}$ where k is the wavenumber. It has been shown that presence of aerosol particles in the mesosphere can increase the Schmidt number to values much greater than unity and extend the viscous cut-off (Cho et al., 1992; Cho, 1993; Cho et al., 1997). In addition to the role of charged aerosol in reducing the diffusion timescale of electron density fluctuation, charged aerosol may also result in radar scatter. The so-called dressed aerosol scatter may increase radar scatter above the incoherent scatter and is not dependent on radar wavelength. This theory can explain the observed PMSE using UHF radars. Electron density fluctuations observed in recent in-situ measurements using rocket probes have shown a good agreement with the theory of air turbulence coupling with charged species (Rapp and Lubken, 2003; Lie-Svendsen et al., 2003a, b).

Fluctuations in dusty plasma may also be generated by ``Fossil turbulence'' when neutral air turbulence is absent (Cho et al., 1996; Rapp and Lubken, 2004). While velocity field is the driving source for active turbulence, electric field is the generation source for Fossil turbulence and fluctuation in plasma and dust densities. It can be shown that electron and ion density fluctuations produced by Fossil turbulence are out of phase. Spatial scale of Fossil turbulence is typically described by $\omega \ll kc_{ns}$ where c_{ns} is the neutral sound speed.

Polar Mesospheric Winter Echoes PMWEs, counterpart of PMSE in winter season, are observed in a lower altitude range (65-75 km) and have a less intensity. Breaking of gravity waves and the generated turbulence are proposed as the major source for PMWE echoes (Zeller et al., 2006). Most of previous PMWE observations were during enhanced electron density conditions. While some theories can explain the PMWE characteristics only by turbulence, there are rocket and radar observations that show the presence of nanometer scale particles throughout PMWE source region (Brattli et al., 2006). Evanescent ion-acoustic waves generated by partial reflection of infrasonic waves may also have a role in PMWE formation. Considering the active role of small charged dust particles, the proposed theory of infrasonic wave to explain PMWE may be difficult to justify (Lübken et al., 2006).

The objective of this paper is to study the coupling of neutral air turbulence with dusty plasma in the mesosphere as the generation source for PMSE and PMWE. A computational model previously used to study the active modulation of PMSE with high-power radiowaves, is used in this work. The computational model and a theoretical model developed to study neutral air turbulence coupling with dusty plasma in polar mesosphere are described in section 2. The coupling of neutral turbulence at different wavelengths and efficiency of coupling with varying dusty plasma parameters are discussed. Then coupling process in the PMWE source region is studied. Finally, a summary and conclusion is provided.

2. Neutral turbulence-dusty plasma coupling model

2.1. Neutral air turbulence model

Robertson (2007) used the momentum, continuity and Poisson's equations to find the neutral air induced fluctuations in the electric field and the charged particle densities including ions, electrons and charged dust particles. It should be noted that charge imbalance produced through the turbulent fluctuations in air velocity will cause the formation of electric fields. Therefore, coupling of neutral air turbulence with mesospheric dusty plasma may result in fluctuations in electron, ion, and dust densities as well as electric fields. The neutral air turbulence model described here represents the turbulent velocity field as a spectral decomposition in frequency ω and wavenumber k. The driving velocity is represented as a superposition of discrete modes with the mode m wavenumbers denoted by k_m and the corresponding random phase ϕ_m. The driving neutral velocity is therefore given by:

$$V_n(x,t) = \delta v_{nm}\cos(k_m x - \omega_m t + \phi_m) \quad (1)$$

An acoustic wave is assumed with the dispersion relationship $\omega = kc_{ns}$ where the neutral sound speed is $c_{ns} = \sqrt{\gamma_n kT_n/m_n}$ and γ_n in general corresponds to the ratio of specific heat for the s species. Using a linearized continuity equation and small amplitude approximation for neutral fluctuations, the following relation can be derived for fluctuation amplitude of neutral density and velocity field.

$$\delta v_n = c_{ns}\frac{\delta n_n}{n_{n0}} \quad (2)$$

The wavenumber of neutral turbulence k and the ratio of the negative charged dust to plasma density determine the efficiency of coupling of neutral turbulence and dusty plasma (Robertson, 2007). It should be noted that in a ``bite-out" region the electric field amplitude may be enhanced as a result of the enhanced coupling due to reduced electron density. The simplified expression for electron density fluctuations induced by the neutral air fluctuations can be written as follows

$$\frac{\delta n_e}{n_{e0}} = \frac{i\omega v_{en}}{\omega^2 + v_{en}[i\omega - \gamma_e D_e k^2]}\frac{\delta n_n}{n_{n0}} \quad (3)$$

where v_{en} and n_{n0} denote electron-neutral collision frequency and neutral density, respectively, and $D_e = kT/m_e n_e$ is the electron diffusivity. Considering $k^2\lambda_{D,e}^2 \ll 1$, ion, dust and electric field fluctuation amplitudes can be simplified to:

$$\frac{\delta n_i}{n_{i0}} = \frac{\delta n_n}{n_{n0}} \quad (4)$$

$$\frac{\delta n_d}{n_{d0}} = \frac{1}{1 - i\omega/v_{dn}}\frac{\delta n_n}{n_{n0}} \quad (5)$$

$$\delta E = -ik\frac{\gamma_e KT_e}{n_e q_e^2}\left(\frac{n_i q_i + \frac{n_d Z_d q_d}{1 - i\omega/v_{dn}}}{1 + \gamma_e k^2 \lambda_{De}^2}\right)\frac{\delta n_n}{n_{n0}} \quad (6)$$

According to Eq. (6), in case of reduced electron density, the electric field may be enhanced by neutral turbulence due to reduced Debye length shielding ($k/\lambda_{De} \ll 1$).

2.2. Dusty Plasma Model

The effect of dust particles on density fluctuations in PMSE region was first investigated using a computational model by Lie-Svendsen et al. (2003). Their model treats plasma as fluid including arbitrary number of charged, and neutral particle species and dust/aerosol particles are modeled as particle in cell (PIC). Transport due to gravity, multipolar diffusion, and discrete charging model were also used (Lie-Svendsen et al., 2003). This model was used to explain the correlation and anti-correlation between electron and ion density fluctuations in the mesopause region. Scales (2004) developed a similar hybrid model including fluid plasma and particle in cell (PIC) dust with continuous dust charging process to study the effect of electron heating using high power radio-waves on dusty plasma irregularities associated with PMSE. Continuous charging model based on the Orbital-Motion-Limited (OML) approach has been used for the time varying charge on the dust particles. It should be noted that the difference between the continuous charging model and discrete charging model based on statistics is negligible in this circumstance. The summer mesopause temperature for both ions and electrons is taken to be $T_e = T_i = 150$ K. The ion-neutral collision frequency is of order of 10^5 s^{-1}. The electron density is assumed to be 10^9 m^{-3}.

The previous work by Lie-Svendsen et al. (2003) and Scales (2004) were assumed that dust and plasma density fluctuations are present in the PMSE and studied how presence of heavy aerosol particles and radiowave heating may affect these density fluctuations, respectively. This paper will be an extension to include neutral turbulence effect on the generation of dusty-plasma density fluctuations. The coupling of neutral air turbulence with dusty plasma is incorporated through collision between dust and neutral as well as neutral velocity in the plasma momentum equation. Driving velocity for neutral air turbulence also incorporated in the ion/electron momentum equations. A Langevin approach based on the model developed by Winske and Rosenberg (1998) is used for dust-neutral collision process. In this model the velocity vector is randomly scattered every time step and the magnitude is conserved. The dust velocity including dust-neutral collision process in the computational model is as follows:

$$v_{dj}(t+\Delta t) = v_{dj}(t)e^{-v_{dn}\Delta t} + V_n(1 - e^{-v_{dn}\Delta t}) + v_{thd}(1 - e^{-2v_{dn}\Delta t})^{1/2}N_i \quad (7)$$

where N_i is a random number uniformly distributed in [0,1] and v_{dn} and v_{thd} are the dust neutral collision frequency and thermal velocity, respectively. The neutral driving velocity is given by V_n described in Eq. (1). Dispersion relation for acoustic wave $\omega = kc_{ns}$ is considered where c_{ns} is the neutral sound speed. The signature of fluctuations starts to appear in plasma density as well as electric field as the attachment process of free electrons and ions onto the dust particles begins.

$$v_\alpha = \frac{1}{v_{\alpha n}}\left(\frac{q_\alpha}{m_\alpha}E - \frac{KT_\alpha}{m_\alpha}\frac{\partial}{\partial x}(\log n_\alpha)\right) + V_n \quad (8)$$

Here α = e or i, and q_α,m_α,T_α and $v_{\alpha n}$ are the species charge, mass, temperature and collision frequency, respectively, of the plasma species with neutral particles, and V_n denoted the neutral velocity.

3. Dusty plasma irregularities associated with PMSE

A neutral wind of the simple monochromatic form which was described earlier in Eq. (1) is imposed on the dusty plasma. Figure 1 shows the coupling of neutral air turbulence with the dust layer in the summer mesosphere. A dust radius of 10 nm and average charge of one electron on the dust particle are considered. The neutral air density fluctuations have scale-size of the order of 5 m. The figure shows the steady state of electric field, electron, ion and dust densities. The dust density is assumed to be 80 percent of the background plasma density. The enhanced electric field in the vicinity of electron density bite-out reaches 50 mV/m. It is observed that the electric field fluctuations are enhanced inside the electron bite-out region. The electric force on the ions can be neglected and fluctuations in ion density are primarily due to drag force exerted by air turbulence. Based on Robertson's theory, in bite-out condition when electron density approaches 90 percent depletion, electrons are less effective to cancel net charge density of dust particles and ions. In this case electric field is expected to increase as a result of $k^2\lambda_{De}^2 \ll 1$ condition. Therefore, based on the theory of Robertson (2007), the electric field amplitude should be enhanced in the vicinity of electron density depletion due to reduced $k\lambda_{De}$. The neutral wind field also couples into electron, ion, and dust density fluctuations as seen in Figure 1, which is consistent with equations (2)-(5). Robertson (2007) predicts that the maximum electric field fluctuations of the order of 100 mV/m occur in full bite-out condition that is consistent with the numerical simulations shown in Figure 1. The DROPS rocket experiment has provided simultaneous measurement of the charged dust cloud, electron density reduction, and fluctuating electric field structures in the mesopause altitude (Pfaff et al., 2002). The in-situ measurement of electric field fluctuations with amplitude 10 mV/m in PMSE region during DROPS experiment are consistent with the enhanced electric field inside the bite-out region shown in Figure 1 (Pfaff et al., 2001). The electron density fluctuation amplitude is of the order of 1 percent. The signature of coupling in the dust density is not clear and the fluctuation amplitude is about 5 percent of the background density. Radar echoes at 53 MHz, which corresponds to the electron density fluctuations of the order of 3 m, were observed in the vicinity of dust cloud, which is in agreement with the irregularity wavelengths of 5 considered in Figure 1.

Figure 2 presents similar results to Figure 1 for irregularity scale-size 64 cm. All other parameters are similar to those in Figure 1. As can be seen, the coupling of neutral air turbulence and the resulted fluctuations in the electric field are much stronger for smaller irregularity wavelengths. The amplitude of the associated electric field increases to 100 mV/m in both cases. The electron density fluctuation amplitude is enhanced by about 5 percent. Strong signature of coupling with the turbulence appear in the dust density which is about 50-60 percent of background dust density for λ_{irreg} = 64 cm. This is also reminiscent of the experimental data in Figure 10 during the DROPS experiment (Goldberg et al., 2001). According to Eq. (3) and (4), the electron and ion density fluctuations are expected to be correlated for small values of ω, which is consistent with the results shown in Figure 2.

The effect of dust and plasma collision frequency on the coupling of neutral air turbulence with mesospheric dust cloud is shown in Figure 3. According to Eq. (7), the coupling process depends on the dust-neutral collision frequency. When dust-neutral collision is zero, dust velocity will remain unchanged and no coupling happens. Variation of ν_{dn} from 1 kHz to 5×10^5 Hz and the associated fluctuations in the electric field are presented in Figure 3. No coupling occurs for ν_{dn} = 1 kHz and 10^4 Hz and the fluctuation amplitude is zero. As the collision frequency increases to 10^5 Hz, clear fluctuation with maximum amplitude of 25 mV/m as a result of coupling appears in the electric field. The electric field amplitude reaches a maximum amplitude of the order of 80 mV/m for $\nu_{dn} = 5\times10^5$ Hz. Therefore, a minimum $\nu_{dn} \sim 10^5$ Hz is required for the coupling of neutral air turbulence with the dust cloud. According to Eq. (5), dust density fluctuations and the correspondent electric field fluctuations follow the fluctuations in neutral air density for frequencies ω much smaller than ν_{dn}. This is in agreement with simulation results shown in Figure 3c and 3d. For $\omega/\nu_{dn} \gg 1$ which corresponds to Figure 3a, the response time of dust particles are reduced by ν_{dn}/ω.

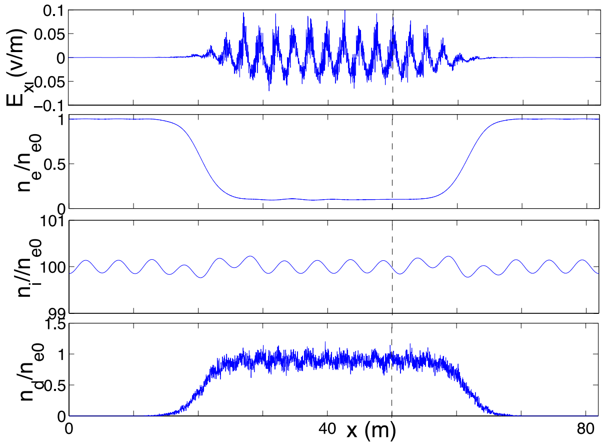

Figure 1. Coupling of neutral turbulence with dust and plasma layers in the polar summer mesosphere for λ_{irreg}= 5m.

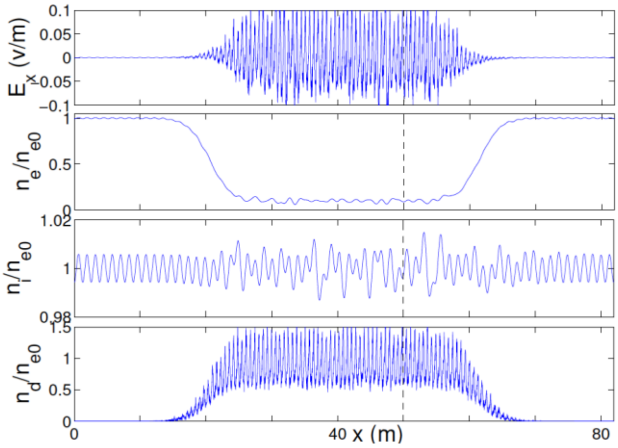

Figure 2. Simulation steady state result of coupling of fluctuating neutral wind field into dusty plasma region in an electron bite-out for λ_{irreg}= 60 cm.

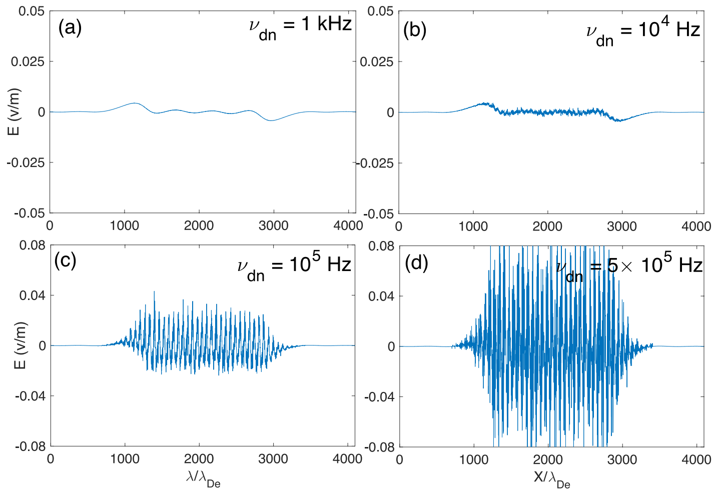

Figure 3. Electric field associated with the effect of dust-neutral collision frequency on the coupling of fluctuating neutral wind field into dusty plasma region.

The other parameter that influences the coupling of neutral air turbulence with the dust layer is the dust density. Figure 4 shows the variation of dust density with background plasma density from 50 percent to 90 percent. According to the simulation results presented in Figure 5, a minimum dust density of about 40 percent is required for the coupling. The electric field amplitude increases from 2 mV/m to 7 mV/m by increasing n_d from 30% to 50%. The coupling becomes stronger as the dust density increases. According to theoretical model of Robertson (2007), for the case of 50 percent dust density and dust radius of 10 nm (50 percent of free electron density will be charged to dust particles) the maximum electric field amplitude will reach 8 mV/m. The computational results for n_d/n_{e0} = 50%, 60% and 70% in Figure 4 shows an electric field amplitude of the order of 10 mV/m, 13 mV/m and 18 mV/m, respectively, which shows a good agreement with the theoretical predictions. Robertson (2007) has shown that due to reduced Debye shielding resulted in the case of higher dust density, electric field amplitude will be larger. The electric field amplitude $|E|$ estimated from the theoretical model for the case of 90 percent of negative charge on the dust particles is about 16 mV/m. The numerical simulations estimate $|E|$ for n_d/n_{e0}= 80% and 90% is about 20 mV/m and 50 mV/m. It should be noted that in the absence of dust particles, the fluctuations in plasma densities will follow the fluctuations in the neutral density. The maximum electric field amplitude reaches 140 mV/m in the case full electron depletion (Full Bite-Out) (Robertson, 2007).

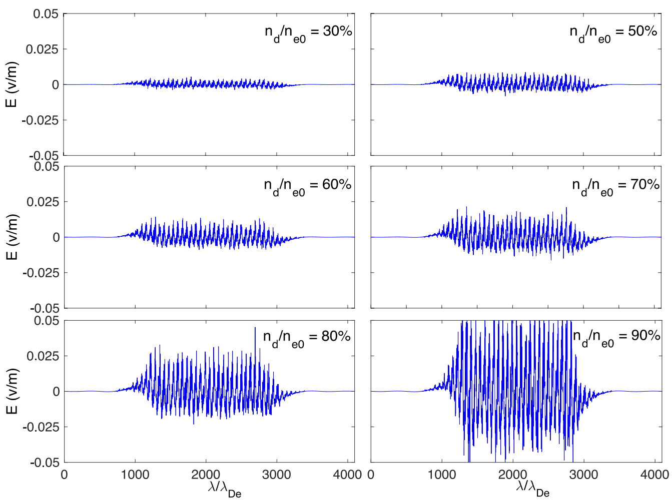

Figure 4. Variation of electric field produced by the coupling of fluctuating neutral wind field into dusty plasma region with dust density.

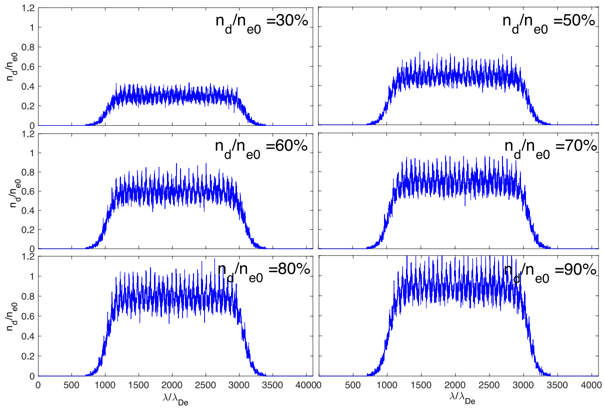

Figure 5. Variation of dust density fluctuations produced by the coupling of fluctuating neutral wind field into dusty plasma region with dust density.

4. Dusty plasma irregularities associated with PMWE

As discussed in section 3, presence of heavy dust particles are critical for generation of irregularity scale sizes from a few meters to a few centimeters in the polar summer mesosphere. According the PMWE observations, electron density fluctuations with small wavelengths in the polar winter mesosphere demand heavy charged dust particles along with high electron density in PMWE. The main focus of this section is to determine the required electron and dust densities to produce electron density fluctuation responsible for PMWE. The mesopause temperature for both ions and electrons is taken to be $T_e = T_i = 250$ K. High atmospheric temperature in winter mesosphere does not allow the formation of ice particles. Therefore, small smoke particles are the main source of dusty plasma in PMWE and influence the plasma and radar echoes (Stebel et al., 2004). The ion-neutral collision frequency is of order of 5×10^5 s^{-1}. Variation of electric field generated in the PMWE source region as a result of neutral air coupling is demonstrated in Figure 6 for electron density variation. The dust density is assumed to be 0.7×10^9 m^{-3} in all cases. According to Figure 6, the electric field fluctuations appear within the dust cloud, which is consistent with the observations that revealed the plasma density fluctuations within PMWE, and no fluctuations outside PMWE (Lubken et al., 2006). Maximum electric field was observed when the dust density equals the background plasma density. The electric field amplitude starts to decrease as the electron density increases. Maximum electric field of 0.2 V/m and minimum electric field of 20 mV/m were observed for $n_e = 0.8\times10^9$ m^{-3} and 1.3×10^9 m^{-3}, respectively. When the background electron density increases, the attachment of electrons on to the dust particles will increase which results in smaller amplitude fluctuations in the electric field. This is mainly due to the reduced fluctuation amplitude in the electron density as a result of enhanced attachment rate of electrons on the dust particles.

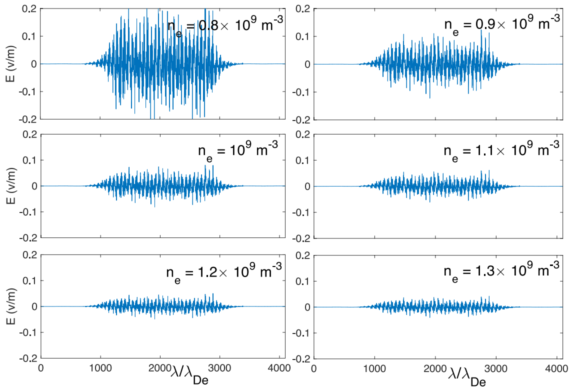

Figure 6. Variation of electric field fluctuations produced by the coupling of fluctuating neutral wind field into dusty plasma region associated with PMWE.

5. Conclusion

Numerical simulations for coupling of neutral air turbulence with the dusty plasma in the mesosphere are presented to study the fluctuations in the electric field, dust and plasma densities. The consistency of fluctuation amplitude of dusty-plasma densities and electric field with the theory of neutral air turbulence developed by Robertson (2007) is discussed. The effect of dust density and dust-neutral collision frequency on the strength of fluctuations in plasma density and electric field as a result of neutral air coupling in the summer polar mesosphere is investigated. It has been shown that a minimum dust density to background plasma density of the order of 30 percent and dust-neutral collision frequency of about 10^5 Hz are required for the coupling to be efficient. The fluctuation amplitude of electric field estimated by computational model shows a good agreement with the theoretical model and in-situ rocket measurements in the vicinity of PMSE source region. Enhancement of electron density fluctuations with smaller wavelengths is observed which that validates the VHF and UHF PMSE observations. Variation of electron density was studied as the main requirement for coupling in the winter polar mesosphere. Maximum fluctuation of amplitude in the PMWE source region is determined when the electron density is equal to the dust density.

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