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Electron–ion temperature ratio estimations in the summer polar mesosphere when subject to HF radio wave heating

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ABSTRACT

We have inferred the electron temperature enhancements above mesospheric altitudes under Polar Mesospheric Summer Echoes (PMSE) conditions when the ionosphere is exposed to artificial HF radio wave heating. The proposed method uses the dependence of the radar cross section on the electron-to-ion temperature ratio to infer the heating factor from incoherent scatter radar (ISR) power measurements above 90 km. Model heating temperatures match our ISR estimations between 90 and 130 km with 0.94 Pearson correlation index. The PMSE strength measured by the MORRO MST radar is about 50% weaker during the heater-on period when the modeled electron-to-ion mesospheric temperature is approximately 10 times greater than the unperturbed value. No PMSE weakening is found when the mesospheric temperature enhancement is by a factor of three or less. The PMSE weakening and its absence are consistent with the modeled mesospheric electron temperatures. This consistency supports to the proposed method for estimating mesospheric electron temperatures achieved by independent MST and ISR radar measurements.

1. Introduction

It is generally believed that the phenomenon of Polar Mesosphere Summer Echoes (PMSE) can be explained by invoking the presence of charged aerosols, which are made up of ice with radii up of to several tens of nanometers. The aerosols are charged due to electric currents produced by the thermal motions of electrons and ions. Owing to the disparity of the electron and ion masses, the electron current flux is much larger than the ion current flux, thus producing an equilibrium state with no current ($I_e + I_i = 0$) when the aerosols are negatively charged (Havnes et al., 1990; Cho et al., 1996; among others). Without the charged aerosols, the electron diffusion rate is too high for the maintenance of electron density PMSE irregularities at the Bragg scales (tens of centimeters to a few meters) that produce the scattering measured by radars. Charged aerosols slow down electron diffusion by making the electrons diffuse as if they had the mass of the aerosols due to the ambipolar forces between them. For more insight about PMSE the reader is referred to the review of Rapp and Lübken (2004). Under heating conditions the electron temperature enhancement accelerates the diffusion process and the electron density irregularities, which produce PMSE, are smoothed out (Rapp and Lübken, 2000; Chilson et al., 2000) producing a reduction in the radar echo strength.

On theoretical grounds, Havnes (2004), predicted a PMSE overshoot effect and shortly afterwards it was confirmed by the experiment (Havnes et al., 2003). He argued that the application of HF heating to the PMSE layers with appropriate on/off time intervals would cause the PMSE strength to exhibit (1) an abrupt weakening followed by some recovery during the heater-on period, (2) an almost instantaneous “overshoot” just after turning off the heater and (3) a slow characteristic relaxation until reaching the former unperturbed state. The weakening during the heater-on period has already been described above. The recovery and overshoot arise because the hotter electrons increase their incident flux on the aerosols, thus increasing their charge, which in turn strengthens the electron density irregularities by virtue of the larger ambipolar field. Finally, when the heat source ceases, the aerosols discharge the extra charge with a characteristic relaxation time before reaching equilibrium. The use of HF heating has significantly contributed to our physical understanding about PMSE; see for instance Chilson et al. (2000) and Belova et al. (2001), Havnes et al. (2003) and Havnes (2004). Recent attempts at identifying similarities between the summer (PMSE) and winter (PMWE) echoes have also led to the modulation of the latter by artificial ionospheric heating, e.g. Kavanagh et al. (2006), La Hoz and Havnes (2008) and Belova et al. (2008). However, complex interactions between plasma particles and neutrals in the mesosphere represent a difficult challenge for estimating plasma parameters like the electron and ion temperatures.

The aim of the present work is to estimate, employing a novel technique, the electron temperature enhancement at mesospheric altitudes when PMSE is subject to powerful HF radio waves. Or equivalently, it is the electron-to-ion temperature ratio T_e/T_i since

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we assume the ion and neutral temperatures are unaffected by the heating due to their large masses and the short heating time scales. The T_e/T_i parameter plays an important role in the morphology of the PMSE overshoot characteristic curve (OCC, Havnes, 2004).

The estimation of electron density in the lower ionosphere using ISR is difficult due to the low signal-to-noise ratio of the measurements. Therefore, below a certain altitude, whose selection is described in Section 2, we use the exponential approximation for the electron density profile. On the other hand, the ISR estimation of plasma particle temperatures from spectral measurements is also difficult for the same reason. Therefore, we use a typical heating model (Kassa et al., 2005) to estimate the electron temperature ranging from 20 up to 130 km. The modeled temperatures above 90 km are matched with estimations based on the ISR power measurements used by the proposed method. The matching process defines the exponential scale height of the assumed exponential function for electron density. The level of this parameter at lower altitudes affects significantly the heating effect upwards according to heating models (e.g. Belova et al., 1995; Routledge et al., 2011). The modeled mesospheric T_e/T_i during the heater-on period is consistent with the levels of PMSE weakening as measured by the MST radar. Other previous studies have reported similar order of PMSE weakening and electron temperature enhancements due to HF heating (e.g. Rapp and Lübken, 2000; Belova et al., 2001). However, we (and also Routledge et al., 2011) have found inconsistencies between the PMSE weakening and the heating levels resulting from the overshoot model of Kassa et al. (2005). Most certainly, this model may not be valid for all conditions.

The plan of the paper is as follows: Section 2 describes a novel method for estimating T_e/T_i in the E-region based on the apparent modulation of electron density due to periodic heating followed by a discussion in Section 3 on physical process that might cause the observed modulation. Section 4 describes the experimental setup of the EISCAT heater, the EISCAT ISR UHF radar and the MORRO MST radar (http://tupac.phys.uit.no/MORROradarSite/MORROradar.html); included also is a description of the ionospheric conditions. The results of the observations are discussed in Section 5, while Sections 6 and 7 describe the discussion and conclusions respectively.

2. Method

The electron density inside the illuminated medium can be estimated through the radar equation. It is found that the electron density is a function of the so-called raw electron density and the radar cross section. The raw electron density is essentially the received power scaled by both the attenuation due to the range R and the instrumental effects on the signal. The radar cross section is defined as (Buneman, 1962),

$$\sigma = \frac{\sigma_e}{(1+\alpha^2)(1+T_e/T_i+\alpha^2)} \tag{1}$$

where σ_e is the electron scattering cross-section, T_e/T_i is the plasma particle temperature ratio, and $\alpha=4\pi(D/\lambda)$ where, D is the Debye length and λ is the radar wavelength. After reformulating expression (28) in Evans (1969), the following equation is obtained:

$$N_e = (1+\alpha^2)\left(1+\alpha^2+\frac{T_e}{T_i}\right)N_e^r \tag{2}$$

where N_e^r is the raw electron density and N_e is electron density that accounts for the thermal and α correction. In this investigation we use data in NCAR format generated by a standard analysis program called Grand Unified Incoherent Scatter Design and Analysis Package GUISDAP (Lehtinen and Huuskonen, 1996). This analysis program assumes that the electron and ion temperatures are equal, which is correct for the undisturbed D-region, (including the mesosphere) and the E-region of the ionosphere. However, under HF heating conditions this assumption is not valid, as the electron temperature may increase by a large factor. Consequently, apparent electron density modulations are present in the results produced by the standard analysis. We further assume that the electron density remains unaltered by the heating pulse, as shown in Section 4. Based on this assumption, the radar equation is evaluated for the two heating states, i.e. Heater *On* and Heater *Off*. We define te/ti (in lowercase) as our first estimate of T_e/T_i considering $\alpha=0$ or extremely small,

$$(te/ti)_{Heat\_on} = 2\frac{(N_e)_{Heat\_off}}{(N_e)_{Heat\_on}} - 1 \tag{3}$$

where $(N_e)_{Heat\_on}$ and $(N_e)_{Heat\_off}$ are the electron density estimations from the GUISDAP analysis, without thermal correction, for both periods of time: during and after the heating pulse respectively. We have chosen to work with N_e instead of N_e^r because the first is provided with proper system calibration and less noisy. The dependence on α in the radar cross-section is considered in our analysis because its contribution is not negligible for the short wavelength of the EISCAT UHF radar (16 cm Bragg scale) together with the expected Debye length. The α parameter is calculated between 90 and 130 km using heating-unperturbed electron density and temperature estimated by the EISCAT UHF analysis. This correctly assumes during heater-off, equal electron and ion temperatures and uses a model for ion composition. In order to account for the effect of α in (3), Moorcroft (1964), proposed the following expression for estimating the "true" T_e/T_i (uppercase):

$$T_e/T_i = (1+\alpha^2)(te/ti) \tag{4}$$

Expression (4) is based on the fact that the radar scattering cross-section, Eq. (1), depends in the same way on both α and te/ti. The assumption of equal electron and ion temperatures during the heating-on periods in the standard ISR analysis produces a false electron density modulation. In Section 4 it is shown that a heater-induced modification of the electron density is not plausible for the heater-on times used in this experiment. Our proposed method exploits the apparent electron density modulation and leads us to estimate the electron temperature enhancement under radio wave heating. Above 90 km, the estimates of electron temperature are compared with a Heating model (Kassa et al., 2005). This model follows the description of Belova et al. (1995) but includes an updated expression for the energy losses due to elastic collisions between electrons and neutrals. The main inputs to the model are atmospheric altitude profiles of atomic oxygen (O), molecular nitrogen (N_2), molecular oxygen (O_2), neutral temperature (parameters provided by the model MSIS-E-90; Hedin (1991)) and composite electron density (N_e) estimations from a model (for lower altitudes) and ISR measurements (for higher altitudes).

At lower ionospheric altitudes, the current ISR measurements have low signal-to-noise ratio. In addition, the EISCAT analysis lacks proper treatment of the enhanced collisions between plasma particles and neutrals. To overcome this situation, we have considered an exponential decay of the electron density below a certain altitude. The strategy of assuming exponential decay below a certain altitude has been used before in D-region studies (Belova et al., 1995; Pashin et al., 1995; Kassa et al., 2005; among others). Based on the quality of the measured density profiles and the guidance from the mentioned works, we have chosen 80 km as the reference altitude. The measured electron density, around this altitude, is close to the radar detection limit previously used by