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The effect of lightning-induced electromagnetic waves on the electron temperatures in the lower ionosphere

Ramazan Atıcı[1,*], Esat Güzel[2], Murat Canyılmaz[2], Selçuk Sağır[3]

[1]*Dept. of Primary School Teacher, Faculty of Education, Mus Alparslan University, 49250 Mus, Turkey*
r.atici@alparslan.edu.tr

[2]*Dept. of Physics, Faculty of Sciences, Firat University, 23119 Elazig, Turkey*
eguzel@firat.edu.tr; mcanyilmaz@firat.edu.tr

[3]*Dept. of Electronics and Otomation, Vocational School, Mus Alparslan University, 49100 Mus, Turkey*
s.sagir@alparslan.edu.tr

[*]*Corresponding author: r.atici@alparslan.edu.tr; ramazanatici24@gmail.com*

Abstract

In this study, the heating of the nighttime lower ionosphere due to electromagnetic radiation in the very low frequency (VLF) band that are transmitted by cloud-to-ground (CG) lightning return strokes is investigated. For this purpose, temperature of electrons in lower ionosphere is calculated by using electron energy balance equation, which is obtained by using Maxwellian distribution. In the result of calculations, in 10 V/m of the electrical field for all modes of electromagnetic (EM) wave, it was observed that the electron temperatures increased by about 9000-11000 K at an altitude of about 85-90 km. With an increase in the electric field, it was observed that the altitude, where the maximum temperatures were reached, shifted higher. The Right-Handed mode of the EM wave, unlike other modes was not return based-state to an altitude of 95-100 km. To fully determine the effect of lightning induced electromagnetic waves on the lower ionosphere, considering the effects of polarized modes (Right and Left) can also provide more information.

Keywords: Electron temperature; EM waves; lightning; lower ionosphere; magnetic field.

1. Introduction

Lightning is a high-current electrical discharge emitted in the atmosphere. Lightning is basically classified into two types as cloud-to-ground (CG) and intra-cloud (IC). The average electromagnetic power emitted by the return strokes of CG discharges used in this study is 20 GW and they last for 100 μs (Taranenko *et al*., 1993). The electrical field of the electromagnetic waves radiated by the return strokes of lightning and other electrical fields (electrostatic and quasi-electrostatic field) speed up the electrons and cause collisions between electrons and neutral components, thus connecting them to the upper atmosphere (Mika, 2007). These electrical fields give rise to heating, ionization, attachment, detachment and excitement in the lower ionosphere (Taranenko *et al.*, 1993).

To address these problems, numerous models (1D, 2D and 3D) were developed in the past 20 years. The first theory of interaction of the lightning induced electromagnetic pulses (EMP) with the lower ionosphere was presented by Inan *et al.* (1991). The first time-domain model of interaction between the ionosphere and the EMPs was presented by Taranenko *et al.* (1993). Veronis *et al.* (1999) created a cylindrical 2D model of an EMP, and simultaneously calculated the effects of both the sprite halos and the elves. Other 2D models have been presented by Cho & Rycroft (1998) and Rowland *et al.* (1995, 1996). The first three-dimensional models were presented by Cho & Rycroft (2001) and Nagano *et al.* (2003). Finally, Marshall *et al.* (2008, 2010) and Marshall (2012) used a 3D model in the Cartesian coordinates, to investigate the effects of horizontal lightning discharges and the magnetic dip angle.

By examining the earlier studies on this topic (e.g., Inan *et al*., 1991; Rodriguez *et al.*, 1992; Nagano *et al.*, 2003), it was observed that the effect of Earth's magnetic field is often neglected, and only two modes of the lightning induced VLF radio wave are used in calculations after entering the ionospheric plasma. To create an exact model of the effect of the electromagnetic energy from lightning on the lower ionosphere, it is essential that all the modes of the radio waves, radiated by lightning return stroke, and the effect of the Earth's magnetic field be taken into consideration. The propagation of an EM wave into plasma changes depending on the presence of a magnetic field. In the absence of a magnetic field, the EM wave has a single mode. In the presence of a magnetic field, an EM wave exhibits multiple modes of propagation, which depend on the direction of propagation with respect to the magnetic field, and the wave polarization. The existence of multiple propagation modes for a single frequency results in observable and scientifically useful effects (Inan & Golkowski, 2010).

In this study, the effect of a lightning-induced VLF radio wave on the electron temperatures in the lower ionosphere is investigated by using the actual geometry of Earth's magnetic field. Earth's magnetic field allocates the lightning-induced electromagnetic (EM) wave to different modes. These modes of EM waves significantly increase the electron temperatures in the lower ionosphere in proportion to the electrical field of the lightning discharges. In Section 2, the method of calculation is detailed; in Section 3, the results and discussion are articulated; and in Section 4, the conclusion is discussed.

2. The method of calculation

The calculation method used in this study is similar to that of an associated study conducted earlier, on the heating of the lower ionosphere by ground-based high-power high-frequency transmitters (Canyilmaz *et al.*, 2013). After entering the D-region of the lower ionosphere, a large amount of energy of the lightning-induced EM wave is transferred to the electrons that freely exist. Thus, the temperature of the electrons increases. The increase in the temperature of the electrons indicates that the power of the EM wave has been absorbed. The accelerated electrons collide with other particles in the medium. In the case of electron collisions, the refractive index becomes a complex expression in the form

$$n^2 = (\mu + i\chi)^2 = M + iN \tag{1}$$

where, μ is the real part of the refractive index that represents the wave propagation, and χ is the imaginary part of refractive index that expresses the wave damping. The imaginary part of the refractive index is expressed by Güzel *et al.* (2011).

$$\chi^2 = \frac{1}{2}\left[\left(M^2 + N^2\right)^{1/2} - M\right] \tag{2}$$

where, M and N are the coefficients of the real and imaginary parts of the refractive indices of different wave modes (Left-Handed (L), Right Handed (R), Ordinary (O) and Extraordinary (X) mode) (Canyilmaz *et al.*, 2013).

The physical meaning of damping is that a portion of wave energy is absorbed in the plasma. This energy is actually divided between the electrons and the neutral particles. However, electrons take all of this energy as they are much lighter than the neutral particles. Using the ideal gas approach, the change in the electron temperature due to absorption is defined by the following nonlinear differential equation (Belova *et al.*, 1995; Kero *et al.*, 2000; Rietveld *et al.*, 1986):

$$\frac{dT_e}{dt} = \frac{2}{3k_B N_e}\left(U - L\right) \tag{3}$$

where, k_B is the Boltzmann constant, U shows the heating due to absorption, L defines the total energy loss resulting from the elastic collisions of the major components N_2 and O_2 with the electrons, due to the rotational and the vibration excitations of the N_2 and the O_2 molecules and due to the electronic and structural excitations of the O atoms (Rodriguez, 1994; Schunk & Nagy, 2004).

The energy transferred by the lightning-induced VLF radio wave passing in the lower ionosphere to the electrons in the environment is given by

$$U = 2\kappa S\,. \tag{4}$$

The absorption coefficient of the EM wave is given as $\kappa = \omega\chi / c$ where ω is the frequency of wave and c is the speed of light in space.

The change in the energy flux of the EM wave with altitude is given as follows (Belova *et al.*, 1995):

$$\frac{dS}{dz} = -2\frac{\omega\chi}{c}S \tag{5}$$

From this equality, the following expression is obtained:

$$S(z) = \frac{ERP}{4\pi z^2}\exp\left(-2\frac{\omega}{c}\int_0^z \chi(z')dz'\right) \tag{6}$$

where, ERP is the effective radiation power of the source (e.g. lightning channel), and z is the reference altitude in kilometers. The effective radiation power of the EMP radiated by lightning channel, based on the electrical field of the wave *E,* is given by

$$ERP = \frac{(E.D)^2}{30}. \tag{7}$$

where, E is the electric field of the wave in V/m, and D is the distance from the lightning channel in km (Richards, 2008). This distance is usually considered as 100 km (Inan *et al.*, 1991, Rodriguez *et al.*, 1992).

The electrons loose the energy gained from the EM wave due to collisions with the neutral particles in environment. The total energy loss is given by the following equation:

$$L_{Top} = \sum_{i=1}^{3} L_i(e,N_2) + \sum_{i=1}^{3} L_i(e,O_2) + \sum_{j=1}^{3} L_j(e,O) \tag{8}$$

Where, i=1,2 and 3 represent the losses in energy via elastic collisions, rotation and vibration excitations with N_2 and O_2 molecules of the electrons, respectively. These energy loss expressions are taken from Rodriguez (1994). j=1 and 2 indicate the losses that occur due to the fine structure and the electronic excitation of the O atom. It is taken from Schunk & Nagy (2004).

When equation (3) is solved for the steady state, the following equation is arrived at:

$$U\ (T_e) - L(T_e) = 0 \tag{9}$$

To calculate the lightning-induced heating, equation (9) is solved by iterations for each altitude.

3. Results and discussion

The neutral density and the temperature values used in the calculations were obtained from the web address (http://omniweb.gsfc.nasa.gov/vitmo/msis_vitmo.html) of MSISE-90 (Mass Spectrometer-Incoherent-Scatter) model for Elazığ city of Turkey (38° 41' N and 39° 13' E) on 21 Jun 2000. As the electron density at an altitude between 50-80 km at night (local time (LT) 2400) could not be obtained from the IRI-2007 (International Reference Ionosphere-2007) model, it is obtained by using the equation (Wait & Spies, 1964)

$$N_e(z) = 1.43\times10^{13}\exp[(-0.15h') + (\beta - 0.15)(z - h')],\ 1/m^3 \tag{10}$$

where, z is the altitude, h' is the reference altitude in kilometers, and β is a parameter determined by the sharpness of the curve of the electron density, depending on its height in km^{-1} (Wait & Spies, 1964). For nighttime conditions, it is assumed that $\beta = 0.5$ km^{-1} and $h' = 85$ km (Inan *et al.*, 1991; Poulsen *et al.*, 1993; Rodriguez *et al.*, 1994). The electron density in the altitude range of 80-120 km was obtained by using the online compiler of the IRI-2007 model(http://ccmc.gsfc.nasa.gov/modelweb/models/iri_vitmo.php) for a case of R=147 as the sunspot number, under the same conditions that neutral densities were obtained.

Generally, mathematical models of the events in the physics are expressed by nonlinear equations. As obtaining an analytical solution of a nonlinear equation is not so easy, it generally has to use numerical integration to obtain approximate solutions for nonlinear equations (Dogan, 2013; Karakoc *et al.*, 2015; Mirzaee *et al.,* 2016; Gokdogan & Merdan, 2013). For this reason, the integral in equation (6) is calculated with steps of 100 meters according to the trapezoidal method and the roots of equation (9) are found by the bisection method. Figure 1 shows the effect of the electrical field of L and R modes of the EM wave of 5 kHz in the VLF band, radiated by the CG lightning discharges, on the electron temperature in the lower ionosphere.

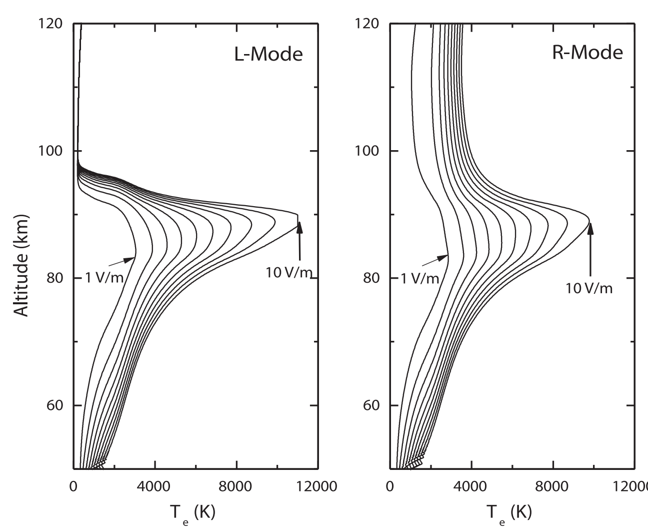

Fig. 1. The variation with altitude of the permutation in the electron temperature in the lower ionosphere, caused by polarized L and R modes of lightning induced VLF radio wave.

As seen from Figure 1, when E_{100} values were increased in steps of 1 V/m, the smallest changes in temperature for 1 V/m and the largest change in temperature for 10 V/m, were calculated. When the E_{100} (electrical field values normalized to 100 km) values were increased regularly, it was observed that the temperature values also increased regularly up to a certain altitude. Also, L and R-modes of the EM wave for the E_{100} value of 1 V/m heated the medium up to about 10 times that of its ground state value (T_n~200 K). However, the L and R- modes for the E_{100} value of 10 V/m were heated the medium up to about 60-

65 times and 40-45 times, respectively. The temperature was reached the maximum value at altitudes between 85 and 90 km. Here, a significant difference between the L-mode and the R-mode is observed. The R-mode of the wave continues to propagate through the ionosphere and did not return to the ground state between the altitudes of 90 and 95 km, as was the case with the L-mode. When comparing the L- and the R-mode waves, for equal values of E_{100}, it is observed that the L-mode wave heats the medium more than the R-mode wave.

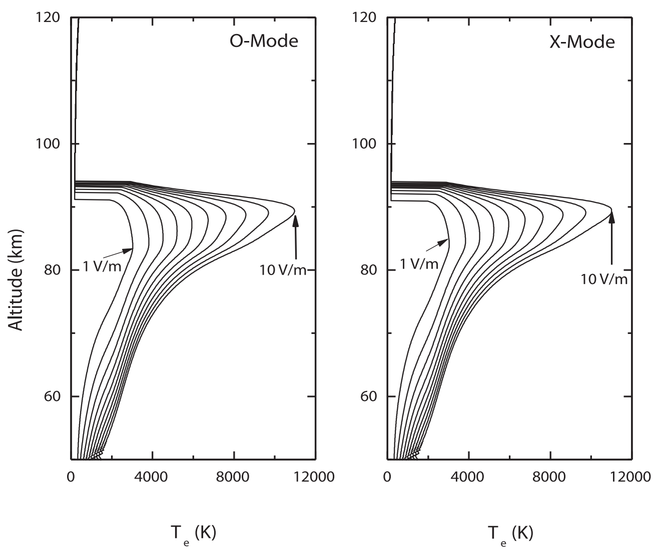

Fig. 2. The variation with altitude of permutation in lower ionosphere electron temperature caused by O and X modes of lightning induced VLF radio wave.

The O-mode of the EM wave, which is not affected by the magnetic field, increased up to about 10 times that of the medium temperature for the E_{100} value of 1 V/m, while it increased by about 55-60 times the electron temperature for the E_{100} value of 10 V/m. At an altitude of approximately 90-95 km, the effect of this mode was eliminated. The X-mode of the EM wave heated the medium to about 10 times for the E_{100} value of 1 V/m and by about 60 times for the E_{100} value of 10 V/m, like the other modes. The X-mode of the wave disappeared at an altitude of approximately around 90-95 km, and the electron temperature returned to ambient value. When O and X modes of the wave are compared, it can be seen that the temperature rise is the same for both modes. However, the temperature for the X-mode of the wave exceeds that of the O-mode of the wave by about 20-30 K degrees at altitudes reaching peak values. A literature review on this topic (e.g., Inan *et al.*, 1991) indicates that there is not much difference between these two modes. This case is supported by the results obtained in this study.

Lightning EM field is treated as a single wave until it reaches the ionosphere. As the ionosphere acts as a birefringent medium, the EM wave is divided to four different modes when it enters the ionosphere. Therefore, the induced heating can be the result of the collection of the effects of all these modes, depending on the polarization of the wave.

As in previous studies (Inan *et al.*, 1991), the electron temperature was calculated by adding together the effects of the different modes. The effects of the polarized R and L modes of the wave, and the O and X modes of wave on the medium, when the wave propagates in the +z direction, were as shown in the Figure 3. As seen Figure 3, when the L and the R modes are considered together, the electron temperature increases by up to 20-25 times that of the medium temperature, for the E_{100} value of 1 V/m. On the other hand, the electron temperature increased by about 100-110 times for the E_{100} value of 10 V/m. When the O and the X modes are considered together, the electron temperature increases by up to 20-25 times of the medium temperature, for the E_{100} value of 1 V/m, while it increases by about 120-130 times for the E_{100} value of 10 V/m.

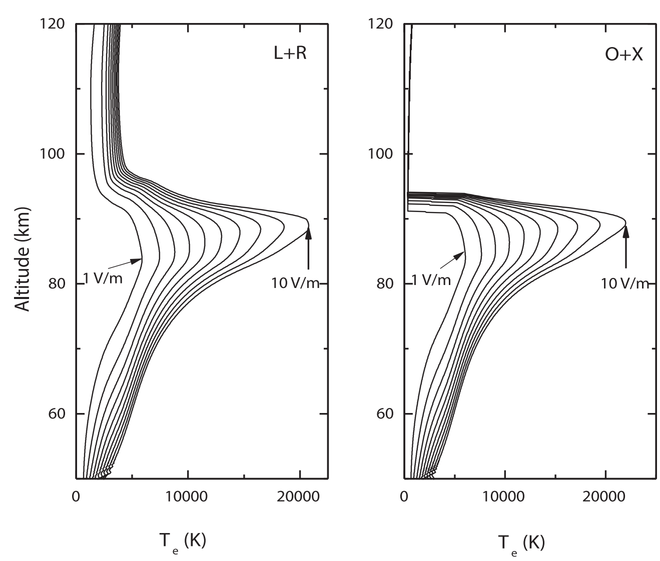

Fig. 3. The variation with altitude of permutation in lower ionosphere electron temperature caused by the collection of different modes of lightning induced VLF radio wave.

4. Conclusion

In the previous studies in general only the O and the X modes of the lightning-induced EM wave were used in the calculations. However, in order to determine the exact effects of the lightning-induced EM wave on the lower ionosphere, all wave modes are required to be taken into consideration.

Calculations reveal that the lightning-induced EM waves increase the electron temperature significantly. This increase in electron temperature is directly proportional to the electric field of lightning-induced VLF electromagnetic wave or to the radiation power of lightning channel, for all modes. The Earth's magnetic field, which was generally neglected in the previous studies related to the heating of the lower ionosphere by the lightning-induced EMPs, was observed to have significant effects, especially over the polarized wave modes. To fully determine the effect of lightning induced electromagnetic waves on the lower ionosphere, accounting the calculations of the effects of polarized modes (Right and Left) can also provide more information about this region. When the effects of four different modes of the lightning-induced VLF radio wave on the electron temperature in the lower ionosphere were investigated, non-linear variations in the heating of the medium were observed. Because of these changes, the altitude at which the electron temperature for all modes reaches the maximum is pushed higher, as the value of E_{100} increases. Also, the R-mode of wave is observed propagate higher, while the other wave modes are absorbed at altitudes of 90-95 km. This situation indicated that, as proposed by the previous studies (Inan & Golkowski, 2010; Nagano *et al.*, 2003), the R-mode wave is the lightning-induced whistler mode wave.

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تأثير الموجات الكهرومغناطيسية الناجمة عن البرق على درجات حرارة الإلكترون في طبقات الأيونوسفير السفلى

رمضان أتيسي[1,*]، عزت جودزل[2]، مراد كانيلماز[2]، سلجوك صقر[3]
[1]قسم معلمي المدارس الابتدائية، كلية التربية، جامعة المصحف الب ارسلان، 49250 موس، تركيا.
[2]قسم الفيزياء، كلية العلوم، جامعة فرات، 23119 إيلازيغ، تركيا.
[3]قسم الكهرباء والحركة، المدرسة المهنية، جامعة موس الب ارسلان، 49100 موس،تركيا.
[*]المؤلف المراسل: ramazanatici24@gmail.com، r.atici@alparslan.edu.tr.

خلاصة

في هذه الدراسة، يتم التحقيق منتسخين الأيونو سفير ليلا نتيجة للإشعاع الكهرومغناطيسي في موجة التردد المنخفض جدا (VLF) التي تنتقل عن طريق ضربات البرق المنتقلة عبر السحاب – الأرض (CG). لهذا الغرض، يتم حساب درجة حرارة الإلكترونات في الأيونوسفير السفلي باستخدام معادلة توازن طاقة الإلكترون التي يتم الحصول عليها باستخدام توزيع ماكسويل. نتيجة للحسابات، في مجال الحقل الكهربائي 10 فولت/ ملجم مع وسائط الموجة الكهرومغناطيسية (EM)، لوحظ أن درجات الحرارة الإلكترون ترتفع بنسبةحوالي 9000-11000 قطان ارتفاع حوالي 85-90 كم. مع زيادة المجال الكهربائي، لوحظ أن الارتفاع –حيث وصلت درجات الحرارة إلى الحد الأقصى– انتقل للأعلى. وضع الجهة اليمنى للموجة الكهرومغناطيسية، علىعكس الأوضاع الأخرى ،لم يعد للحالة الأساسية في ارتفاع 95-100 كم. لتحديد تأثير البرق الناجم عن الموجات الكهرومغناطيسية على الأيونوسفير السفلي بشكل تام، فإن النظرفي الآثار المترتبة على وسائط الاستقطاب (اليمين واليسار) يمكن أيضا أن توفرمزيد من المعلومات.

كلمات البحث : درجة حرارة الإلكترون، الموجات الكهرومغناطيسية ، البرق؛ الأيونوسفير السفلي، الحقل المغناطيسي.