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Electron density changes in the nighttime *D* region due to heating by very-low-frequency transmitters

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Abstract. Modification of the nighttime *D* region electron density (N_e) due to heating by very-low-frequency (VLF) transmitters is investigated theoretically using a four-species model of the ion chemistry. The effects of a 100 kW, a 265 kW, and a 1000 kW VLF transmitter are calculated for three ambient N_e profiles. Results indicate that N_e is reduced by up to 26% at ~80 km altitude over a 1000 kW transmitter.

1. Introduction

Heating of the ionosphere by man-made transmitters [*Jones*, 1990] and by lightning [*Inan et al.*, 1991] is believed to result in modification of the electron number density (N_e). For example, suppression of a solar-flare-induced sudden phase anomaly observed on a 60-kHz signal passing over the high-frequency Platteville heater [*Utlaut*, 1975] has been ascribed by *Tomko et al.* [1980] to an increase in electron attachment in the heated daytime *D* region. In the case of heating by powerful (~ 20 GW radiated power) electromagnetic pulses (~ 100 μs duration) from lightning discharges, the dominant processes affecting N_e are two-body attachment to O_2 and collisional ionization by electrons in the tail of the distribution [*Taranenko et al.*, 1993]. In contrast, heating by man-made transmitters (~ 1 MW total radiated power) alters the ion chemistry that determines N_e. In this paper we investigate theoretically the modification of N_e in the lower ionosphere due to heating of the nighttime *D* region by very-low-frequency (VLF) transmitters [*Inan*, 1990; *Inan et al.*, 1992].

2. Model of Nighttime *D* Region Chemistry

Under steady-state conditions, the chemical processes in Fig. 1*a* can be represented by a set of linearly-dependent equations [*Glukhov et al.*, 1992] relating the number densities N_e, N^+, N^-, and N_x^+, respectively, of electrons, primary positive ions (NO^+ and O_2^+), negative ions (e.g., O_2^-, CO_3^-, NO_2^-, NO_3^-), and positive water cluster ions or proton hydrates ($H^+(H_2O)_n$):

$$\frac{dN_e}{dt} = 0 = I_o + \gamma N^- - \beta N_e - \alpha_d N_e N^+ - \alpha_d^c N_e N_x^+ \quad (1)$$

$$\frac{dN^-}{dt} = 0 = \beta N_e - \gamma N^- - \alpha_i N^-(N^+ + N_x^+) \quad (2)$$

$$\frac{dN^+}{dt} = 0 = I_o - BN^+ - \alpha_d N_e N^+ - \alpha_i N^- N^+ \quad (3)$$

$$\frac{dN_x^+}{dt} = 0 = -\alpha_d^c N_e N_x^+ + BN^+ - \alpha_i N^- N_x^+ \quad (4)$$

where I_o is a steady, external ionization source; α_d [*Tomko et al.*, 1980] and α_d^c [*Reid*, 1977; *Huang et al.*, 1978] are the effective coefficients of electron recombination with primary positive ions and water cluster ions, respectively; α_i is the effective mutual neutralization coefficient for all types of positive ions with negative ions [*Rowe et al.*, 1974]; β is the effective three-body electron attachment rate [*Rowe et al.*, 1974; *Tomko*, 1981, p. 163]; B is the effective rate of conversion of primary positive ions (especially NO^+) into water cluster ions [*Rowe et al.*, 1974]; and γ is the effective collisional electron detachment rate [*Bailey*, 1959]. Reaction rates, coefficients, and their known dependences on the electron and neutral temperatures T_e and T_n are listed in Table 1. This four-species model is appropriate since we are interested primarily in the response of N_e to heating.

Below 80 km, the most rapid processes under this model are electron attachment (e + O_2 + M → O_2^- + M; M is O_2 or N_2) and detachment due to collisions between negative ions and neutrals (e.g., O_2^- + O → O_3 + e). Following *Glukhov et al.* [1992], we adopt a detachment rate γ [*Bailey*, 1959] that effectively represents the entire system of reactions involving collisional electron detachment [*Ivanov-Kholodnyi and Nikol'skii*, 1972, p.205]. The dependence on γ of changes in N_e due to VLF heating is discussed in a later section. The rates β and γ are shown in Fig. 1*b* as functions of altitude.

At night, the *D*-region positive ion population is comprised almost entirely of positive water cluster ions $H^+(H_2O)_n$ below 80 km and NO^+ and O_2^+ above 85 km [*Danilov and Semenov*, 1978]. Therefore, the loss of electrons through dissociative recombination with both primary positive ions (e.g., NO^+ + e → N + O) and cluster ions ($H^+(H_2O)_n$ + e → neutrals) must be considered. The coefficient of dissociative recombination with cluster ions (α_d^c) is a function of T_n and the relative abundances of the different cluster ion species; however, for simplicity, we adopt a single ambient $\alpha_d^c = 3 \times 10^{-12}$ m^3 s^{-1} [*Reid*, 1977], with $\alpha_d^c \sim (T_n/T_e)^b$, where $0 \leq b \leq 0.08$ [*Huang et al.*, 1978; *Tomko*, 1981]. The coefficients of dissociative recombination of electrons with NO^+ (α_{NO^+}) and O_2^+ ($\alpha_{O_2^+}$) depend more strongly on T_e than α_d^c yet are significant at night only above 85 km. The coefficients $\alpha_d = (\alpha_{NO^+}N_{NO^+} + \alpha_{O_2^+}N_{O_2^+})/N^+$ and α_d^c (heated only) are shown in Fig. 1*c* as functions of altitude.

3. Method of Calculation

The first step in the solution of eqs. 1-4 is the adoption of an N_e profile. The three ambient N_e profiles used in this paper (Fig. 2*a*) represent a tenuous (I), moderate (II), and dense (III) nighttime *D* region [*Inan et al.*, 1992]. The ambient T_n profile is from the *U. S. Standard Atmosphere* [1976], as are

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TABLE 1. *D* Region Reaction Rates and Coefficients

Coefficients ($m^3\ s^{-1}$)

$$
\begin{aligned}
\alpha_d &= \left(\alpha_{NO^+} N_{NO^+} + \alpha_{O_2^+} N_{O_2^+}\right) / N^+ \\
\alpha_{NO^+} &= 4.1 \times 10^{-13} \left(300\ T_n^{-0.5}\ T_e^{-0.5}\right) \\
\alpha_{O_2^+} &= 2.1 \times 10^{-13} \left(300^{0.7}\ T_n^{-0.1}\ T_e^{-0.6}\right) \\
\alpha_d^c &= 3 \times 10^{-12} (T_n/T_e)^b,\ 0 \le b \le 0.08 \\
\alpha_i &= 10^{-13}
\end{aligned}
$$

Rates (s^{-1})

$$
\begin{aligned}
\beta =\ & 10^{-43} N_{N_2} N_{O_2} + k_{O_2} N_{O_2}^2 \\
& k_{O_2} = K T_e^{-0.65} \exp\left[-\frac{a_1}{T_e} - \left(\frac{a_2}{T_e}\right)^2 - \left(\frac{a_3}{T_e}\right)^3\right] \\
& K = 1.1617 \times 10^{-39} - 3.4665 \times 10^{-42} T_n \\
& \quad +3.2825 \times 10^{-45} T_n^2 \\
& a_1 = 7.8193 \times 10^2 - 3.2964 T_n \\
& a_2 = -1.9159 \times 10^2 + 3.7646 T_n \\
& \quad -4.5446 \times 10^{-3} T_n^2 \\
& a_3 = -7.6834 \times 10^1 + 1.2277 \times 10^{-2} T_n \\
& \quad -7.6427 \times 10^{-3} T_n^2 + 1.7856 \times 10^{-5} T_n^{-3} \\
B =\ & 10^{-43} N_n^2,\quad N_n \equiv \text{total neutral number density} \\
\gamma =\ & 3 \times 10^{-23} N_n
\end{aligned}
$$

the neutral density profiles below 86 km. The neutral density profiles above 86 km are from the MSIS-86 thermospheric model [*Hedin*, 1987]. The ambient effective electron-neutral collision frequency (ν_{eff}) profile (Fig. 2*a*) is that used in previous VLF propagation studies [*Poulsen et al.*, 1993].

Eliminating N^+ and N_x^+ from eq. 2 by assuming charge neutrality ($N_e + N^- = N^+ + N_x^+$), we solve for the ratio λ of N^- to N_e:

$$\lambda \equiv \frac{N^-}{N_e} = \frac{\frac{2\beta}{\alpha_i N_e}}{1 + \frac{\gamma}{\alpha_i N_e} + \sqrt{\left(1 + \frac{\gamma}{\alpha_i N_e}\right)^2 + \frac{4\beta}{\alpha_i N_e}}} \quad (5).$$

Below 80 km, λ is independent of N_e (Fig. 2*c*) since $\lambda \to \beta/\gamma$ as $N_e \to 0$ [*Glukhov et al.*, 1992]. Above 80 km, λ is smallest in the dense *D* region (profile III), though always > 87% of λ for profile I (Fig. 2*d*). Using eq. 5 in eq. 4 we have:

$$\frac{N^+}{N_x^+} = \frac{\alpha_d^c + \lambda \alpha_i}{B} N_e \quad (6).$$

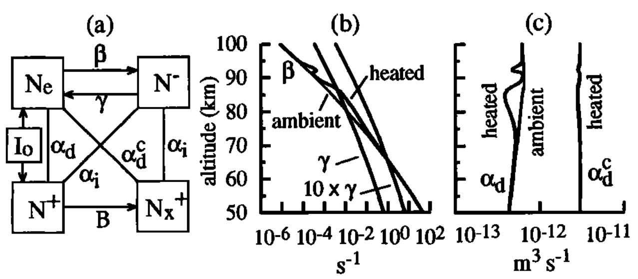

Fig. 1. (*a*) Four-component *D*-region ion chemistry model. (*b*) Electron attachment and detachment rates β and γ, and $10 \times \gamma$. Also shown is β in the case of heating by NAA, assuming N_e profile I (Fig. 2*a*), $\gamma = 3 \times 10^{-23} N_n$, and $\alpha_d^c \sim T_e^{-0.08}$. (*c*) Electron recombination coefficients α_d and α_d^c. The heated values are for the same parameters as in *b*.

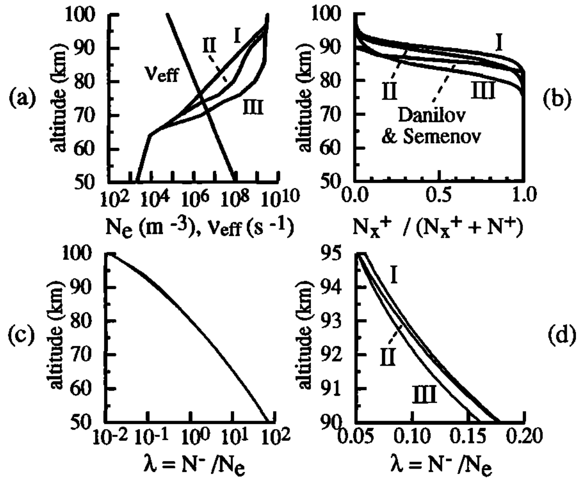

Fig. 2. (*a*) The nighttime ambient electron density (N_e) and collision frequency (ν_{eff}) profiles used here. (*b*) Relative positive ion composition in the nighttime *D* region for the three N_e profiles in *a*, and measured by *Danilov and Semenov* [1978]. (*c*) Ratio of negative ions to electrons, λ, for the three N_e profiles in *a* (logarithmic abscissa). (*d*) λ between 90 and 95 km for the three N_e profiles in *a* (linear abscissa).

The relative composition of positive cluster ions $N_x^+/(N^+ + N_x^+) = 1/(1 + N^+/N_x^+)$ is shown in Fig. 2*b* for the three N_e profiles along with results from a nighttime rocket mass spectrometer measurement [*Danilov and Semenov*, 1978].

Using the assumption of charge neutrality and the adopted N_e profile, eqs. 5 and 6 are solved for the N^-, N^+, and N_x^+ profiles, which are used to determine a source profile I_o from eq. 1 that is consistent with the N_e profile. This source profile is assumed to represent the ambient in the calculation of N_e under heated conditions. We use the VLF heating model of *Inan et al.* [1992], modified to include the *Sen and Wyller* [1960] refractive index model and the electron cooling rates used by *Barr and Stubbe* [1992]. The heated T_e profile is used to calculate new values of α_d, α_d^c, and β. Eqs. 1, 3, and 5, and the charge-neutrality condition are then combined to obtain an implicit function of N_e that is solved for N_e iteratively at each altitude.

4. Results

We examine the effect of the VLF transmitters NAU (Aguadilla, P.R.; 100 kW; 28.5 kHz), NSS (Annapolis, Md.; 265 kW; 21.4 kHz), and NAA (Cutler, Me.; 1000 kW; 24.0 kHz) on the tenuous (I), moderate (II), and dense (III) nighttime *D* regions (Fig. 2*a*). First, we assume that α_d^c does not vary with T_e ($b = 0$) and that γ is as listed in Table 1. The upper panels in Fig. 3 show the ambient and heated T_e profiles through the point of maximum heating ($\Delta\nu/\nu_o$).

Assuming a toroidal radiation pattern, the transmitter-induced T_e enhancement is minimum directly above the transmitter and maximum due geomagnetic north of the transmitter [*Galejs*, 1972; *Inan et al.*, 1992]. For example, in a heated tenuous *D* region (profile I) over NAA, the point of maximum heating is at 85 km altitude, 94 km due geomagnetic north of NAA. At this altitude, the radius at the outer half-maximum

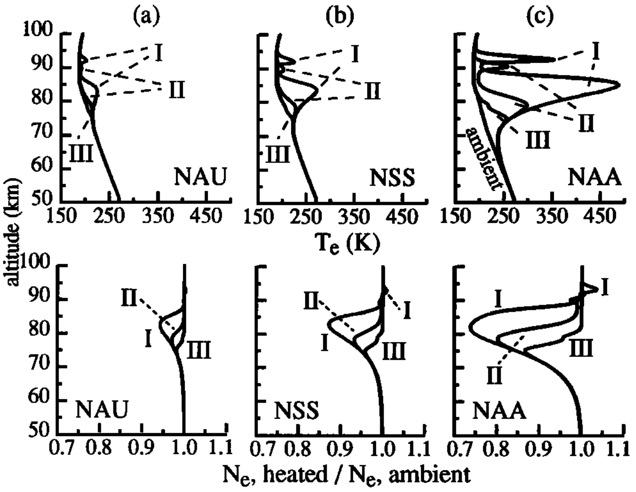

Fig. 3. Ambient and heated electron temperatures (T_e), above, and ratio of heated to ambient electron density N_e, below, in the case of heating by (*a*) NAU, (*b*) NSS, and (*c*) NAA, for three N_e profiles (Fig. 2*a*).

of the T_e enhancement is about 200 km. The shape and extent of the density depletion should be similar.

The lower panels show the corresponding ratios of heated to ambient N_e. In all cases, the dominant effect is depletion of N_e due to the increase of β with T_e (Fig. 1*b*). In a tenuous *D* region (I) over NAA, N_e is reduced by 26% (Fig. 3*c*). The increase in N_e above 90 km, where NO^+ dominates, is due to the decrease in α_d with increasing T_e (Fig. 1*c*).

Next, the calculation is performed for each transmitter under a tenuous *D* region (profile I), adopting γ from Table 1 and $\alpha_d^c \sim T_e^{-0.08}$. The results differ little from the case of no T_e dependence for α_d^c (Fig. 4*a*). Finally, in the case where γ is ten times higher (Fig. 4*b*), N_e decreases much less below 90 km (about 6% for NAA and N_e profile c), and the amount of decrease is much more sensitive to the temperature dependence of α_d^c.

The three transmitters considered here encompass a 1:10 range in radiated power, including one of the most powerful (NAA). Similar results would be expected for other VLF transmitters in operation, some equally powerful [*Inan et al.*, 1984].

5. Discussion

Prior theoretical work on the chemistry of a heated *D* region differs from the present work in important ways. *Galejs* [1972] predicted an increase in N_e due to VLF heating, just as our results show between 90 and 95 km for a tenuous *D* region (I). However, he took into account only the decrease in α_d and assumed a sharp lower *D* region boundary at 85 km, so could not have predicted the N_e decrease below 90 km due to increased β. The theoretical results of *Tomko et al.* [1980] showing density depletion in the lower *D* region were for daytime conditions, and therefore are not applicable to the nighttime conditions under which VLF heating has been observed [*Inan*, 1990; *Inan et al.*, 1992].

Since we neglect the effect of the density depletion on the heating itself, and the increase in T_e varies roughly as $N_e^{-0.5}$

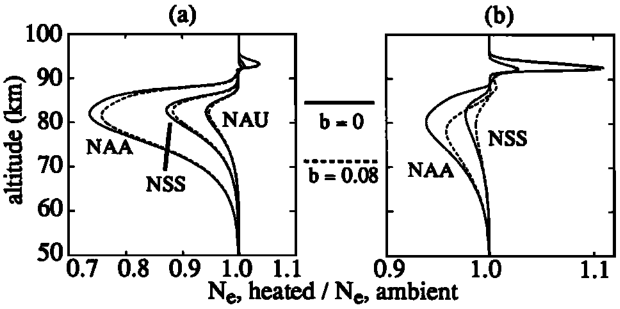

Fig. 4. Ratios of heated to ambient electron density (N_e profile I, Fig. 2*a*) for b = 0 and 0.08, where $\alpha_d^c \sim T_e^{-b}$. (*a*) $\gamma = 3 \times 10^{-23} N_n$ (Table 1). (*b*) $\gamma = 3 \times 10^{-22} N_n$. In this case, the density depletion over NAU (not shown) is < 1%.

[*Inan et al.*, 1992], the magnitude of the density depletions should be larger than estimated here. However, the tendency for decreasing N_e would be inhibited ultimately by a maximum in β around T_e = 700° K [*Tomko*, 1981, p. 163].

Remote sensing with subionospheric VLF probe waves, as used to detect lightning-induced ionization enhancements [e.g., *Wolf and Inan*, 1990], may be used to verify experimentally the predicted N_e changes. Based on a simple model [*Inan et al.*, 1985], a 26% decrease in density would result in a 0.7° phase lag on a 12.9 kHz signal, which lies in the range of commonly detected perturbations [*Wolf and Inan*, 1990]. However, the transverse structure of the depleted region as well as the waveguide mode structure of the probe wave [*Poulsen et al.*, 1993] must be considered to more accurately assess the detectability of the predicted density changes. Note also that, based on the fastest reaction time constant $1/(\beta+\gamma)$, which is about 100 s at 80 km [*Glukhov et al.*, 1992], the density depletions should evolve and disappear over tens of seconds following transmitter turn-on and turn-off, respectively. Since the ionosphere exhibits natural variations with similar time constants, it may be difficult to recognize the signatures of transmitter-induced N_e changes in subionospheric VLF data.

6. Conclusions

A four-species model of the nighttime *D* region ion chemistry has been used to estimate the magnitude of electron density changes resulting from heating by ground-based VLF communications transmitters. Results indicate that a 250% increase in electron temperature results in a 26% depletion of electron density between 70 and 90 km altitude. In view of the continuous operation of several VLF transmitters around the globe, this phenomenon may constitute a significant man-made input to the nighttime midlatitude ionosphere.

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