INTERNATIONAL JOURNAL OF GEOMAGNETISM AND AERONOMY
VOL. 6, GI2007, doi:10.1029/2005GI000094, 2006

On the electrical coupling between the troposphere and the mesosphere

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Received 11 January 2005; revised 9 August 2005; accepted 11 October 2005; published 28 February 2006.

[1] A new electrodynamic mechanism for coupling the electrically active mesosphere to the troposphere during disturbed conditions is discussed. It is based on the existence of large V/m mesospheric electric fields that violate local thermodynamic equilibrium in the lower D region. We have suggested a simple electric circuit for troposphere-mesosphere coupling. An order of magnitude increase in the tropospheric conductivity, which has been observed over both seismically active regions and nuclear power plant accidents, acts to redistribute the circuit currents by increasing the tropospheric current, thereby decreasing the current flowing through the mesospheric resistance. This reduces the large electric fields and consequently the electron temperature and effective collision frequency. The net effect is electron cooling in the D region. The resulting variations in the ionospheric conductivities can be remotely sensed with instruments employing radio wave techniques, and they have already been detected in a few experiments. *INDEX TERMS:* 2411 Ionosphere: Electric fields; 2427 Ionosphere: Ionosphere/atmosphere interactions; 2435 Ionosphere: Ionospheric disturbances; *KEYWORDS:* Troposphere–mesosphere coupling; Mesospheric electric fields.

Citation: Martynenko, S. I., and S. F. Clifford (2006), On the electrical coupling between the troposphere and the mesosphere, *Int. J. Geomagn. Aeron., 6,* GI2007, doi:10.1029/2005GI000094.

1. Introduction

[2] The studies in both the local and global atmospheric electric circuit arena are an important area of research in atmospheric electrodynamics because the processes acting in the atmosphere are most likely related not only to the variations in the atmospheric conductivity but also to the changes occurring both in the troposphere and in space weather [e.g., *Rycroft et al.,* 2000]. An increased interest in electrical processes in the middle atmosphere has resulted from recent advances in the study of the nature and sources of middle-atmospheric discharges occurring in the upward branch of the global circuit above thunderstorms [e.g., *Rodger*, 1999] and in the newly discovered effects of atmospheric electricity on the lower ionosphere [e.g., *Inan et al.*, 1996; *Rodger et al.,* 2001]. Unlike the traditional ideas concerning the mesosphere described by, e.g., *Bering et al.* [1998], it may not be treated as a passive element in the atmospheric electric circuit even under conditions of fair weather, since the inherent current sources [e.g., *Aikin and Maynard*, 1990; *Curtis*, 1987; *Polyakov et al.*, 1990; *Zadorozhny and Tyutin*, 1998] may generate large DC electric fields in the 50- to 70-km region [e.g., *Goldberg*, 1984, 1989, 1990; *Zadorozhny and Tyutin,* 1998]. These fields were observed via a few tens of in situ rocket measurements at various sites [*Bragin et al.*, 1974; *Croskey et al.*, 1985, 1990; *Hale*, 1984; *Hale and Croskey,* 1979; *Hale et al.*, 1981; *Kelley et al.*, 1983; *Maynard et al.*, 1981, 1984; *Tyutin,* 1976; *Zadorozhny and Tyutin,* 1998] (see, e.g., Figure 1) and remotely via a few hundreds of MF radar measurements [*Gokov and Martynenko*, 1997; *Martynenko et al.*, 1999, 2001; *Meek et al.*, 2004] (see, e.g., Figures 2 and 3). The mesospheric generator sources in the 50- to 70-km region are deduced to be current sources [*Martynenko et al.*, 2001].

[3] Usually, the large DC mesospheric electric fields affect the electron temperature, T_e, and effective collision frequency, ν_e, in the ionospheric D region [*Martynenko*, 1999a, 1999b; *Martynenko et al.*, 2001]; that is, they maintain elevated electron temperatures. This state may change due to

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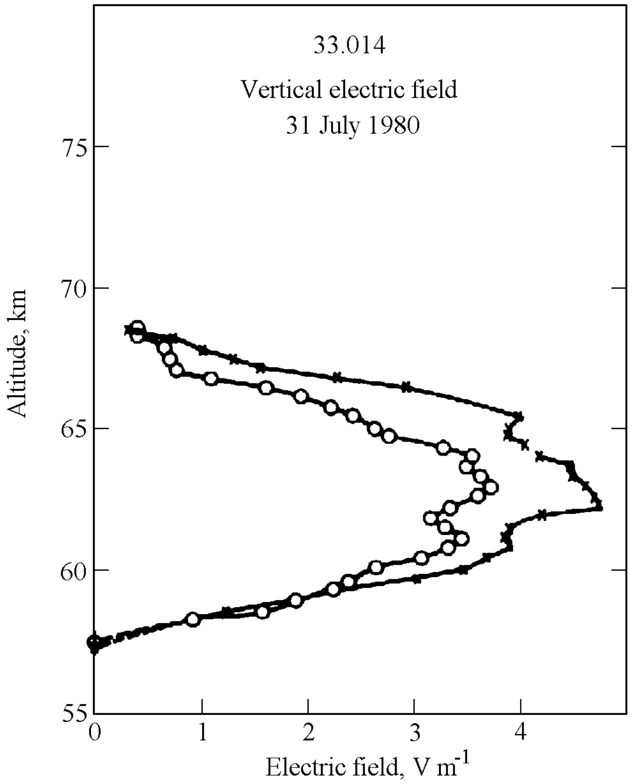

Figure 1. Vertical electric field profiles from rocket-borne symmetric double probes at Wallops Island, Virginia, on 31 July 1980. The two profiles represent x and y axis sensors, which were prepared with different coatings [from *Maynard et al.*, 1981].

the electrical coupling between the troposphere and the electrically active mesosphere. Thus the tropospheric conductivity may undergo a dramatic increase during nuclear power plant accidents with the discharge of radioactive materials [*Fuks and Shubova*, 1994; *Fuks et al.,* 1997; *Martynenko et al.*, 1994, 1996] or prior to, during, and after earthquakes, when experiments show additional ion production rates attaining $\sim 7.6 \times 10^3$ cm^{-3} s^{-1} [e.g., *Pulinets et al.*, 1998]. The purpose of this paper is to present a simplified model of a localized electrical coupling between the troposphere, the electrically active mesosphere, and the ionosphere. The model permits the description of the effects of large disturbances in the tropospheric conductivity on the parameters of the ionospheric D region.

2. Ionospheric *D*-Region Disturbances Under Quiet Conditions

[4] In the absence of external tropospheric disturbances, i.e., under quiet conditions in a plane stratified medium, the basic functional relations between the ionospheric parameters and the parameters of large mesospheric electric fields are given by [*Martynenko*, 1999a, 1999b; *Martynenko et al.*, 2001]

$$\frac{\partial N}{\partial t} = q_i - \beta N + \gamma\lambda N - \alpha_r(1+\lambda)N^2 + \frac{\partial}{\partial z}\left[(D_t + D_\alpha)\frac{\partial N}{\partial z}\right] \tag{1}$$

$$\frac{\partial N^-}{\partial t} = \beta N - \gamma\lambda N - \alpha_i\lambda(1+\lambda)N^2 + \frac{\partial}{\partial z}\left[(D_t + D_\alpha)\frac{\partial N^-}{\partial z}\right] \tag{2}$$

$$\frac{\partial T_e}{\partial t} = \frac{2Q_e}{3kN} - \delta\nu_e(T_e - T_n) = 0 \tag{3}$$

$$j_e = \sigma_e(E)E \tag{4}$$

where q_i is the ion production rate, β is the effective electron attachment rate, γ is the effective electron detachment rate, $\lambda = N^-/N$, N is the electron number density, N^- is the negative ion number density, α_r is the effective coefficient of electron-ion recombination, α_i is the effective coefficient

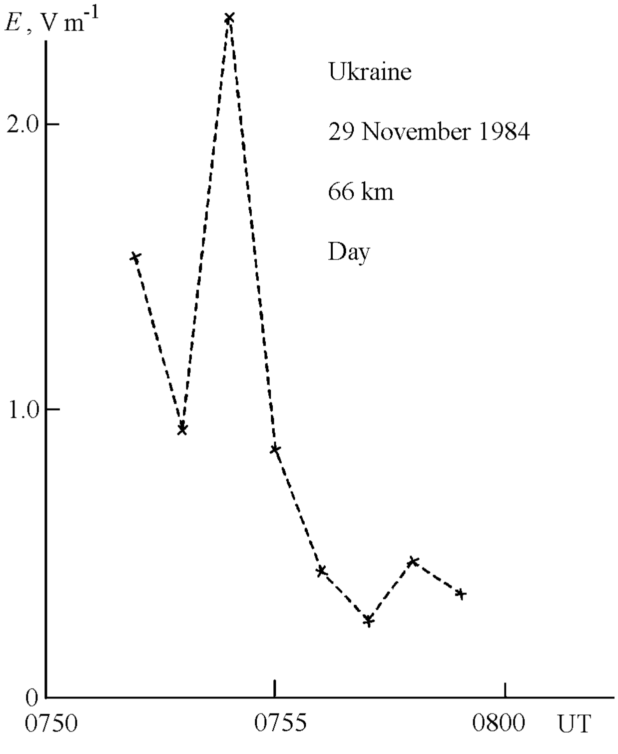

Figure 2. Universal time dependence of large mesospheric electric field intensity obtained at Kharkov National University near Kharkov city. Reprinted from [*Meek et al.*, 2004] with permission from Elsevier.

of ion-ion recombination, D_t is the coefficient of eddy diffusion, D_a is the coefficient of ambipolar diffusion, Q_e/N is the mean energy imparted to an electron by the mesospheric DC electric fields, T_n is the neutral species temperature, δ is the fractional loss of energy per electron collision with a molecule, j_e is the density of the current driven by a mesospheric current source, σ_e is the electron conductivity of the ionospheric D-region plasma, and E is the intensity of the quasi-steady mesospheric electric field. Here, equations (1) and (2) are the nonlinear continuity equations for the electrons and negative ions, respectively, (3) is the nonlinear energy equation for the electrons, and (4) is the nonlinear Ohm's law for the large mesospheric electric field. In writing equations (1)–(3), the weakly ionized, ionospheric plasma is assumed to be quasi-neutral, and the positive and negative ion temperatures to be equal to the neutral constituent temperature. In the D region, $Q_e = j_e E = \sigma_e E^2$. In addition, the following dependences are taken into account [e.g., *Gurevich*, 1978; *Tomko et al.*, 1980]:

$$\sigma_e = K_\sigma(0)\frac{e^2 N}{m\nu_e} \tag{5}$$

$$\nu_e = 5.8 \times 10^{-11} N_n T_e^{5/6} \tag{6}$$

,

$$\delta = \delta_0(T_n/T_e) \text{ for } T_e/T_n < 4$$

$$\delta = 0.2\delta_0 \quad \text{for} \quad 4 < T_e/T_n < 15 \tag{7}$$

$$\beta = (1.4 \times 10^{-29}(300/T_e)\exp(100/T_n)\times$$

$$\exp(-700/T_e)N(\mathrm{O_2}) + 1.0 \times 10^{-31}N(\mathrm{N_2}))N(\mathrm{O_2}) \tag{8}$$

$$\alpha_r \approx 6.0 \times 10^{-6}\left(\frac{300}{T_n}\right)^{1/2}\left(\frac{T_n}{T_e}\right)^{1/2} \tag{9}$$

where $K_\sigma(0) = 1.42$ [*Gurevich*, 1978], e is the electron charge, m is the electron mass, N_n is the number density of neutral particles, $N(\mathrm{O_2})$ is the number density of molecular oxygen in cm^{-3}, $N(\mathrm{N_2})$ is the number density of molecular nitrogen in cm^{-3}, T_e and T_n are in K, v_a in s^{-1}, α_r in cm^3 s^{-1}, subscript "0" is used to denote the magnitude of the plasma parameters in the absence of large mesospheric electric fields.

[5] *Martynenko* [1999a, 1999b] and *Meek et al.* [2004] have shown that the diffusion processes may be neglected in treating the evolution of the disturbed ionospheric D region parameters over spatial scales of more than 150 m and temporal scales less than a few tens of minutes. Then the relation between the disturbing electric field intensity $E(z)$ and the disturbed ν_e and δ values in the lower part of the D region is given by [*Martynenko,* 1999a, 1999b; *Martynenko et al.*, 2001]

$$E^2 = \frac{kmT_{e0}(z)}{0.97e^2}\delta(z)\nu_e^2(z)\left[\left(\frac{\nu_e(z)}{\nu_{e0}(z)}\right)^{6/5} - 1\right] \tag{10}$$

where k is Boltzmann's constant and $T_{e0}(z)$ and $v_{e0}(z)$ are related by (6). Relation (10) is a quasi-stationary solution to the set of nonlinear equations (3)–(5) closed by the electron heat flow (Joule heating) equation $Q_e = \sigma_e E^2$. It describes, along with the collision term (6) and (7), the dependence $\nu_e(E)$ implicitly. The disturbed value of $N(z)$ is given by

$$N(z) = q_i^{1/2}(z)[(1+\lambda(\theta))(\alpha_r(\theta) + \lambda(\theta)\alpha_i(z))]^{-1/2} \tag{11}$$

where $\theta = T_e/T_{e0}$.

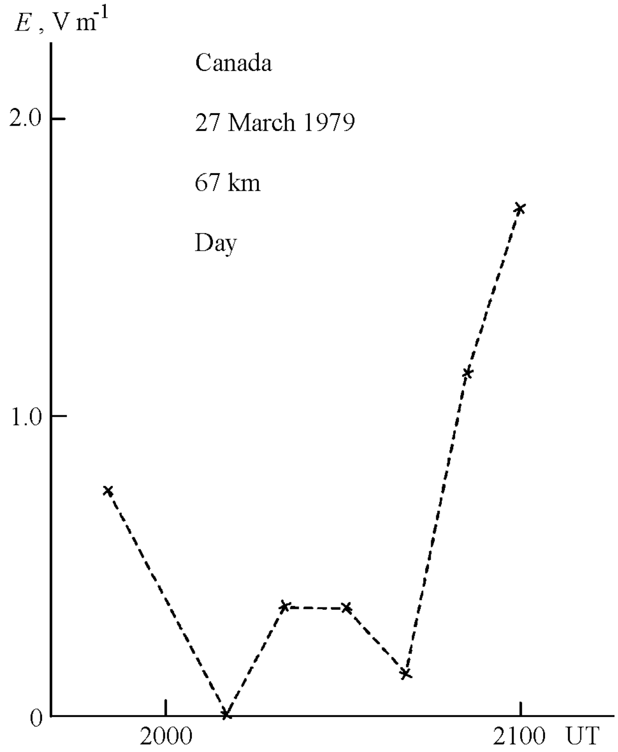

Figure 3. Universal time dependence of large mesospheric electric field intensity obtained at ISAS, Saskatoon Reprinted from [*Meek et al.*, 2004] with permission from Elsevier.

[6] Hence the set of theoretical relations (1)–(11) provides the framework for modeling studies of how large mesospheric electric fields affect the ionospheric D-region parameters. The disturbances in the electron temperature and effective collision frequency (see equations (6) and (10)) are the primary cause of disturbances in other parameters. Equation (4) relates large mesospheric electric fields and the low-frequency conductivity of electron plasma. Equation (6) provides the relationship between disturbances in the electron temperature and the effective collision frequency. Equation (7) establishes disturbances in the fractional loss of energy per electron collision with a heavy particle. Equation (8) is used to calculate the effective rate at which the negative ions are formed by attachment of electrons to neutral constituents. Equation (9) shows disturbances in the effective rate of electron-ion recombination. Equation (11) defines explicitly, the disturbances in the electron number density. The quantity θ characterizes the degree to which the iono-

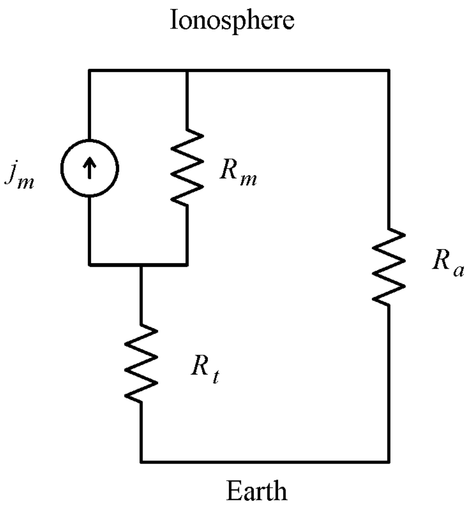

Figure 4. A simplified equivalent circuit for tropospheric mesospheric electrical coupling with R_m the localized mesospheric electric current load resistor, R_t the resistor representing the local troposphere and stratosphere, and R_a the global fair weather load resistor external to the circuit. The current source generates a constant direct current j_m.

spheric plasma departs from local thermodynamic equilibrium, with $\theta = 1$ being for the ionosphere in local thermodynamic equilibrium in the absence of large mesospheric electric fields. The relative disturbance $\eta = \nu_e/\nu_0$ is related to θ by the relation $\eta = \theta^{5/6}$ (see (6)). Estimates show that $\theta = 1.8$ for the most probable value of $E = 0.57$ V m^{-1} at midlatitudes [*Martynenko*, 2002; *Meek et al.,* 2004], with a disturbance of N of a few percent (see (11)).

[7] Thus the electrically active mesosphere is the cause of the observed violation of local thermodynamic equilibrium in the lower part of the D region, $z < 70$ km, with the electron temperature enhanced above the neutral temperature. The MF radar observations of *Meek et al.* [2004] have revealed elevated electron temperatures in approximately 70–75% of the cases when the MF radar echoes occur from the 60–67 km altitude.

3. A Simplified Tropospheric Mesospheric Local Electric Circuit

[8] The proposed simplified circuit for tropospheric mesospheric electrical coupling, which includes the electric current generator source inherent to the mesosphere, is presented in Figure 4. The localized or large-scale mesospheric local emf source delivers an electric current density of $j_m = 10^{-9} - 10^{-8}$ A m^{-2} that perturbs T_e and ν_e [*Martynenko et al.*, 2001]. The resistor R_t represents the localized troposphere and the stratosphere, and R_m designates the localized mesospheric electric current load resistor. The global fair weather load resistor R_a, external to the circuit, has resistance of approximately 200 Ω [e.g., *Bering et al.*, 1998]. Under undisturbed atmospheric conditions in the absence of local thunderstorm activity, the density of the return electric current through the fair weather atmosphere, j_a, has the value $j_a \approx 10 - 12$ A m^{-2} [e.g., *Bering et al.*, 1998; *Rycroft et al.*, 2000], and therefore the j_a may be neglected compared to j_m. Also, for an undisturbed troposphere, $R_t \gg R_m \gg R_a$ and the total mesospheric source load resistance $R_i = R_m R_t/(R_m + R_t) \approx R_m$, i.e., the electrical troposphere-mesosphere coupling does not occur, and the j_m violates local thermodynamic equilibrium in the lower part of the ionospheric D region with enhanced electron temperatures.

4. Effect of Ionospheric *D*-Region Cooling

[9] During disturbed conditions, the resistance R_t could decrease by an order of magnitude or more due to, e.g., an increase in the level of radiation at ground level in the vicinity of strong earthquakes or during accidents at nuclear power plants with the discharge of radioactive materials [e.g., *Fuks and Shubova*, 1994; *Fuks et al.*, 1997; *Martynenko et al.*, 1994, 1996]. Consequently, the ratio between R_t and R_m varies, and this leads to a lowering of R_i. If a decreased R_t value satisfies the inequality $R_t \ll R_m$, then $R_i \approx R_t$ (see Figure 4). Then the potential difference, U, across the mesosphere and the large mesospheric electric field intensity, E, become dependent on R_t. A decrease in R_i and R_t results in a decrease in E and consequently in T_e and ν_e down to unperturbed values at $\theta = 1$. Hence a large increase in the tropospheric conductivity may result in local thermodynamic equilibrium in the ionospheric plasma, and in electron cooling in the lower part of the ionospheric D region. This effect of electron cooling is due to electrical coupling between the troposphere and the electrically active mesosphere (see Figure 4). The values of the cooling rates follow a decrease in R_t and lie in the ~0.1- to 1-ms range [e.g., *Martynenko*, 1999a, 1999b]. These changes are accompanied by a rise in the high-frequency conductivity and by a reduction in the low-frequency (down to DC) conductivity.

5. Conclusions and Discussion

[10] The newly defined mechanism for electrical coupling between the troposphere and the electrically active mesosphere, which reveals the effect of electron cooling in the ionospheric D region, consists of the following.

[11] 1. Large mesospheric electric fields, which have a probability of occurrence of 0.7–0.75, ensure that the ionospheric D region departs from local thermodynamic equilibrium with enhanced electron temperatures. However, this state may be modified by large disturbances in the tropospheric conductivity when coupling between the troposphere and the lower ionosphere develop.

[12] 2. A significant increase in the tropospheric conductivity, by 1 or 2 orders of magnitude, as over seismically active regions or at nuclear power plants with the discharge of

radioactive materials, results in grounding the mesospheric current source and in a significant decrease in the intensity of large mesospheric electric fields. This process may be accompanied by a large-scale redistribution of the inherent mesospheric electric potentials.

[13] 3. The reduction in large mesospheric electric fields leads to a decrease in the electron temperature and effective collision frequency with a characteristic time constant of less than 1 ms. The corresponding variations in the high- and low-frequency (down to DC) conductivity of the lower ionosphere are remotely detected by sensing instruments employing radio wave techniques.

[14] Our observations show that the large mesospheric electric fields are absent during 25–30% of the entire measurement interval, and therefore the ionospheric D region is in the state of local thermodynamic equilibrium. Consequently, the troposphere–mesosphere electrical coupling, which is discussed in this paper, does not occur during these time intervals.

[15] *Fuks and Shubova* [1994], *Martynenko et al.* [1994, 1996], and *Fuks et al.* [1997] observed the localized disturbances of this kind in the VLF perturbations. The perturbations were caused by rapid VLF conductivity enhancements resulting from the electron cooling in the lower ionospheric *D* region over seismically active regions and nuclear power plant accidents with radioactive fallout.

[16] The model of electrical coupling between the troposphere and the mesosphere proposed in this study is in agreement with earlier measurements. Prior to and during the 17 January 1995 Kobe earthquake with 7.2 magnitude, *Maeda and Tokimasa* [1996] observed two sequences of 22 MHz radio bursts at a distance of 77 km from the epicenter. They may be explained by two sequences of reductions in the ionospheric *D*-region HF conductivity, and hence in the HF absorption due to the decreases in electron collision frequencies.

[17] *Warwick et al.* [1982] were the first to report radio wave disturbances associated with seismic activity. The large-scale ionospheric disturbances caused by strong seismic activity persisted for a few days prior to and during the 22 May 1960 Chile earthquake with magnitude 9.6. The measurements were taken using a net of 18 MHz riometers in North America and spaced by thousands kilometers from each other. The increases in the signal amplitude by a factor of up to 2 over a background noise were observed to correlate with the seismic disturbances. *Warwick et al.* [1982] and *Maeda and Tokimasa* [1996] interpreted the HF bursts to be generated in the seismically active region, which is difficult to reconcile with the current descriptions of seismic activity. We propose that the enhancements in HF signal amplitudes may be due to the effect of electron cooling that could cause a large-scale reduction in the HF total absorption in the ionospheric *D* region.

[18] We believe that the proposed mechanism for troposphere–mesosphere coupling through large mesospheric electric fields could provide the basis for developing coupled troposphere–mesosphere–ionosphere electrodynamic models under disturbed conditions. The results would be of use for developing new techniques for monitoring the near-Earth environment and remotely sensing disturbances from various physical origins.

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