Whether variations of radon activity in a seismically active region can affect the ionosphere?

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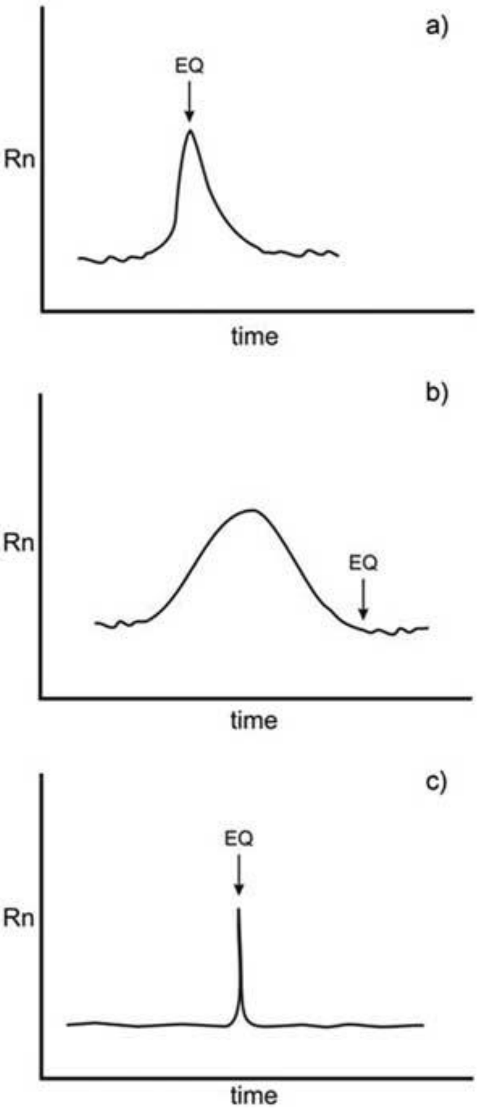
1. Introduction

Much possibilities of global monitoring of virtually entire ionosphere have opened with advent of global navigation satellite system (GNSS), like GPS, GLONASS, etc. The facilities of GNSS provide information on variations of **radiopath-integrated ionospheric parameter - the total electron content (TEC)**. The easy availability of huge amounts of TEC data enabled a burst of studies aimed at search for the ionospheric precursors of earthquakes.

Many of them reported **the evidence of the abnormal GPS/TEC variations observed several days prior to earthquake occurrence** [Calais and Minster, 1995; Ouzounov et al., 2011; Hasbi et al., 2011; Xia et al., 2011; Le et al., 2011, 2013; Chauhan et al., 2012; Heki and Enomoto 2013, 2015; Sonakia et al., 2014; Pundhir et al., 2015; Liu et al., 2015; Sunardi et al., 2018].

Nonetheless, **many researchers still doubt the occurrence of the earthquake precursors in the ionosphere** and consider the claimed effects as controversial [Afraimovich et al., 2004; Rishbeth, 2006; Dautermann et al., 2007; Kamogawa and Kakinami, 2013; Thomas et al., 2017].

It was hypothesized that the abnormal TEC variations in the ionosphere can be related to the enhancement of radon Rn emanation from soil.



Yasuoka et al. (2009) observed a gradual increase in the concentration of atmospheric radon 2 months prior to the earthquake in Kobe (January 17, 1995; M_w=6.9). Just before the earthquake onset, the radon activity was 2 times higher (20 Bq/m^3) than the average level [Virk and Singh, 1994; Giuliani and Fiorani, 2009; Yasuoka et al., 2009].

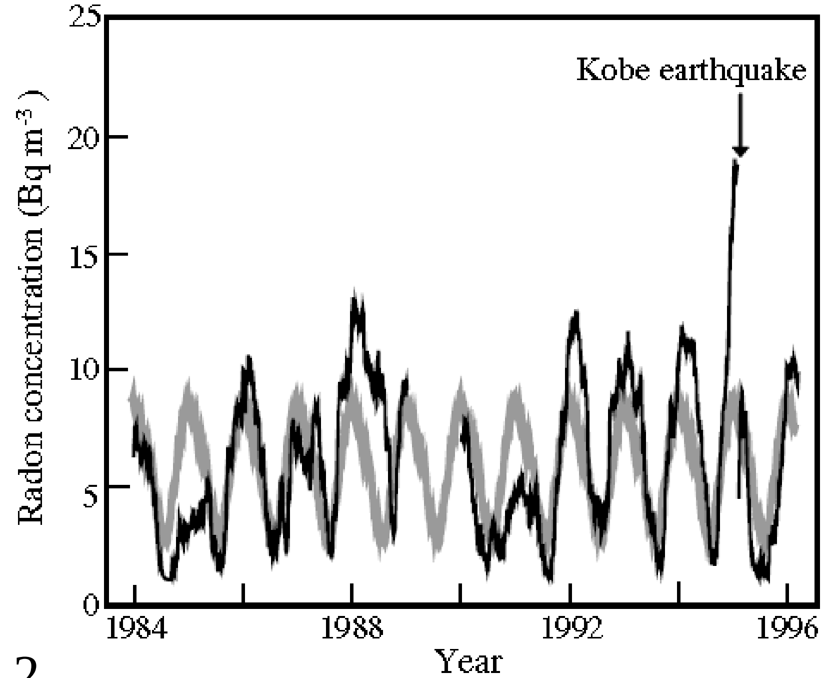


Fig. 2

However, some researchers have not found statistically significant changes in the radon concentration before earthquakes [Geller 1997; Inan et al., 2008; Pitari et al., 2014; Cigolini et al., 2015].

Fig. 1. An example of time variation of Rn data from a continuous soil gas monitoring site prior to (a) nearby earthquakes (<150 km) with 4.0< M< 5.3, (b) close earthquakes (<60 km) with 4.0< M< 5.3, (c) distant earthquakes (> 150 km) with magnitude 4.0-5.3 [Inan et al., 2008].

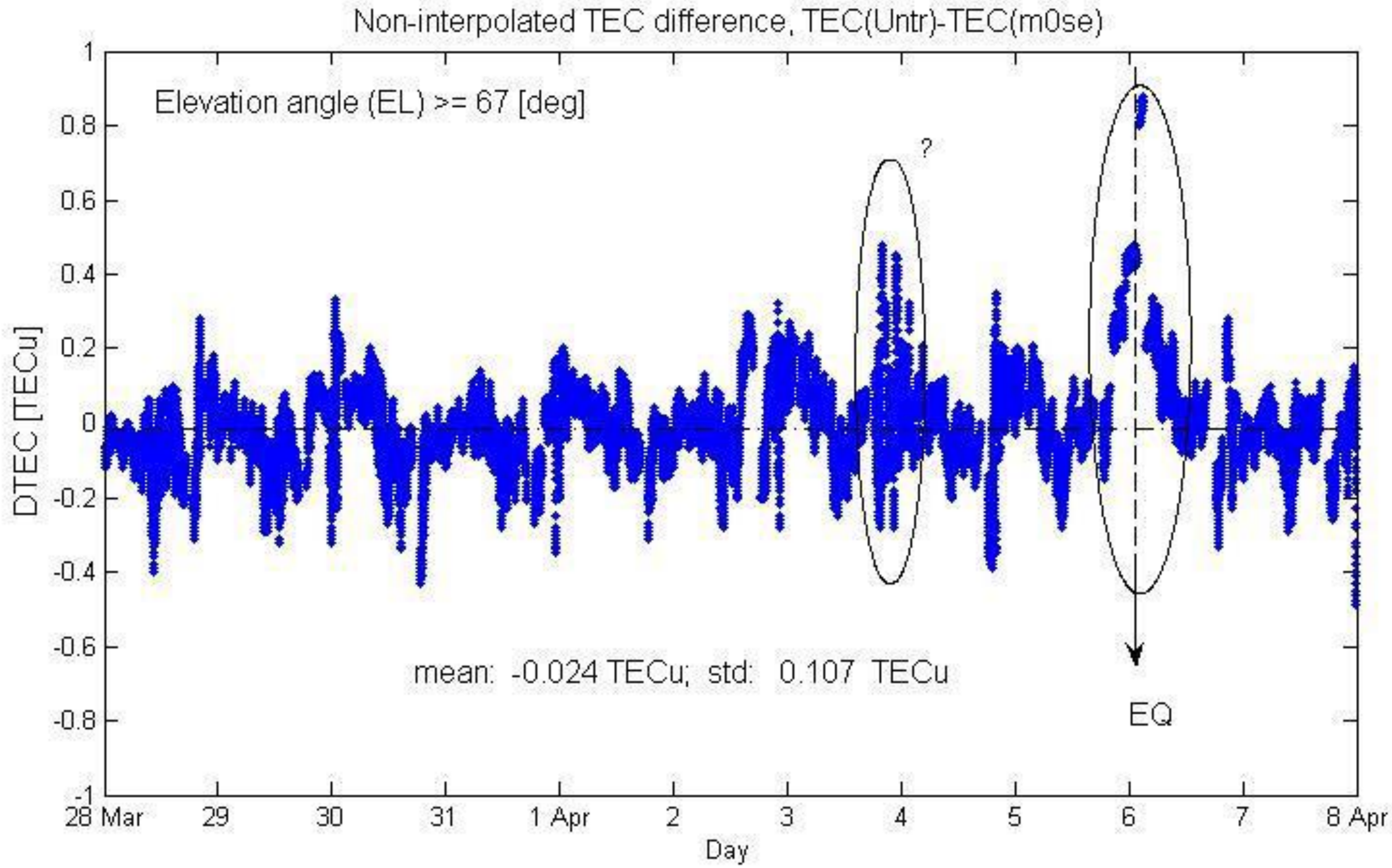


Fig.3. Non-interpolated vertical TEC difference TEC(untr)–TEC(m0se) for 28 March–8 April taken from all satellites crossing GPS stations in Central Italy with elevation angle >67° at two stations. This difference is typically close to 0 (with a mean value of 0.024 TECu).

The only exception is a time interval (of several hours) around the EQ shock moment (marked with an ellipse). In that time interval, the TEC difference reaches amplitude of ~0.8 TECu centered at the EQ shock moment. *Taken from [Nenovski et al., 2015]* .

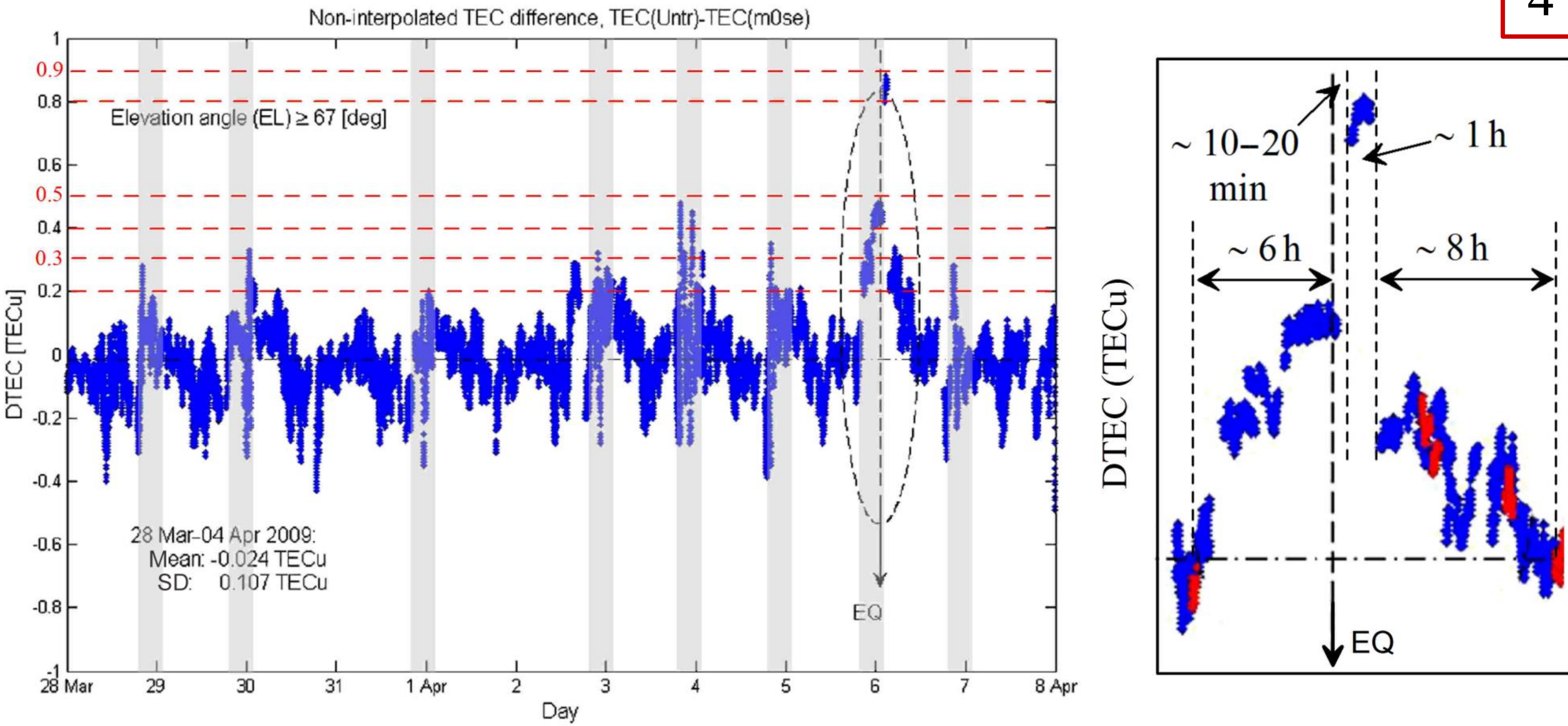
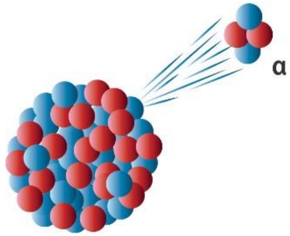


Fig. 4. VTEC difference $DTEC=DTEC_{UNTR} - TEC_{M0SE}$ from all satellites crossing Central Italy with an elevation angle >67° [Nenovski et al. 2015]. DTEC clearly shows a diurnal variation throughout the investigated period.

EQ refers to the 6 April 2009 main shock. The dashed ellipse highlights the hump-like variation in DTEC during 5–6 April 2009 that according to Nenovski et al. (2015), may be related to the earthquake!? The shadowed areas (that we have superimposed onto the original view) highlight DTEC maxima that, as for 5–6 April, occur in the same night period. *from [Masci et al., 2017].*

The nuclei $^{222}_{86}Ra$ are effective sources of air ionization because their half-life is 3.82 days. The decay of one radon nucleus leads to the formation of 10^5 pairs of ions

$$^{222}_{86}Ra \rightarrow ^{218}_{84}Po + ^{4}_{2}He$$



An increase in radon activity before earthquake occurence can cause a decrease in the resistance of the near-surface atmospheric layer by 15% for clean air and by 25% for dusty air [Harrison et al., 2010; Surkov, 2015].

This is the basis for the hypothesis that this effect leads to changes in the background atmospheric current flowing in the global electrical circuit. Modification of this current can lead to variations in the electron density in the ionosphere [Ouzounov et al., 2011; Nenovski et al., 2015].

However, there are no theoretical estimates that could confirm or refuse this hypothesis. **The main purpose of this study is to examine this hypothesis and to study whether the radon effect on the conductivity of the lower atmosphere can produce detectable anomalies in ionospheric parameters.**

2. Model of medium and basic equations

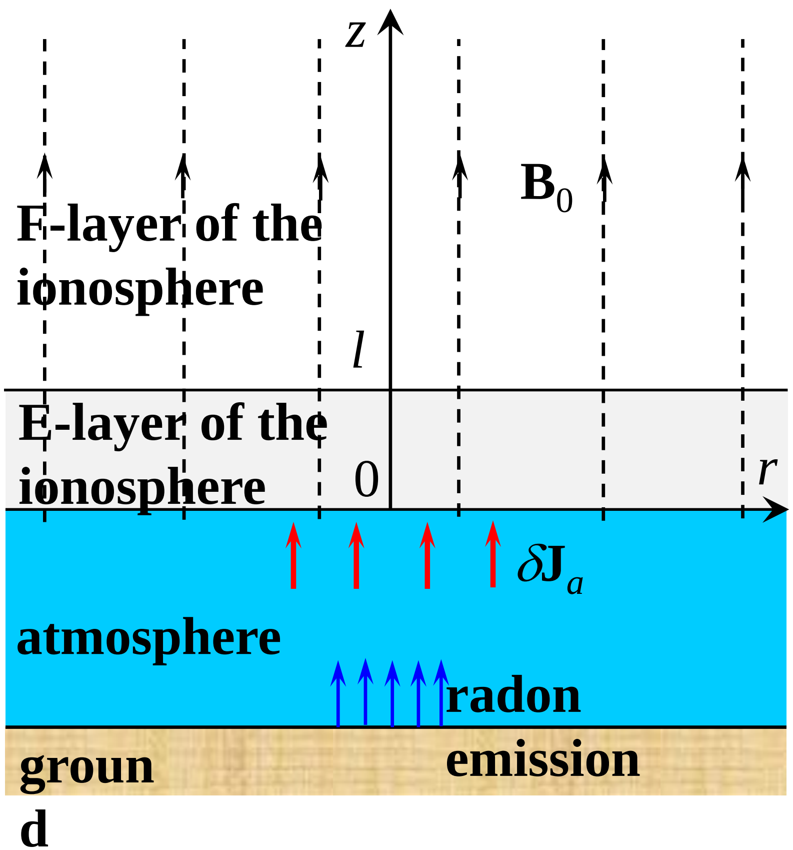


Fig. 5. A plain-stratified model of the ionosphere and magnetosphere

$$J_a = |J_z| = \frac{\varphi_a}{R}, \quad R = \int_0^h \frac{dz}{\sigma_a(z)}, \qquad (1)$$

$$\Rightarrow \quad \frac{\delta J_a}{J_a} = -\frac{\delta R}{R}. \qquad (2)$$

A decrease in the electrical resistance of the vertical air columnm ($\delta R < 0$) results in a corresponding increase in the density of the background atmospheric current.

$$\delta J_a(r,0) = \delta J_{\max} \exp\left(-r^2/r_0^2\right), \qquad (3)$$

where r_0 is the characteristic transverse size of the disturbed region, which has the same order of magnitude as the earthquake focus or the fault width, i.e., of the order of 100 km.

The Ohm's law for the current density $\delta\mathbf{J}$ and electric field $\mathbf{E}$ in the conductive gyrotropic E-layer of the ionosphere

$$\delta\mathbf{J} = \sigma_{\|}\mathbf{E}_{\|} + \sigma_P\mathbf{E}_{\perp} + \sigma_H\left(\mathbf{B}_0 \times \mathbf{E}_{\perp}\right)/B_0\,, \tag{4}$$

where $\sigma_{\|}$ is the field-aligned plasma conductivity, while σ_P and σ_H are Pedersen and Hall conductivities, respectively. Here $\mathbf{E}_{\|}$ and $\mathbf{E}_{\perp}$ denote the components of the electric field that are parallel and perpendicular to the undisturbed geomagnetic field $\mathbf{B}_0$.

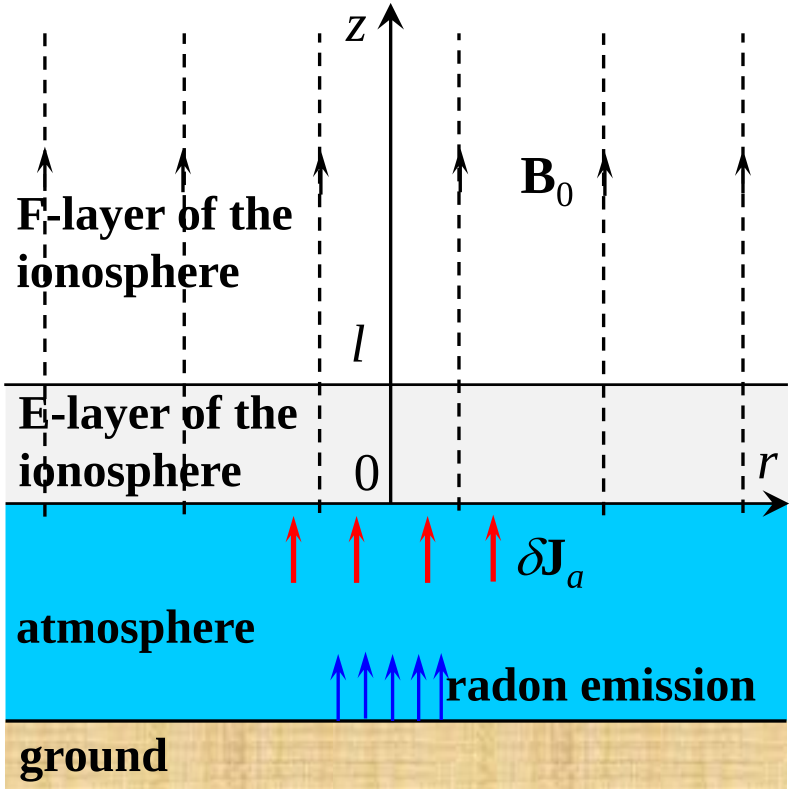
To simplify the problem, the conductivity components of the ionospheric plasma are assumed to be constant within the E-layer of the ionosphere. Using a cylindrical coordinate system, yields $\left(0 < z < l\right)$

$$\delta J_z = \sigma_{\|}E_z, \quad \delta J_r = \sigma_P E_r, \quad \delta J_{\varphi} = \sigma_H E_r. \tag{5}$$

Substituting this equation for $\delta\mathbf{J}$ into continuity equation for the current, gives

$$\nabla\cdot\delta\mathbf{J} = 0 \quad \Rightarrow \quad \sigma_{\|}\frac{\partial E_z}{\partial z} + \sigma_P\frac{1}{r}\frac{\partial}{\partial r}\left(rE_r\right) = 0, \tag{6}$$

$$\nabla\times\mathbf{E} = 0 \quad \Rightarrow \quad \frac{\partial E_r}{\partial z} - \frac{\partial E_z}{\partial r} = 0. \tag{7}$$



The boundary condition for the lower surface of the ionospheric *E*-layer is given by

$$\delta J_z(r,0)=\delta J_a(r,0). \qquad (8)$$

In order to estimate the maximum effect in the E-layer, we will first neglect the current flowing into the F-layer, thereby assuming that at the upper boundary of the E-layer:

$$\delta J_z(r,l)=0. \qquad (9)$$

The exact solution of this boundary problem is given by $(0<z<l)$

$$E_r=\frac{\delta J_{\max} r_0^2}{2\sigma_{\parallel}}\int_0^{\infty}\frac{\cosh\{\lambda(l-z)\}}{\lambda\sinh(\lambda l)}\exp\left(-\frac{kr_0^2}{4}\right)\mathrm{J}_1(kr)k^2dk, \qquad (10)$$

where $\lambda=k(\sigma_P/\sigma_{\parallel})^{1/2}$ while $\mathrm{J}_1(kr)$ denotes the Bessel function of the first kind of the first order.

3. Estimate of electric field and variation of electron density in the ionosphere

$$E_r = \frac{\delta J_{\max} r_0^2}{2\sigma_{\|}} \int_0^{\infty} \frac{\cosh\{\lambda(l-z)\}}{\lambda \sinh(\lambda l)} \exp\left(-\frac{k r_0^2}{4}\right) J_1(kr) k^2 dk. \qquad (10)$$

The integral sum in the above solution accumulates mainly within interval $0 \le k < k_0 = 2/r_0$ since at $k \gg k_0$ the integrand decreases rapidly due to the exponentially decreasing factor $\exp(-k^2 r_0^2/4)$. Choosing, for example, the numerical values the parameters: $r_0 = 100$ km, $l = 30$ km, $\sigma_{\|} = 0.1$ S/m, $\sigma_P = 10^{-4}$ S/m, (daytime conditions), we obtain that $\lambda l < k_0 l (\sigma_P/\sigma_{\|})^{1/2} \approx 0.02$.

After these simplifications we arrive at

$$E_r \approx \frac{\delta J_{\max} r_0^2}{2r\sigma_P l}\left\{1 - \exp\left(-\frac{r^2}{r_0^2}\right)\right\}, \quad E_z \approx \frac{\delta J_{\max}}{\sigma_{\|}}\left(1 - \frac{z}{l}\right)\exp\left(-\frac{r^2}{r_0^2}\right). \qquad (11)$$

Whence it follows that $E_r \gg E_z$ since formally $\sigma_{\|} \to \infty$.

The variation of the electron number n_e density in the ionosphere is described by equation

$$\frac{\partial n_e}{\partial t} = \gamma_c - \alpha n_e n_+ - \nu_a n_e + e^{-1}\nabla \cdot \mathbf{j}_e + \nabla \cdot \left(D_e \nabla n_e \right), \tag{12}$$

where γ_c is a number of electron-positive ion pairs produced per unit volume and per unit time under the influence of shortwave radiation and cosmic rays; $\alpha(z)$ is the coefficient of electron-ion recombination; n_+ is the number density of positive ions; ν_a is the attachment rate of electrons to neutrals; $\mathbf{j}_e$ is the electron current density; and D_e is coefficient of electron diffusion. All the functions depends on altitude *z*.

In what follows we assume that the electron attachment and diffusion can be neglected as compared to electron-ion recombination whence it follows that $n_+ \approx n_e$.

As before, we consider the stationary case. Making variation of the functions entered into the above equation we come to

$$\delta n_e \approx \frac{1}{2\alpha n_e e} \nabla \cdot \delta \mathbf{j}_e. \tag{13}$$

The components of the vector $\delta \mathbf{j}_e$ can be found from the equations: $\delta j_{ez} = \sigma_{e\|} E_z$ and $\delta j_{er} = \sigma_{eP} E_r$, where $\sigma_{e\|}$ and σ_{eP} denote the field-aligned and Pedersen plasma conductivities caused by the motion of electrons only.

The electron current density $\delta \mathbf{j}_e$ is derivable through the electric field (11). Then substituting $\delta \mathbf{j}_e$ into equation (13), and taking into account that $\sigma_{e\|} \gg \sigma_{i\|}$ and $\sigma_{\|} \approx \sigma_{e\|}$ we obtain

$$\frac{\delta n_e}{n_e} \approx \frac{\delta J_{\max} \sigma_{iP}}{2\alpha e n_e^2 l \sigma_P} \exp\left(-\frac{r^2}{r_0^2}\right) \tag{14}$$

For numerical estimates, we use the typical parameter of the E-layer of the ionosphere for the nighttime conditions: $\alpha = 10^{-13}\,\mathrm{m}^3/\mathrm{s}$, $n_e = 3.1 \cdot 10^9\,\mathrm{m}^{-3}$, $\sigma_{iP} = 3.3 \cdot 10^{-7}$ S/m, $\sigma_P = 5.8 \cdot 10^{-7}$ S/m, $l = 20$ km, $\delta J_{\max} = 10^{-12}$ A/m^2 [Ivanov-Kholodny, 1990].

Final estimate for the E-layer of the ionosphere $\left(\delta n_e / n_e\right)_{\max} \approx 6 \cdot 10^{-5}$

In the F region of the ionosphere $\sigma_{\|} \gg \sigma_P$ and $j_z \gg j_r$. So we use a rough estimate $\nabla \cdot \delta \mathbf{j}_e \approx \delta J_{\max} / L$, where $L \approx 300 - 500$ km. Using typical parameters of F-layer $\alpha = 10^{-16} - 3 \cdot 10^{-14}\,\mathrm{m}^3/\mathrm{s}$, $n_e = 10^{10} - 10^{11}\,\mathrm{m}^{-3}$ (nighttime conditions), we finally obtain

Final estimate for the F-layer of the ionosphere $\left(\delta n_e / n_e\right)_{\max} \approx 2 \cdot 10^{-8} - 10^{-3}$

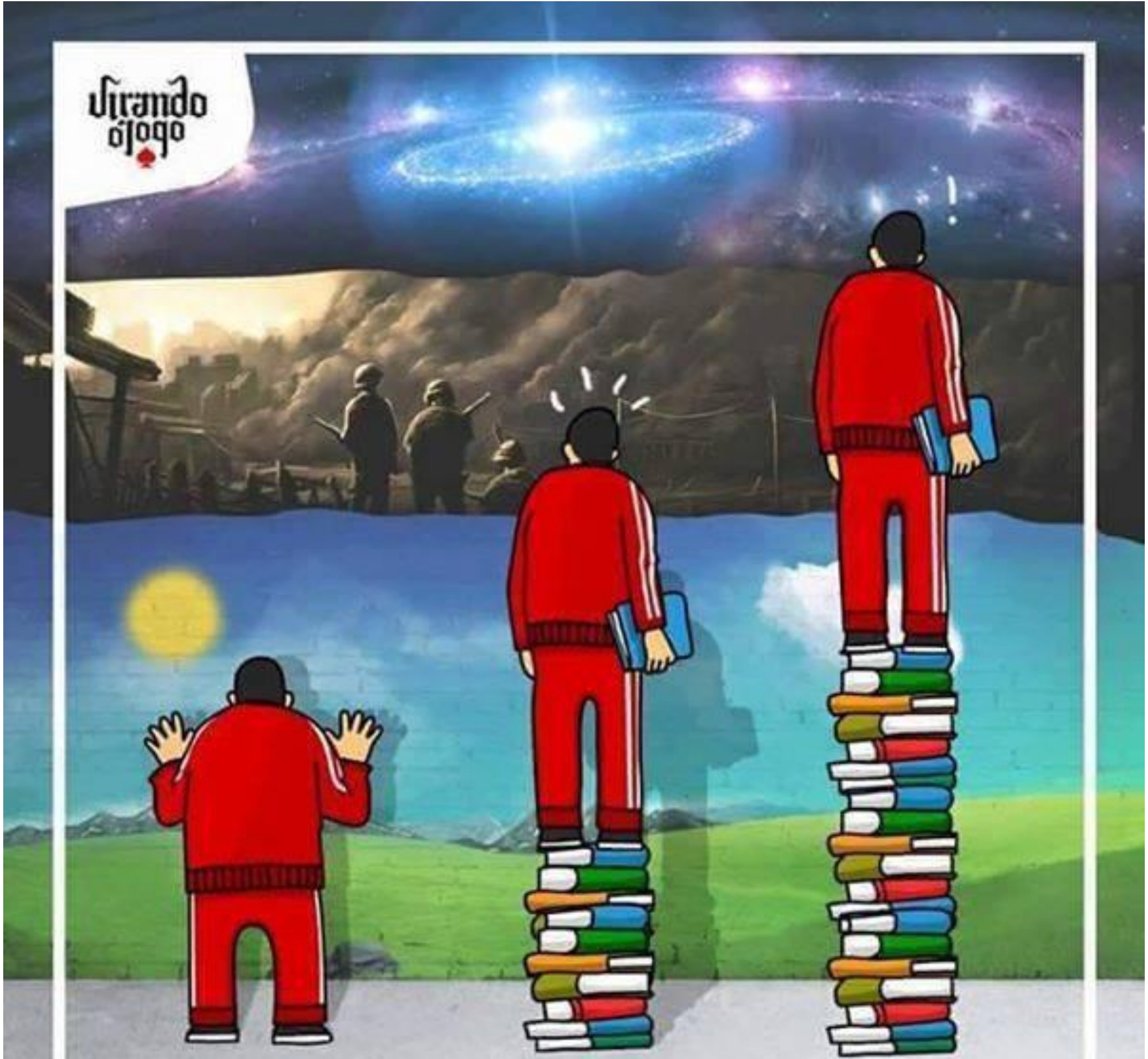
4. Conclusions

(1) We have examined the hypothesis that abnormal variations in radon emission possibly related to earthquake occurrence can result in detectable changes in ionospheric parameters.

(2) It follows from the estimates that the TEC variations due to “radon effect” is 3 – 5 orders of magnitude smaller than the diurnal TEC oscillations.

(3) **Our analysis has demonstrated that the local variations of the background atmospheric current due to the radon emission variations have almost no effect on the variations in electron density and TEC in the ionosphere.**

(4) It seems likely that the change in the electrical conductivity of the lower atmosphere is the only "radon effect“, which can be supported by a theory.



Thank you for attention!