



Calculating the peak effect of 25th solar cycle on ionospheric plasma over Iraq

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This study investigates the effects of peak activity in the 25th solar cycle on plasma properties in the F ionosphere above Baghdad, Iraq. Electron temperature (T_e), electron density (n_e), and plasma parameters in the F layer of the ionosphere in the city of Baghdad (44.30°E, 33.30°N) are analyzed during the four seasons (winter, spring, summer and autumn) of 2024. The International Reference Ionosphere (IRI-2020); temperature and density profile are acquired at 150-500km altitudes in 50km steps. Findings have shown that the electron density and electron plasma frequency are lower in the summer and winter seasons, compared to the equinoxes. One of the most interesting observations is that in the lower altitudes the temperatures are similar across seasons with maximum temperatures recorded at 500km. As a result, the thermal velocity of the electrons and Debye length is greater and the plasma coupling coefficient is smaller during the study period. In addition, a definite correlation between electron temperature and altitude is discovered, where it is greatest at 500km in the F 2 ionosphere. The study highlights the need to track these changes to improve space-weather predictions and its consequences to communication and navigation systems, especially when the solar activity is more intense. Also, the paper suggests potential advantages of nano- based sensing and modeling instruments in enhancing accuracy of future ionospheric electron density and temperature measurements.

Keywords: F Layer; Ionosphere; IRI – 2020; Solar Cycle 25; Plasma properties.

1. INTRODUCTION

The ionosphere is the highest ionized layer of the atmosphere and it ranges between 50km and 1,000km in altitude [1]. It is formed by a combination of solar radiations, that is, X-rays and ultraviolet rays, with the atmospheric constituents causing a separation of electrons with atoms [2]. Plasma is

therefore emitted in this layer through ionization. Plasma, which is a collection of charged particles (electrons or ions) [3], is a collective behavior, meaning particles do interact with each other, and with nearby electric and magnetic fields [4]. The density of the electron of this plasma increases alongside the amount of ultraviolet radiation and X-ray emitted by solar flares [5]. There are various ways in which plasma is produced in the universe; neutral atoms are ionized by the high temperatures that exist in stars and ultraviolet radiation ionizes interstellar gases [6]. There is a wide range of temperatures and pressures in both naturally occurring and laboratory plasmas [7]. The plasmas can be classified according to characteristics of permeability, quantum state, density, and classical nature that have been dictated by the parameter of Debye length and frequency depending upon the density of electrons and the temperature [8]. Examples of natural plasmas are lightning, auroras, the solar corona, and solar wind, and artificial plasmas are used in illumination to ozone production among others [9]. The ionospheric character indicates that there is time variance in the diurnal cycle across the ionospheric layers, which develop or weaken according to the sun activity [10]. The least ionized layer is the D one which can only be seen when it is day time. The E layer can be observed during daylight but it is weak or disappears at night [11]. The F layer has two sublayers (F1 and F2) the F1 layer is moderately ionized and only visible in daylight whereas F2 layer is more ionized, electron-rich and can be observed in the day and night [12]. In addition to bouncing off high-frequency radio waves, the ionosphere is also affected by solar events like sunspots and radiation and can hence offer a good source of information in the study of the atmosphere and space sciences [13]. Those correlations have been quantified [14] between the variations in the characteristics of ionospheric and the variations in solar activity. An example is that a single study showed that it is possible to calculate the electron transport coefficients in the ionosphere based on the BolsiG simulation software [15,16]. This has been accompanied by other studies which have dealt with changes in the ionosphere seasonally and recorded the aberrations during solstices and equinoxes [17]. The latest developments in the field of nanotechnology have created new possibilities in terms of improving ionospheric monitoring and characterization of the plasma [18]. Even though this exploration is based on traditional ionospheric information, sensing and nanoscale modelling strategies would definitely enhance the accuracy of measurements of electron density and temperature in the future studies of the ionosphere [19]. This paper particularly analyzes how peak solar activity will have an effect on the plasma characteristics in the F layer of the ionosphere.

2. THE EARTH IONOSPHERE

The Earth's ionosphere is divided into layers based on the abundance of electrons and atoms: the D layer, the E layer, and the F layer, as shown in Figure1. The electron density in the ionosphere varies during the day and night. Only the D, E, and F1 layers are visible during the day, while the D layer disappears in the evening. The E layer weakens, while F1 and F2 merge to form a single layer called the F layer. The F2 layer has the highest electron density during the day, but it does not disappear at night, making it of great importance [15].

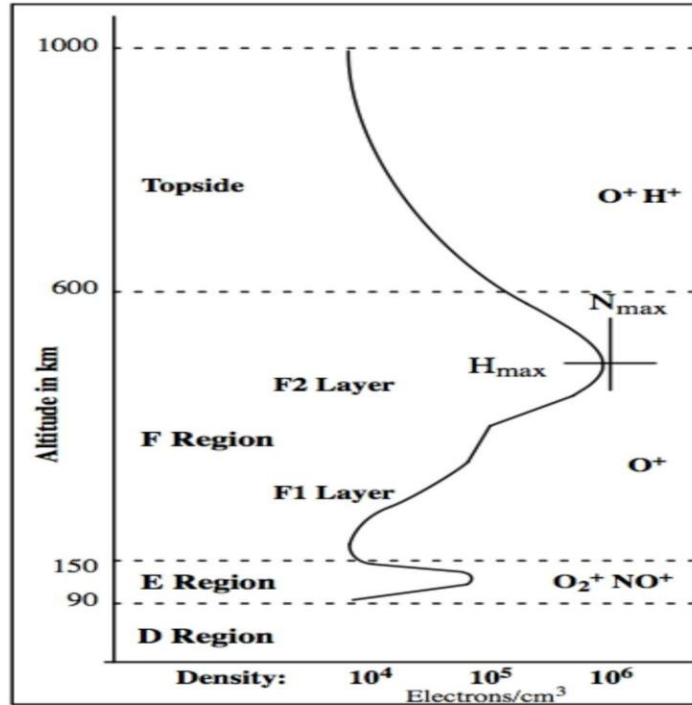


Figure 1 Depiction of the different layers of the Earth's ionosphere [20].

Figure 1 shows that the ionosphere is divided according to the electronic density into the D, E, F1, and F2 Layers. The F Layer has the highest electron density and is therefore the most important. This division is due to the influence of ultraviolet radiation and X-rays emitted from the Sun [20].

3. PLASMA PARAMETERS

Plasma parameters are among the most important physical quantities for studying plasma properties, as they play a significant role in explaining changes in the atmosphere and ionosphere [21]. Studying plasma parameters can explain plasma interactions with magnetic fields, wave propagation, and the effects of solar activity [22].

3.1. Debye length

The Debye length is one of the most important physical parameters. It represents the distance over which the influence of charges remains apparent before shielding or neutralizing the charges within the plasma[23]. The smaller the Debye length, the more tightly packed the plasma is, which distinguishes plasma from ordinary gases[24].

$$\lambda_{De} = \sqrt{\frac{\epsilon_0 k_B T_e}{n_e e^2}} = 69 \sqrt{\frac{T_e}{n_e}} \quad (1)$$

Where: n_e is the density of electrons in m^{-3} , T_e is the temperature in kelvin, Boltzmann constant is ($K_B=1.38 \times 10^{-23} \text{ J.K}^{-1}$), λ_{De} is the Debye length (m), e represents the charge of the electron ($e=1.602 \times 10^{-19} \text{ C}$), and ($\epsilon_0= 8.85 \times 10^{-12} \text{ Fm}^{-1}$).

3.2. Plasma frequency of electron (ω_{pe}):

One of the most important properties of the ionosphere for studying the effect of electromagnetic fields on plasma is the plasma frequency [25], which is the frequency of electron oscillations resulting from their displacement from equilibrium within the plasma [26].

$$\omega_{pe} = \sqrt{\frac{n_e e^2}{\epsilon_0 m_e}} \quad (2)$$

where m_e is electron mass ($m_e = 9.11 \times 10^{-31}$ kg). And the frequency is given by:

$$f_{pe} = \frac{\omega_{pe}}{2\pi} = 8.98 \sqrt{n_e} \quad (3)$$

3.3. Number of particles in a Debye sphere (ND)

One of the most important measures for determining the nature of a medium is that the ND must be large to be considered a plasma medium to which plasma laws apply [27]. This number represents the number of electrons or charged particles within a spherical medium with a radius equal to the Debye length [28].

$$N_D = \frac{4\pi}{3} n_e \lambda_{De}^3 = 1.38 \times 10^6 \frac{T_e^{\frac{3}{2}}}{n_e^{\frac{1}{2}}} \quad (4)$$

3.4. The plasma coupling coefficient (Γ)

The plasma coupling coefficient is the ratio of the magnitude of the hydrostatic interaction to the thermal energy of the charged particles [29]. If $L \ll 1$, the medium is in a weak plasma coupling state, as in the ionosphere, while if $L \gg 1$, the medium is in a strong plasma coupling state, as in neutron stars [30].

$$\Gamma = \frac{1}{(4\pi \lambda_{De}^2 n_e^{2/3})} \quad (5)$$

3.5. Thermal velocity of electron (v_{te})

The thermal velocity of an electron represents the velocity of an electron in a plasma without the influence of electric and magnetic fields. It reflects the extent of electron diffusion within the plasma [31]. Electrons have a higher thermal velocity than ions, due to the difference in mass between them. This is important in calculating the properties of wave reflection and absorption in the ionosphere [32].

$$v_{te} = \omega_{pe} \lambda_{De} \quad (6)$$

$$v_{te} = \sqrt{\frac{k_B T_e}{m_e}} \quad (7)$$

4. INTERNATIONAL STANDARD MODEL FOR IONOSPHERIC PROPERTIES (IRI)

The International Ionosphere Reference Model (IRI) is an international project sponsored by the Committee on Space Research (COSPAR) and the International Union of Radio Sciences (URSI) [33]. IRI provides monthly averages of electron density, electron temperature, ion temperature, and ion composition over the ionospheric altitude range [34]. In this study, the IRI-2020 model is chosen because it is the most recent version based on sunspot and solar flux data [33], as shown in Table 1.

Table 1 Smoothed sunspot numbers (SSN) and the smoothed solar radiative flux (F10.7cm) [33].

Month	SSN-2024	2024 - $F_{10.7}$
Jan.	131.1	164.7
Feb.	136.9	169.5
Mar.	141.4	175.1
Apr.	144.4	180.2
May	149.1	185.4
Jun.	152.8	189.0
Jul.	155.0	191.9
Aug.	156.8	193.4
Sep.	159.3	194.3
Oct.	160.8	194.7
Nov.	158.8	193.7
Dec.	154.7	191.6

5. RESULTS AND DISCUSSION

The results show the importance of the year 2024 as it has the highest solar activity during solar cycle 25. Smoothed sunspot number (SSN) and smoothed solar radio flux ($F_{10.7} \text{ cm}$) which are also relevant to nanoscale plasma processes and nanotechnology-related research show in table (1) [35].

The values of temperature and electron density show variations between the seasons of the year. It is also revealed that there is a difference between the values during the day and night, as the temperature of electron density increased during the day due to solar radiation. Therefore, the time 12 pm is adopted to study the properties of plasma.

Figure 2. shows electron temperature (T_e) changes at an altitude of (150-500) km with an increase of 50 km for the ionosphere layer F in 2024, which represented the peak of solar cycle 25, on the ionospheric plasma over the capital, Baghdad, during the seasons of the year.

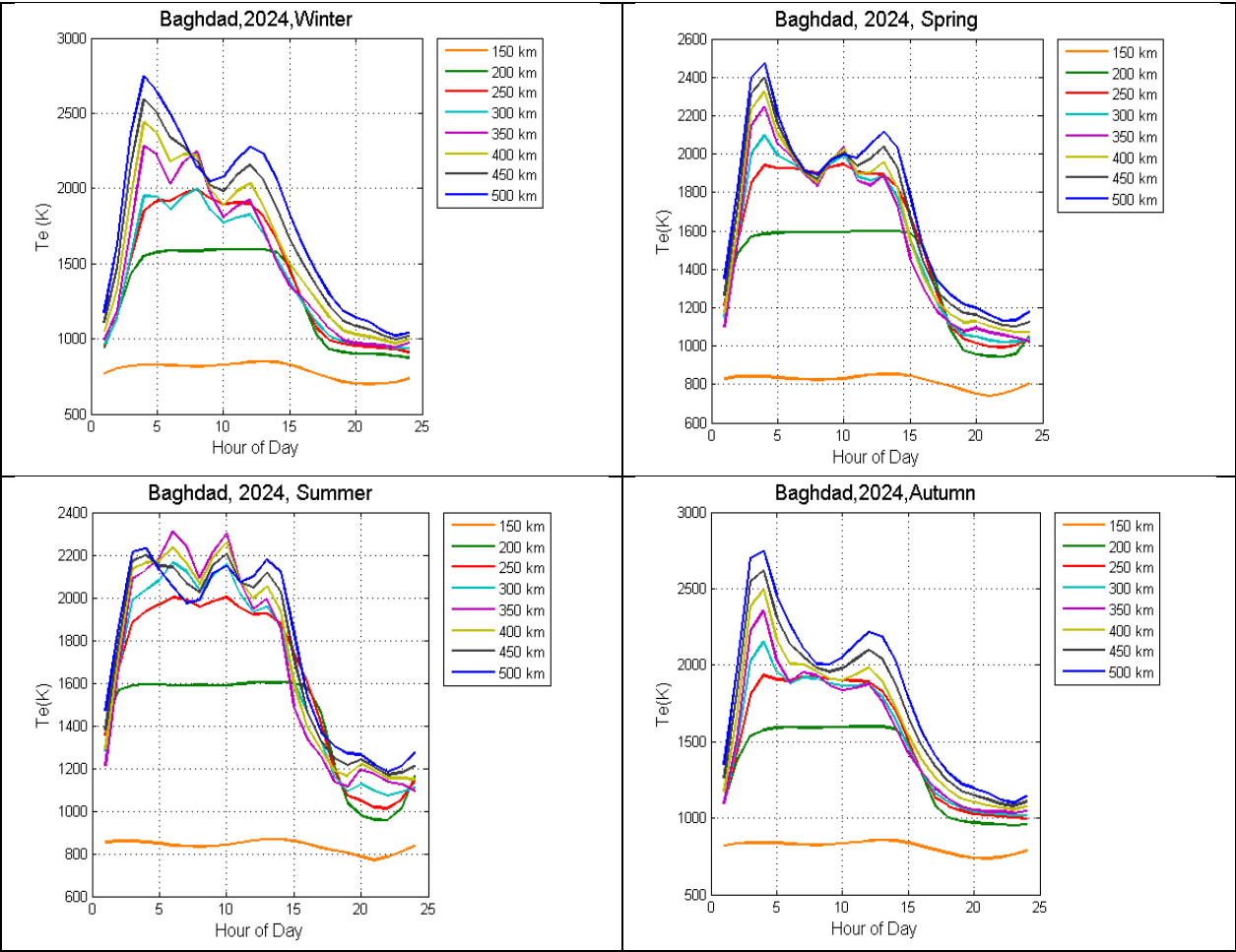


Figure 2 Difference in the electron temperature (T_e) at an altitude of (150-500) km.

Figure 3. shows the density of electrons (n_e) changes at an altitude of (150-500) km with an increase of 50 km for the ionosphere layer F in 2024, which represented the peak of solar cycle 25, on the ionospheric plasma over the capital, Baghdad, during the seasons of the year.

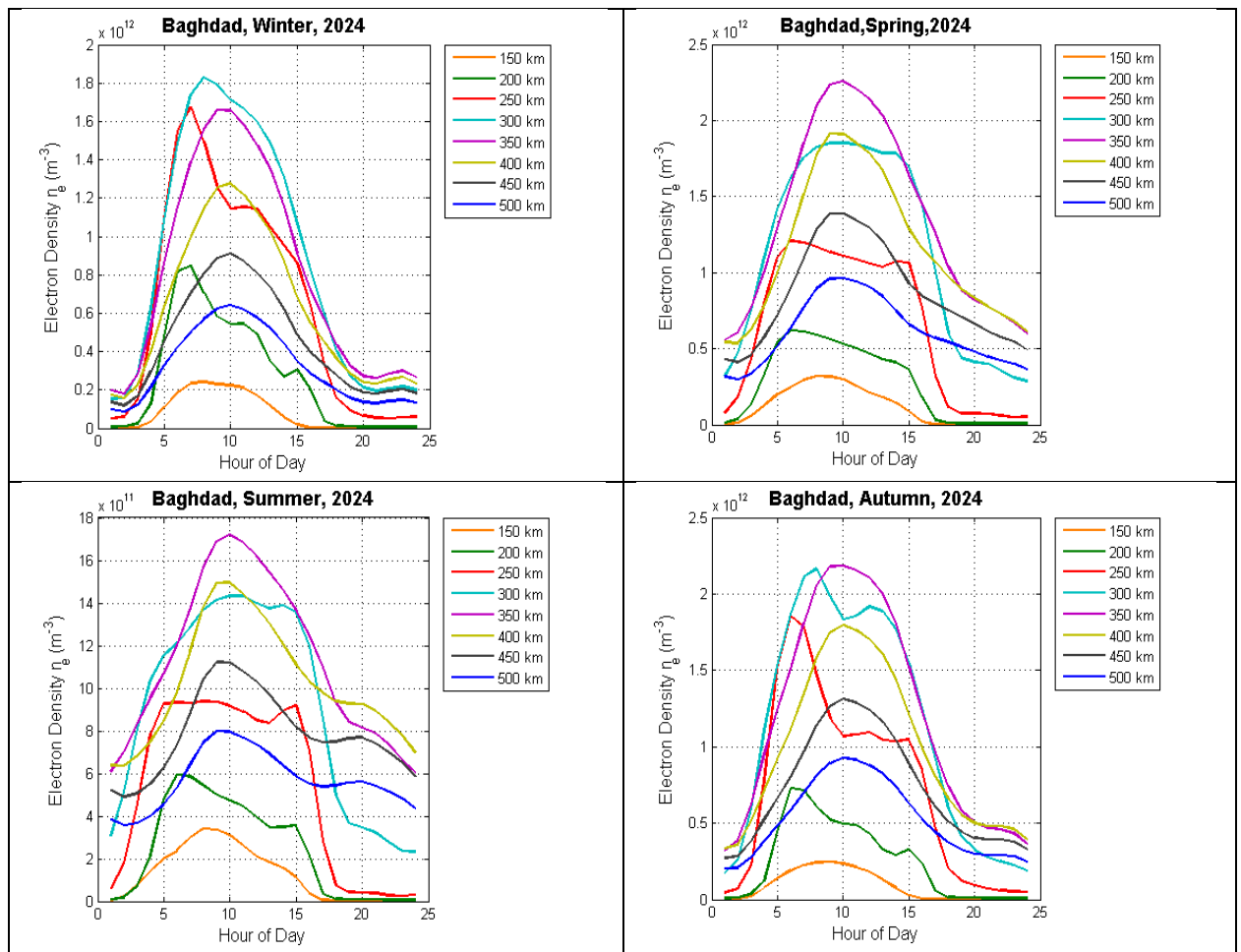


Figure 3 Difference in the density of electrons (n_e) at the altitude range of (150-500) km.

Figure 4. shows the difference in the electron temperature (T_e) at 12 pm at an altitude of (150-500) km with an increase of 50 km for the ionosphere layer F in 2024 during the seasons of the year (winter, spring, summer, and autumn). It is noted that temperatures increase with increasing altitude until they attain their maximum value at an altitude of 500 km.

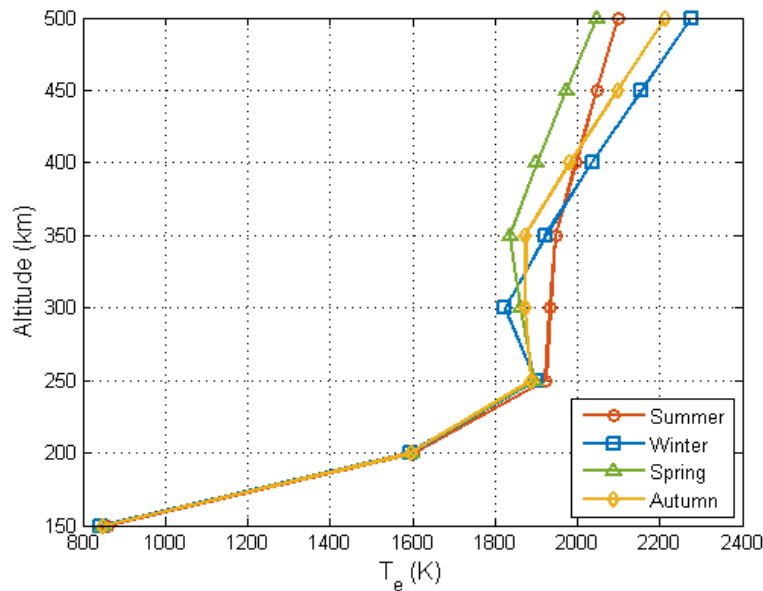


Figure 4 Difference in the electron temperature (Te) at 12 pm at an altitude of (150-500) km.

Figure 5. shows the difference in the electron density (ne) at 12 pm at an altitude of (150-500) km with an increase of 50 km for the ionosphere layer F in 2024 during the seasons of the year (winter, spring, summer, and autumn). It is noted that the electron density increased with increasing altitude until it reached its highest level at an altitude of 350 km due to the chemical composition of this altitude, then it decreased after crossing 350 km.

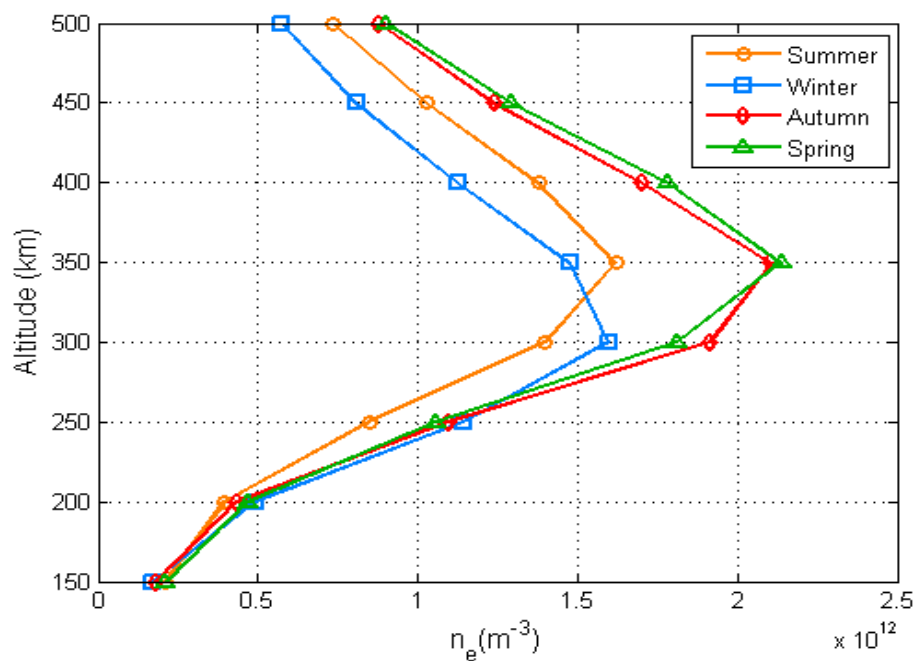


Figure 5 The difference in the electron density (ne) at 12 pm at an altitude of (150-500) km.

Figure 6. shows that the Debye length decreased between 300 and 400 km due to increasing electron density, then began to improve at other altitudes. Due to the increasing density and seasonal fluctuations, the Debye length reached its highest values during the 2024 equinoxes.

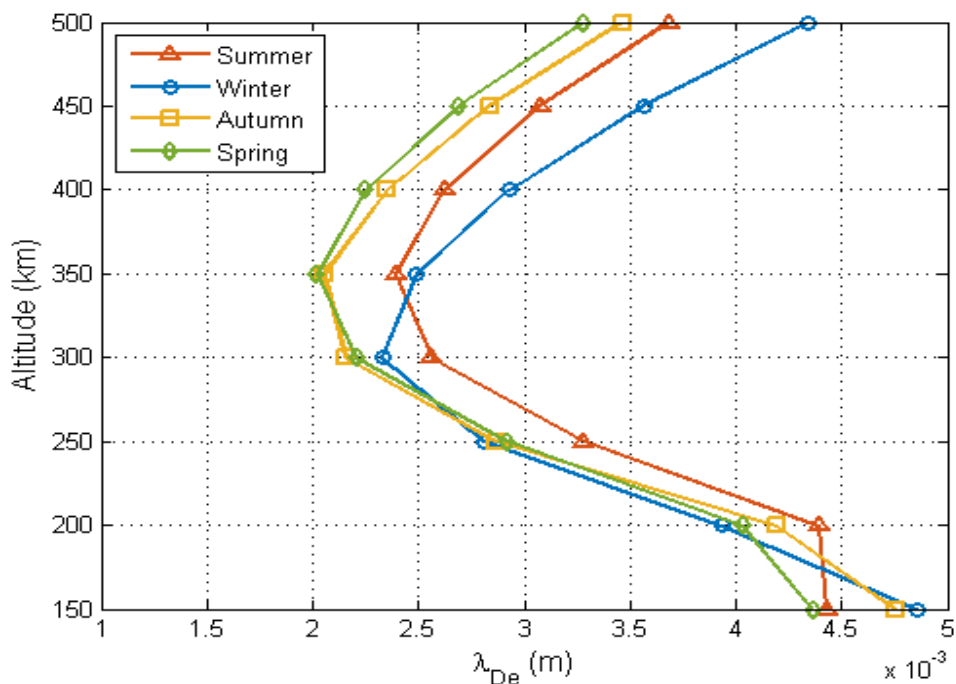


Figure 6 Difference in the Debye length at 12 pm at an altitude of (150-500) km.

Figure 7. shows that the plasma frequency values increased from 150 km to 300 km to 400 km and reached their highest level at 300 to 400 km. This is due to the high ionization at this altitude. It is noted that the plasma frequency during the summer and winter seasons is lower than during the equinoxes.

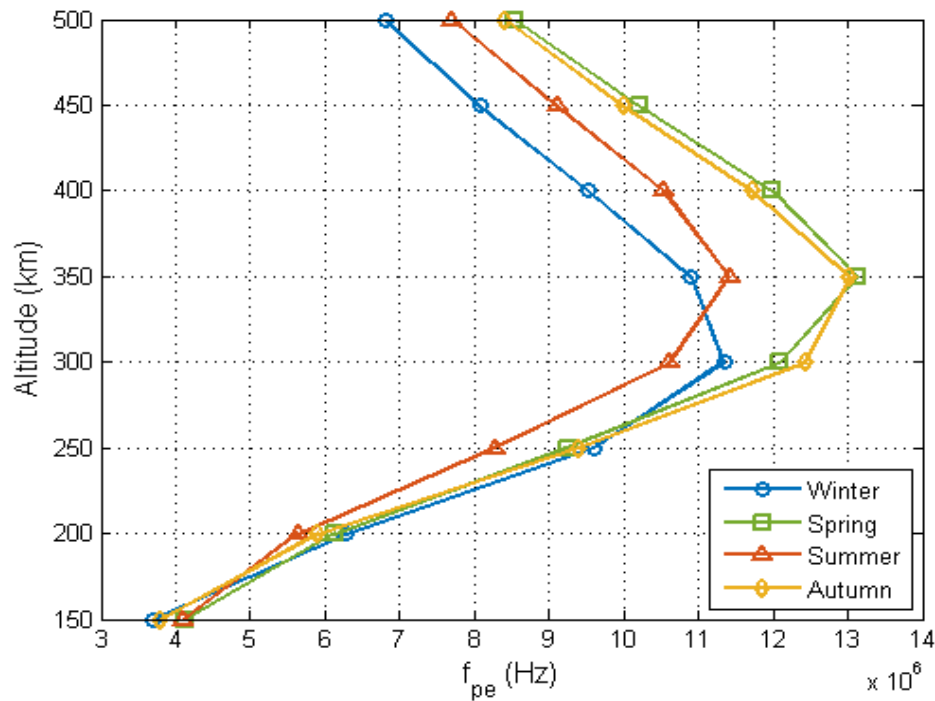


Figure 7 Difference in the plasma frequency at 12 pm at an altitude of (150-500) km.

Figure 8. shows the plasma coupling coefficient (Γ) at its highest level at a height of 150. The values continued to decline, reaching their minimum at an altitude of 200 km, which means that the plasma is weakly bound. Then it increased to reach 350 km, then returned to a decrease at higher altitudes. The results indicate that the plasma coupling coefficient values in summer and winter are lower than during the equinoxes due to the presence of seasonal disturbances.

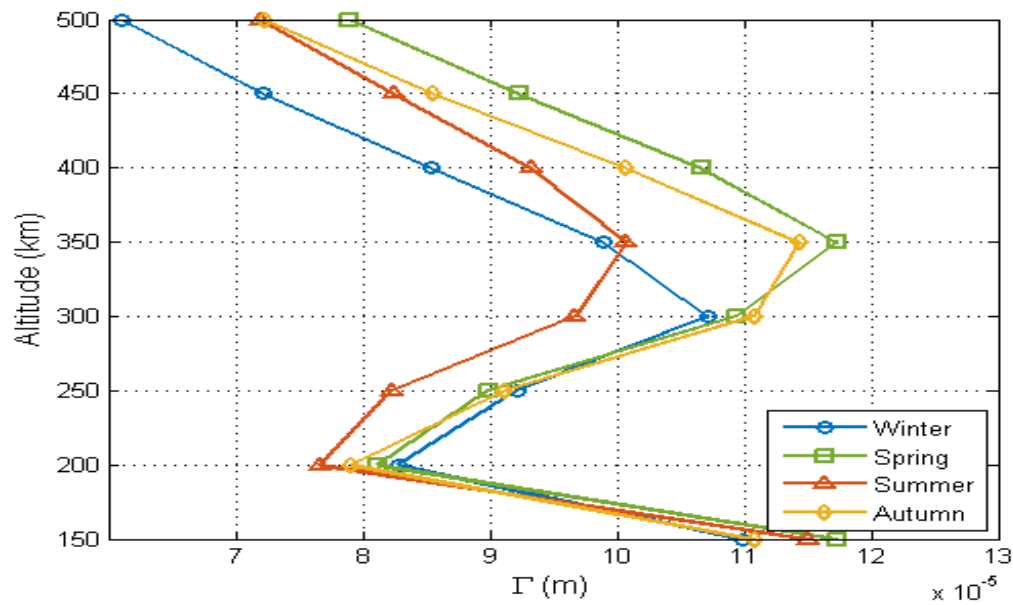


Figure 8 Difference in plasma coupling coefficient (Γ) at 12 pm at an altitude of 150-500 km.

Figure 9. shows the number of particles inside the Debye sphere, where the values rose at an altitude of 200 km, then began to decline to reach their lowest level between 300 and 400 km, to rise again with increasing altitude.

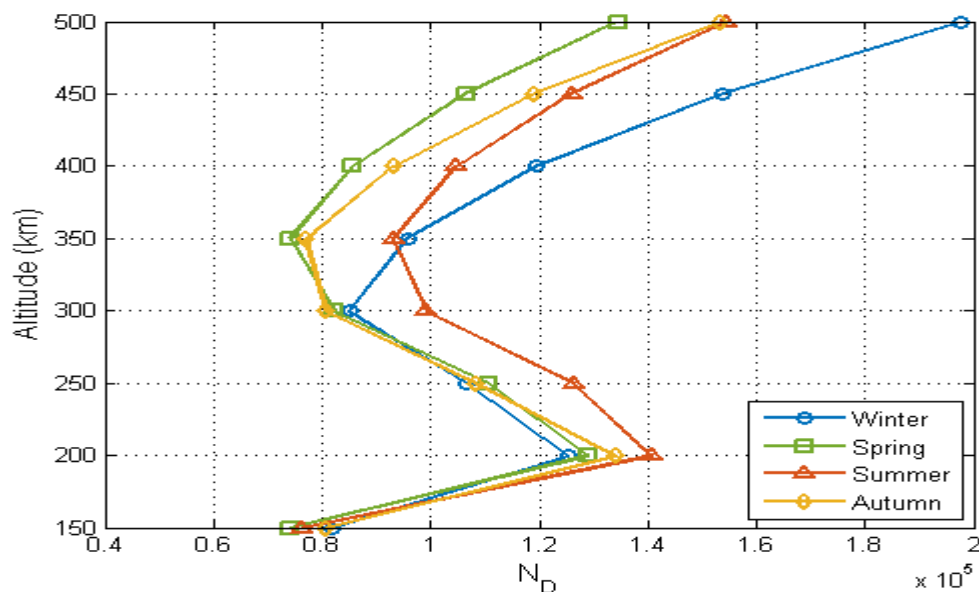


Figure 9 Difference in the number of particles confined within the Debye sphere at 12 pm is shown at an altitude of (150-500) km.

Figure 10. shows the electron's increase in thermal velocity from 150 km to 250 km, after which it began to reach a near-constant level at higher altitudes.

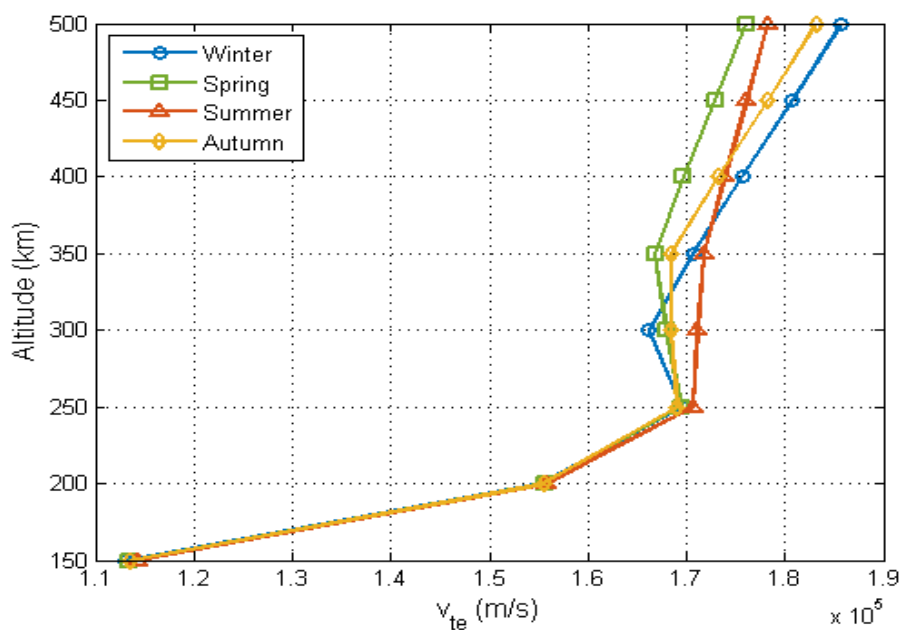


Figure 10 Shows the difference in the thermal velocity at 12 pm at an altitude of (150-500) km.

6. CONCLUSIONS

The study revealed a clear impact of solar activity, represented by the solar radiation flux ($F_{10.7}$ cm), and the number of sunspots during the year 2024, on the electron temperatures (T_e), electron density (n_e), and the ionosphere, which in turn directly affected plasma parameters. It also showed that temperatures at altitudes below 250 km were similar in all seasons, while differences were evident at higher altitudes, reaching their highest values at 500 km, causing an increase in the Debye length (λ_{De}) and the electron thermal velocity. The results also demonstrate the presence of causal relationship between solar activity and electron density in F2 ionosphere that is the most vulnerable layer to perturbations by solar activities. The experiment detected low plasma coupling coefficient ($\Gamma \leq 1$) during all the seasons chosen. Among others, it is notable that temperatures in low altitude did not vary much between seasons and they reached their highest value at the altitude of 500km. This temperature profile enabled an increase in the Debye length and electron thermal velocity which was accompanied by a decrease in the plasma coupling coefficient throughout the life span of the study. These observations highlight the need for monitoring solar activity and ionospheric plasma parameters in real-time for improving space weather predictions and assessing their impacts on communication, navigation, and satellite-based systems. Moreover, the study of plasma behavior across macro ionospheric and nanoscale physical processes is still relevant, especially under high solar activity conditions.

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