IRAQI JOURNAL OF APPLIED PHYSICS
Vol. 22, No. 2, April-June 2026, pp. 289-298

Effect of Solar Wind Speed on Ionospheric Electronic Content Over Baghdad City

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This paper is one of few studies that investigate the effect of the solar wind speed (SWS) on the ionospheric electron content of the ionosphere over Baghdad city based on a statistical analysis of the data obtained during the period 1996-2009 using the International Reference Ionosphere (IRI-2020) model. Vertical variations of main ionospheric parameters such as electron density (Ne), electron temperature (Te), ion temperature (Ti) within an average height interval from 100 to 1000 km are investigated in relation of their correlation with solar wind speed variation along entire solar cycle. The results show that the electron density has a marked peak structure to the altitude of 300-400 km, which corresponds to the F2 layer, exhibits a seasonal change at low altitudes, but irregular variation at high altitudes probably due to geomagnetic disturbances. The correlation analyses show the altitude dependent relations between solar wind speed and ionospheric parameters, weak correlations (R=0.5 for Ne, R=0.002 for Te) at 100 km but strong ones (R=0.85 for Ne, R=0.964 for Te) at 500 km. Because of the dominance of local processes and enough collision with neutral particles between Solar Wind (SW) speed and the ionospheric parameters, the SW speed exerts little effects on the lower ionosphere. However, large and positive correlations are found in the middle and upper ionosphere where reduced atmospheric density allows enhanced coupling between the magnetosphere and ionosphere. The study concludes that, above 300 km, the energy transfer of solar wind dominates the energy of electron and ion heating in the F2 layer region. The results are useful for explaining ionospheric dynamics and space weather impact on the radio system and satellite communication in the Middle East.

Keyword: Solar wind speed; Ionosphere structure; Electron density; IRI-2020 model
Received: 26 July 2025; Revised: 22 October 2025; Accepted: 29 October; Published: 1 April 2026

1. Introduction

The ionosphere plays an important role in the propagation of radio waves and serves as a link between the interactions of the Earth's atmosphere and outer space. It is an ionized layer of the Earth's upper atmosphere, extending approximately 1,000 km above the Earth's surface [1]. Solar wind alters the electron distribution of the ionosphere substantially. Solar wind is a persistent flow of plasma with a large amount of charge and energy coming out of the sun. To comprehend solar-terrestrial relationships, investigation of the ionospheric response to the solar wind is important for our understanding of the nature of this relationship in the upper atmosphere and for their influences on technological systems [2]. The solar wind velocity determines the amount of energy and momentum transported into the Earth's magnetosphere and then into the ionosphere. Variations in the speed of the solar wind in solar events, such as coronal mass ejections, changes in primary solar flux, result in a complicated response of the electron in the ionospheric electron density and temperature structure [3]. The impulsive increase in solar wind speed also enhances the level of magnetic reconnection activity in the magnetosphere, resulting in increased energy flow toward the polar ionosphere; this in turn leads to changes in the ionosphere's ionic conductivity and electron density distribution along the magnetic field lines. This results in variations in the dynamic characteristics and altitude of the ionospheric layers, too. These effects are evidenced in the telecommunications and navigation systems [4].

Recently, some studies have shown that the solar wind speed plays a decisive role for the ionosphere in its response to solar variations and processes such as fast solar wind (HSS) streams can produce a complex response in the ionosphere, including electron density and temperature during geomagnetic storms [5,6]. The energy transferred to the electronic structures of the ionosphere (electrons and ions) depend on the densities and temperature of the electrons and ions when the solar wind strikes them [7].

Numerous investigations of the effect of solar activity on the ionospheric morphology, particularly on the Earth and other planets of the solar system, have been carried out in recent years. This influence can be positive or negative, according to the solar factor, time of the day, season and geographic location. To investigate this effect, particularly for low latitude regions, a study has been carried out at Kolhapur station, India, to investigate this effect using solar storms that occurred on 23 and 24 April 2023 on the TEC and density of the ionosphere. The research found the magnetic storms changed the electron density of the ionosphere significantly, increased in some cases and decreased in others, depending on the severity and the location of the storm in the solar atmosphere [8]. Two years later, in 2025, Wang and his team studied the potential of forecasting solar wind speed and interplanetary sector structure over solar cycles 21 to 25 with potential-field source-surface (PFSS) models applied to photospheric field distribution maps of the sun. The model is based on the observed anti-correlation between the solar wind speed and the expansion factor of coronal magnetic flux tubes. We compare these predictions with direct measurements at Earth orbit by the Wilcox Solar Observatory (WSO) and other observatories (NSO, GONG and HMI). The accuracy of the predictions is best during the declining phases of the solar cycle (with correlation coefficients between 0.35 and 0.5) since recurring fast jets from polar coronal holes also extend latitudinally to smaller-foots subpolar wind streams observed closer to the solar equator. In contrast, the model overpredicted fast winds during solar minimum periods (particularly in 2009 and 2019), due to overestimation of the size of residual coronal holes and distortion of the streamer belt, which may be due to underestimation of the strength of the solar polar field [9]. While Prikryl et al. (2021) attempted to study the effect of coupling high-speed solar winds with the magnetosphere-ionosphere-atmosphere system on heavy rainfall events, floods, and flash floods. The study used superposed epoch (SPE) analyses of solar wind variables and rainfall data from rain gauges and satellites. The results showed an increase in high rainfall rates following the arrival of high-speed solar winds from coronal holes, including recurrences with a solar rotation period of 27 days. Cross-correlation analysis also revealed clear correlations between the green corona intensity, solar wind parameters, and daily precipitation rates, with correlation peaks spaced apart by the solar rotation period. The study confirmed that floods and flash floods tend to occur following the arrival of high-speed solar wind flows. The study suggested that downward gravity waves from the lower thermosphere can be excessively reflected into the upper atmosphere. And trigger an existing moist instability, initiating convection and releasing latent heat, thus intensifying storms [10]. Frolov, Andreeva, and Padokhin (2024) have analyzed the spatial structure of plasma concentration disturbances in the upper and outer layers of the ionosphere, resulting from modification of the F2 layer using powerful short-band (HF) radio waves with O polarization, emitted by the SURA heating facility located in Russia. The results obtained using low-orbit satellite radio tomography enabled the detection of electron concentration that changes at altitudes between 200 and 800 km. The results revealed the formation of low-concentration plasma cavities near the radio wave reflection height, with the formation of plasma-dense regions in the upper layers because of plasma pushed along the geomagnetic field lines. Wave disturbances and regions of strong plasma concentration fluctuations were also observed over a wide range of distances, sometimes exceeding the direct wave-ionosphere interaction zone. The explanation of such structure of radiation is assumed to lie in complicated nonlinear mechanism of interaction of electron beam with plasma, secondary effects, like artificial ion turbulence [11], whose influence leads to distances of hundreds of kilometers from the radiation center. Lei et al. (2020) studied the impact of high-speed solar wind (HSS) on the ionosphere in the recovery phase of the geomagnetic storm on August 2018. Satellite observations and numerical simulations by applying a TIEGCM model indicate that high-speed solar winds remarkably enhanced the electron density at the upper ionospheric regions, in particular in the region of the Aurora oval and at lower latitudes. Results show that HSS induced expansion of the aurora to equatorial and enhanced molecular precipitation during HSS event days; the TEC observed at higher layers increased by up to 2 TECU. The increased penetration of the higher speed solar winds interacting with parts of the IMF Bz also increased the penetration of electric fields into the equatorial plane, enhancing the penetration of the "equatorial jet effect". However, the model used was unable to explain the large increase of more than 10 TECU observed at low latitudes during the same period, suggesting the presence of additional mechanisms that are not yet fully understood. The study explains the importance of HSS as a potential source of positive ionospheric storms during recovery phases and highlights the need for further research to understand the combined effects of solar wind on the upper atmosphere, especially under the relatively calm conditions following geomagnetic storms [6].

2. Methodology

2.1 Study area

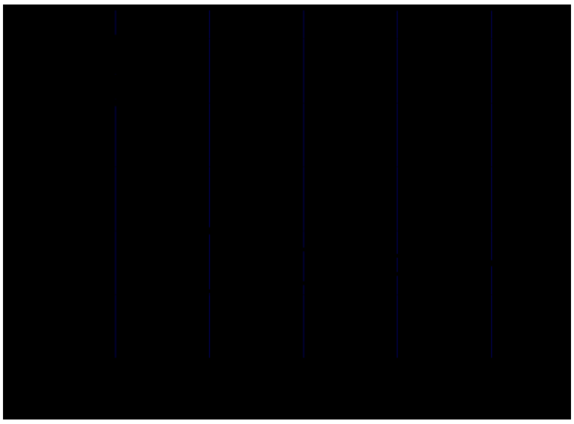
Since Iraq, and specifically Baghdad, is geographically located within the subtropical latitude range of the Northern Hemisphere, between 38.45° and 48.45° east of the Greenwich meridian, and 29.5° and 37.5° north of the equator, Baghdad is the capital of the Republic of Iraq and one of the major cities in the West Asia region. It is also known as the country's administrative and commercial center. Baghdad is located at 33.3° north of the equator and 44.4° east of the Greenwich meridian [12].

2.2 Data set

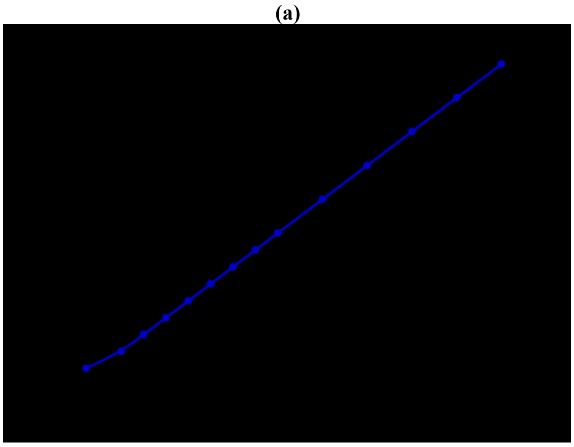
To investigate fluctuations in the solar wind and ionosphere over Baghdad, Iraq, we utilized ionospheric parameters from the International Reference Ionosphere (IRI-2020) model (Bilitza et al., 2022) as well as solar wind speed measurements. IRI-2020 model outputs were obtained from NASA CCMC (https://ccmc.gsfc.nasa.gov/models/IRI~2020/), with NeQuick topside formulation, URSI foF2 coefficients, AMTB-2013 hmF2 model, Ion composition: RBV-2012 model and Neutral atmosphere: NRLMSISE-00. The model was driven by the F10.7 cm solar radio flux index (daily and 81-day running average) provided by NOAA Space Weather Prediction Center through the IRI internal database. Electron density (Ne, m^{-3}), electron temperature (Te, K), and ion temperature (Ti, K) in 100, 150, 200, 300, 400, 500, 600, 700, 800, 900, and 1000 km altitude were derived over Baghdad (33.3°N, 44.4°E) at 12:00 UT each day from January 1996 to December 2009, spanning Solar Cycle 23 (5114 days). Daily solar wind speed (SWS, km/s) data from the OMNI 2 database (https://omniweb.gsfc.nasa.gov/) at 12:00 UT each day from January 1996 to December 2009, which provides time-shifted measurements from multiple spacecraft to the Earth's bow shock. Missing SWS values in gaps ≤3 consecutive days were filled using linear interpolation via Python's pandas library (DataFrame.interpolate(method='linear')); longer gaps were excluded from analysis. Planetary Kp and Ap indices were obtained from GFZ Potsdam (ftp://ftp.gfzpotsdam.de/pub/home/obs/kp-ap/) to account for geomagnetic activity levels.

3. Result and Discussion

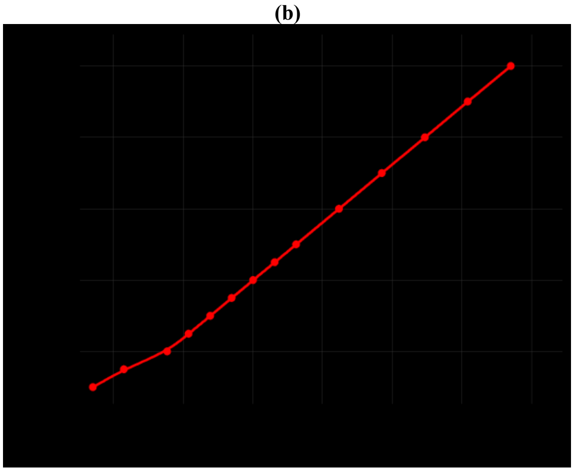
Figure (1) shows the vertical variation of three key ionospheric parameters: (a) electron density (Ne), (b) electron temperature (Te), and (c) ion temperature (Ti). These graphs offer valuable insights into the vertical structure of the ionosphere and its response to various conditions. Figure (1a) shows the vertical distribution of electron density (Ne) as a function of altitude. This figure shows that the electron density starts at relatively low values at low altitudes, then increases significantly, reaching a maximum value at a certain altitude (around 300-400 km), which corresponds to the F2 layer region, or the ionospheric peak. After this peak, the electron density gradually decreases with increasing altitude. This behavior reflects the ionization and recombination processes occurring in the different ionospheric layers (D, E, F1, and F2), where the ion and electron density are highest in the region where the rates of production and loss are balanced. The numerous secondary peaks or significant changes in the density curve indicate the presence of sublayers or complex structures within the ionosphere, which may be affected by conditions such as solar activity or geomagnetic disturbances. Figure (1b) shows the linear variation of electron temperature (Te) with altitude. The electron temperature increases steadily with altitude, starting at relatively low values at low altitudes and reaching much higher values at higher altitudes (about 1000 km). This behavior is attributed to the fact that lighter electrons gain thermal energy more efficiently than heavier ions from solar UV radiation and X-rays. The lower particle density at higher altitudes also reduces the rate of thermal energy transfer from electrons to neutral or ion ions, allowing the electrons to retain their thermal energy and thus have a higher temperature. Figure (1c) shows the vertical variation of ion temperature (Ti). Similar to electron temperature, ion temperature also shows a steady increase with altitude, although the rate of increase and actual temperatures are lower than those of electrons at the same altitudes. This discrepancy between (Te) and (Ti) is a characteristic of the upper ionosphere, which is due to differences in the heating mechanisms of electrons compared to ions and the efficiency of energy exchange between them.



(a)



(b)



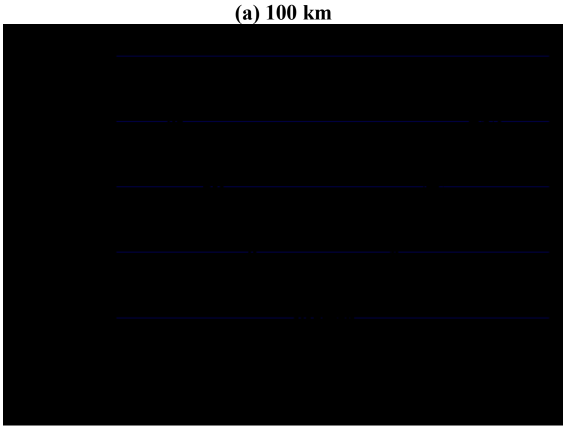
(c)

Fig. (1) The vertical variation of (a) electrons density Ne, (b) electron temperature Te, and (c) Ion temperature Ti

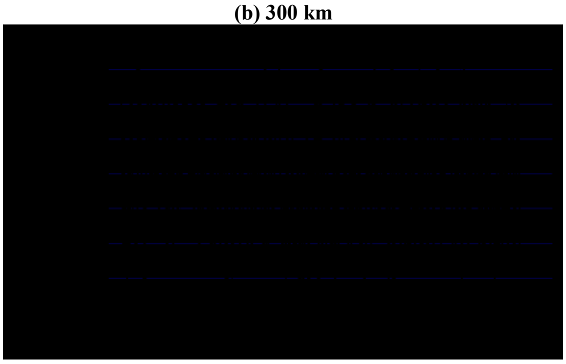
At low altitudes, the ion temperature is close to that of a neutral gas due to frequent collisions. As altitude increases, the particle density decreases, and the efficiency of ion heating by hot electrons increases, resulting in higher ion temperatures. At very high altitudes, the temperatures of electrons and ions tend to converge, as the heat exchange between them becomes more efficient, and both are affected by the temperature of the outer atmosphere. Together, these three figures reveal a comprehensive picture of the complex changes in the physical properties of the ionosphere with altitude. Understanding these changes is crucial for studying upper atmospheric dynamics, radio wave propagation, and the impact of solar activity on Earth's environment.

Figures (2a), (2b), and (2c) illustrate the annual variation of ionospheric electron density (Ne) over Baghdad during 1996 at selected altitudes of 100 km, 300 km, and 800 km, respectively. These graphs highlight the complex dynamics of the ionosphere and its influence on various factors throughout the year. Figure (2a) - at 100 km altitude - shows a clear change in electron density during 1996, with values ranging between approximately 1.5×10^{11} and 3.2×10^{11} electrons/cm³. A near-sinusoidal pattern can be observed, with electron density reaching its lowest levels in the middle of the year (summer months) and gradually increasing during the spring and autumn, reaching its peak at the end of the year and the beginning of the following year. This behavior is consistent with seasonal changes in solar radiation and solar azimuth, which directly affect ionization and recombination processes in the D and E layers of the ionosphere. The decrease in summer may be due to increased recombination rates due to higher temperatures. In Fig. (2b), at 300 km, which lies within the F2 layer, the electron density shows a similar pattern to the mid-year decrease and the peripheral increase, but with higher values ranging from approximately 1.0×10^{12} to 2.0×10^{12} electrons/cm³. This higher density compared to 100 km is normal because the F2 layer is the most ionized layer of the ionosphere, and electron density is highest there. The similar seasonal pattern at 100 km confirms that solar radiation remains an important factor controlling electron density even at these altitudes, although plasma dynamics (such as diffusion and ionospheric winds) play a more prominent role here. Figure (2c) - at 800 km altitude - shows a strikingly different behavior. Although there is some variation, the clear seasonal decline pattern seen at the lower two altitudes becomes much less pronounced. Electron density values here range from 6.0×10^{8} to 6.8×10^{8} electrons/cm³, which is much lower than at lower altitudes. This suggests that we have entered the upper ionosphere (chromosphere plasma) region, where electron densities are strongly influenced by fluxes from the Earth's plasmasphere and polar winds. The large and irregular fluctuations at this altitude may indicate influences from geomagnetic events, such as sub-magnetic storms or other geomagnetic disturbances, as well as the dipolar propagation processes that become dominant at these altitudes. The lack of a clear seasonal pattern can be explained by the fact that electron density at this altitude is less affected by changes in direct solar radiation and depends more on the flux of ions and electrons into and out of the plasmasphere. These figures clearly show how the behavior of electron density changes with altitude in the ionosphere. While seasonal variations related to solar radiation dominate at low and medium altitudes (100 and 300 km), complex dynamical processes and space weather effects become dominant factors at high altitudes (800 km).

(a) 100 km



(b) 300 km



(c) 800 km

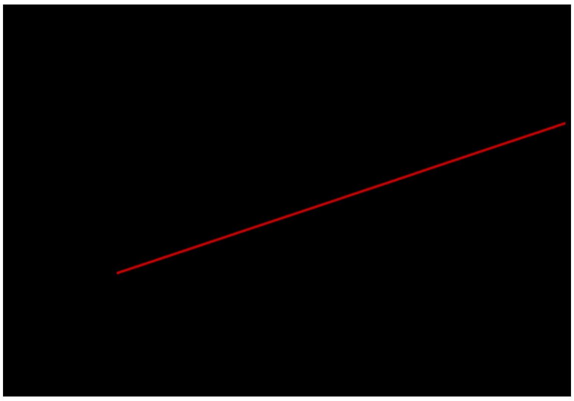
Fig. (2) Annual electron density variation behavior for the year 1996 in selected altitudes over Baghdad city (a) 100 km, (b) 300 km, and (c) 800 km

For time series of solar wind speed over the entire solar cycle (1996-2009), figure (3) presents the time series of solar wind speed (SWS) measured in kilometers per second (km/s) for the period from 1996 to 2009. The solar wind is a continuous stream of charged particles (plasma) emitted from the Sun's outer atmosphere (the solar corona). It plays a crucial role in controlling the dynamics of Earth's magnetosphere and many space weather phenomena. The graph shows a marked variation in solar wind speed over this period, which covers almost a complete solar cycle (Solar Cycle 23, which began in May 1996, peaked around 2000-2001, and ended in December 2008). Observed speeds generally range between about 350 km/s and 650 km/s, with periods of high speeds (fast solar wind) and periods of low speeds (slow solar wind). The main features observed in Fig. (3) are: Long-term (solar cycle) variability.

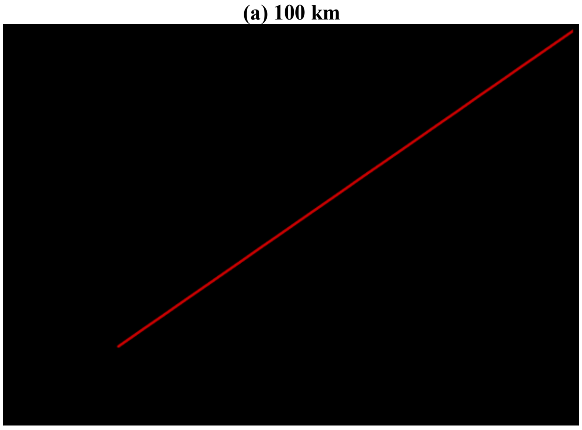
Fig. (3) Time series of solar wind speed to the period 1996-2009

The average solar wind speed does not remain constant throughout a solar cycle. Fast solar winds tend to occur more frequently and more strongly during the waning phase of the solar cycle and solar minimum. While slow solar winds are more common near solar maximum, peak solar activity is also characterized by fast jets associated with coronal mass ejections (CMEs) and solar flares. Figure (3) shows significant daily and weekly fluctuations in solar wind speed. These fluctuations reflect changes in the solar structures from which the solar wind stream originates. For example, fast solar winds are typically associated with coronal holes, open regions in the Sun's magnetic field that allow plasma to be accelerated away from the Sun. Slow solar winds typically originate from regions near the solar equator over regions of intense activity. Relationship to Solar Activity 1996-2001 (Rise and Maximum); This period shows an increase in solar wind speed, with several peaks that may be associated with increased solar activity, coronal mass ejections, and flares. 2002-2006 (Declining Phase): The solar wind tends to exhibit more regular and robust fast flows during this period, often associated with the emergence of stable coronal mass ejections in the Sun's polar regions and their extension toward the equator. 2007-2009 (Solar Minimum): During this period, which represents the deep solar minimum between cycles 23 and 24, an overall decrease in the average solar wind speed can be observed. However, periods of high speeds persist, indicating the persistence of acceleration mechanisms even during periods of low solar activity.

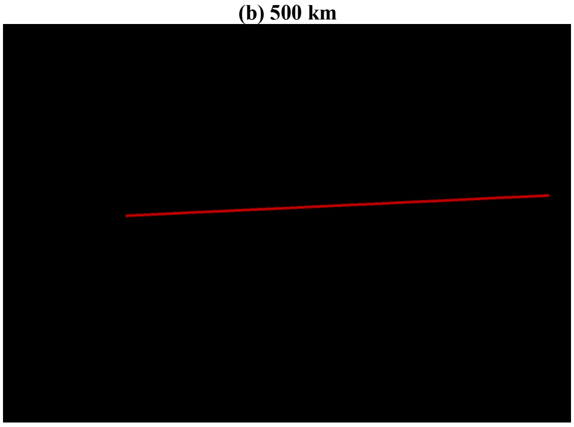
Figures (4a), (4b), and (4c) present an analytical study of the relationship between solar wind speed (SWS) and ionospheric electron density (Ne) over Baghdad at three different altitudes: 100 km, 500 km, and 1000 km. In relationship at 100 km, figure (4a) shows the distribution of data points representing electron density versus solar wind speed at 100 km. The electron density at this altitude (the E layer) primarily represents the product of ionization by solar X-rays and extreme UV radiation. A linear correlation coefficient (R) value of 0.5 shows a moderate positive relationship between solar wind speed and electron density. The linear relationship indicates that an increase in solar wind speed is associated with an increase in electron density. This relationship can be explained by the fact that a higher solar wind speed may reflect higher levels of overall solar activity (such as solar flares or coronal mass ejections), which in turn leads to increased ionizing solar radiation, enhancing ionization in the E layer. In Fig. (4b), the relationship at 500 km altitude (within the upper F2 layer) between solar wind speed and electron density becomes significantly stronger, with a correlation coefficient (R) of 0.85. The linear relationship indicates a strong positive correlation, with an increase in solar wind speed leading to a larger increase in electron density compared to an altitude of 100 km. This strong correlation is attributed to the F2 layer being the most sensitive layer to changes in the solar wind and geomagnetic disturbances. Fast solar winds are typically accompanied by increased energy and matter transfer to the Earth's magnetosphere, heat in the thermosphere, and changes in the composition of the ionosphere, thus affecting electron density through complex mechanisms involving changes in ionization, recombination, and diffusion processes. Figure (4c) shows the relationship between solar wind speed and electron density at 1000 km (within the upper ionosphere/lower plasmasphere) shows a significant weakening, with a correlation coefficient (R) of only 0.04. This indicates that solar wind speed has little effect on electron density at this altitude. This weak correlation can be explained by the fact that electron density at very high altitudes is more influenced by dipolar flows into and out of the Earth's plasmasphere, temperature changes, and electric field effects, rather than the direct influence of solar wind speed, which is more pronounced in the denser layers affected by direct solar flows. The upper ionosphere is also less affected by direct ionization from solar radiation and is dominated by different dynamical processes. These relationships highlight the large variation in the effect of solar wind speed on ionospheric electron density with altitude. While there is a clear positive relationship, the strength of which increases from low altitudes to the F2 layer (100 km to 500 km), it weakens significantly at very high altitudes (1000 km). This suggests that the physical mechanisms controlling electron density change significantly with altitude, and that different layers of the ionosphere respond differently to the external conditions of the solar wind. These findings contribute to a deeper understanding of ionospheric dynamics and their interactions with space weather.



(a) 100 km



(b) 500 km



(c) 1000 km

Fig. (4) The effect of solar wind speed on the electron density in the ionosphere over Baghdad at different altitudes (a) 100 km, (b) 500km and (c) 1000 km

Table (1) indicates that the influence of the solar wind on the ionosphere varies with altitude. At lower altitudes, where the atmospheric density is higher, the complex processes of ionization, recombination, and transport may have the greatest influence on electron density, reducing the direct impact of the solar wind. However, at higher altitudes, the interaction of the solar wind with the ionosphere becomes more pronounced, resulting in a strong linear relationship with electron density. This relationship may be related to the influence of the solar wind on the flux of energy and particles into the ionosphere, which affects electron production and distribution. The table also shows that there is a linear relationship between solar wind speed and electron density, but the strength and direction of this relationship vary significantly with altitude. The relationship is weak at low altitudes and becomes very strong in the upper ionosphere, emphasizing the important role of the solar wind in ionospheric dynamics at high altitudes. These variations require further analysis to understand the physical mechanisms underlying these relationships at different atmospheric layers. Figure (5) shows the vertical variation of the correlation coefficient between the solar wind speed (SWS) and the electron density (Ne).

Table (1) Linear relationship parameters and correlation coefficient values for the independent parameter solar wind speed (SWS) and the dependent parameter electron density (Ne) for different altitudes for N=5114

Heights	Model	a	b	R	P
100	Linear	8.7	4.8	0.5	< 0.0001
150	Linear	1.8	1.3	0.06	0.2
300	Linear	-8.6	5	0.6	< 0.0001
400	Linear	1.3	4.6	0.85	< 0.0001
500	Linear	5	1.7	0.85	< 0.0001
600	Linear	1.4	6.8	0.84	< 0.0001
700	Linear	6.6	2.3	0.84	< 0.0001
800	Linear	2.4	8,5	0.85	< 0.0001
900	Linear	9	3	0.85	< 0.0001
1000	Linear	6.2	3	0.04	0.5

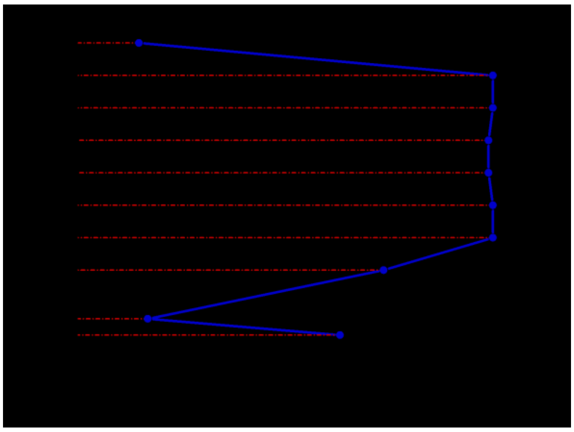
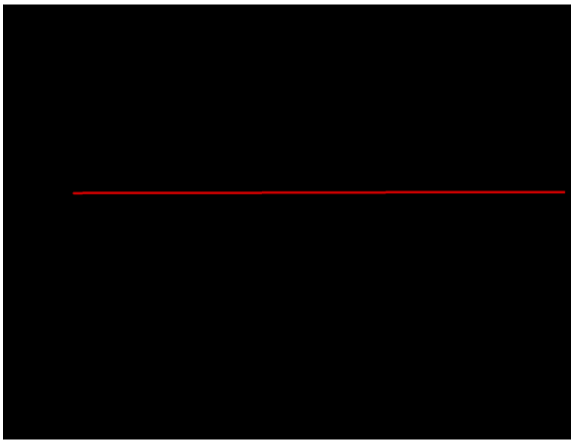
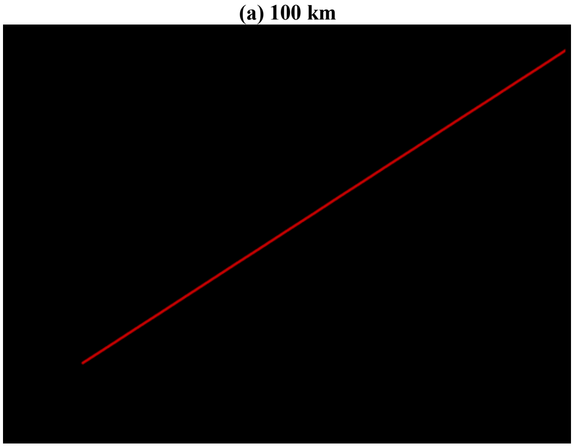


Fig. (5) The vertical variation of the correlation coefficient between the solar wind speed (SWS) and the electron density (Ne)

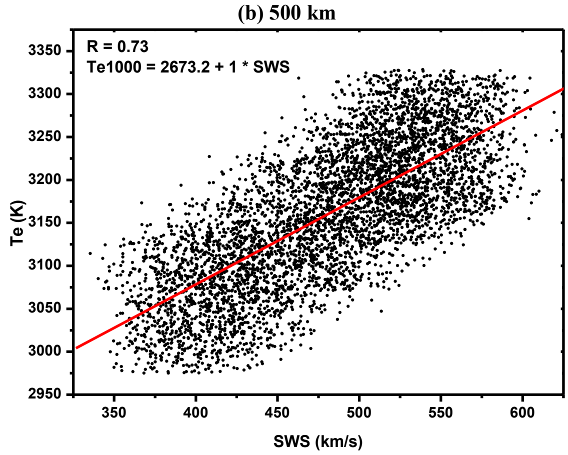
Figure (6) presents three scatter plots illustrating the relationship between solar wind speed (SWS) and ionospheric electron temperature (Te) over Baghdad, at representative altitudes of 100 km, 500 km, and 1000 km. These plots highlight the differential effect of solar wind on the thermal properties of ionospheric plasma depending on altitude. Figure (6a) shows an almost complete lack of relationship between solar wind speed and electron temperature at 100 km altitude. This is evident from the random scattering of points and the lack of a clear trend, as well as the extremely low correlation coefficient (R) value of 0.002. This value indicates that solar wind speed does not significantly contribute to determining electron temperature at this altitude. The linear equation (Te = 400 - 0*SWS) reflects this observation. The slope of the line is nearly zero, meaning that Te remains constant at about 400 K regardless of SWS changes. This behavior is attributed to the fact that the ionosphere at this altitude (the D/E layer) is largely influenced by local ionization and recombination processes, primarily driven by solar ultraviolet radiation and X-rays, rather than by the dynamics directly associated with the solar wind. The high atmospheric density at this altitude also leads to a high frequency of collisions between electrons and neutral molecules, which cools the electrons, bringing their temperature closer to that of a neutral gas and reducing their response to changes in the external magnetic environment. In stark contrast, figure (6b) shows a very strong positive linear relationship between solar wind speed and electron temperature at 500 km altitude. The high correlation coefficient (R = 0.964) indicates that SWS is the dominant factor determining Te at this altitude. The linear equation (Te500 = 1172.4 + 1*SWS) clearly expresses this relationship, with Te increasing significantly with increasing SWS. This strong relationship can be explained by the direct influence of the solar wind on the Earth's magnetosphere and the subsequent transfer of energy and particles to the upper ionosphere (F-layer). Increasing solar wind speed increases the rate of magnetic reconnection, increases energy deposition in the ionosphere, and effectively heats electrons. At this altitude, the neutral density is much lower, reducing collisions and facilitating the accumulation of thermal energy in electrons due to energy flows from the magnetosphere. Figure (6c) - at 1000 km - also shows a positive linear relationship between solar wind speed and electron temperature, with a correlation coefficient (R = 0.73) that is considered strong but lower than that recorded at 500 km. The linear equation (Te1000 = 2673.2 + 1*SWS) indicates that Te responds to increasing SWS, but the degree of response (slope) is slightly lower compared to 500 km. This slight decrease in correlation strength at 1000 km can be attributed to several factors. At these high altitudes, the plasma becomes less dense, and the dynamics of the outer magnetosphere and open magnetic field lines play a greater role in controlling the energy flow. Hot electrons escaping may affect open magnetic field lines, or the presence of other heating sources, such as ion waves and plasma waves, may disrupt the direct correlation with SWS compared to 500 km, where electrons are better confined within closed field lines and directly affected by solar wind changes.



(a) 100 km



(b) 500 km



(c) 1000 km

Fig. (6) The effect of solar wind speed on the electron Temperature in the ionosphere over Baghdad at different altitudes (a) 100 km, (b) 500km and (c) 1000 km

According to table (2), which includes the parameters of the linear relationship and the values of the correlation coefficient (R) between solar wind speed (SWS) as the independent variable and electron temperature (Te) as the dependent variable, at different altitudes in the ionosphere, the data show that the effect of solar wind speed on ionospheric electron temperature is strongly altitude-dependent. While the effect is negligible in the lower ionosphere due to the dominance of local processes and collisions, the influence of the solar wind becomes dominant and very significant in the middle and upper ionosphere (above 300 km). This suggests that the energy flow from the solar wind to the magnetosphere and ionosphere becomes a major factor in electron heating at these altitudes. However, the strength of the correlation may decline slightly at higher altitudes (above 500 km) due to other potential physical mechanisms affecting the plasma dynamics in those layers.

Table (2) Linear relationship parameters and correlation coefficient values for the independent parameter solar wind speed (SWS) and the dependent parameter electron temperature (Te) for different altitudes for N=5114

Heights	Model	a	b	R	p
100	Linear	399	2.3	0.002	0.8
150	Linear	1051	-0.3	-0.2	0.4
300	Linear	572	1	0.87	< 0.0001
400	Linear	870	1	0.86	< 0.0001
500	Linear	1172	1	0.84	< 0.0001
600	Linear	1476.5	1	0.82	< 0.0001
700	Linear	1774.4	1	0.8	< 0.0001
800	Linear	2068.3	1	0.78	< 0.0001
900	Linear	2374	1	0.76	< 0.0001
1000	Linear	2673.2	1	0.73	< 0.0001

Figure (7) confirms that the effect of solar wind velocity on the ionospheric electron temperature (Te) varies significantly with altitude. The effect is very weak or nonexistent in the lower ionosphere, increases dramatically to a peak in the middle ionosphere (about 300 km), and then remains strong but gradually decreases at higher altitudes. This result highlights the structural complexity of the ionosphere and the interaction of various physical processes (ionization, recombination, collisions, and energy fluxes from the magnetosphere) in determining the thermal properties of the ionospheric plasma at different altitudes.

Figure (8) presents three scatter plots illustrating the relationship between solar wind speed (SWS) and ion temperature (Ti) in the ionosphere over Baghdad at three representative altitudes: 100 km, 500 km, and 1000 km. These plots highlight how the effect of solar wind on the thermal properties of ions changes with altitude, reflecting the different physical processes that dominate each ionosphere. Figure (8a) shows a very weak relationship between solar wind speed and ion temperature at 100 km altitude. This is evident from the wide scatter of points, the lack of a clear linear trend, and the correlation coefficient (R) value of -0.07. This value, close to zero, indicates that solar wind speed has no significant or direct effect on ion temperature at this altitude.

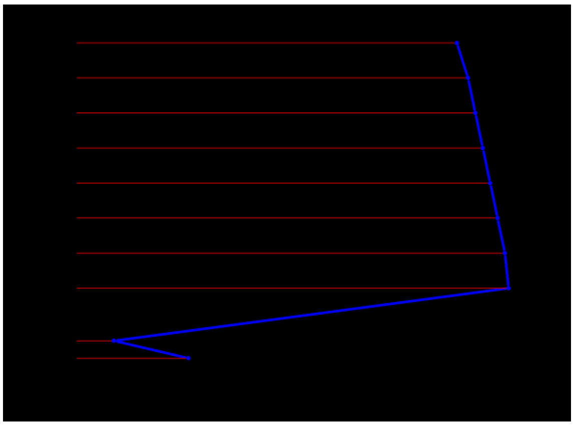
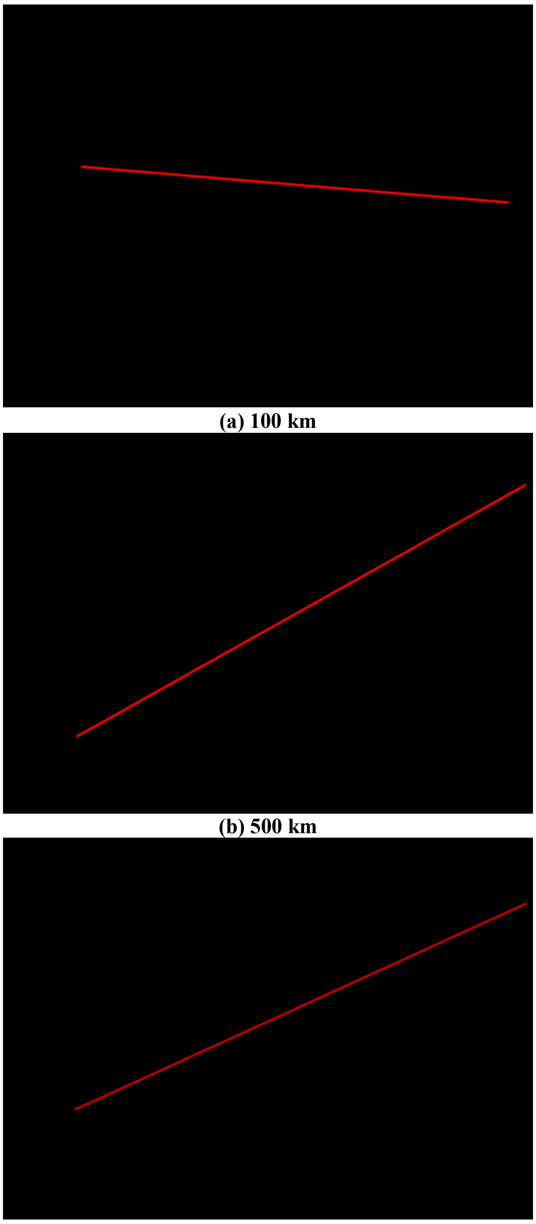


Fig. (7) The vertical variation of the correlation coefficient between the solar wind speed (SWS) and the electron Temperature (Te)

The linear equation (Ti100 = 328.2 + (-0.01)*SWS) reflects this observation, with a negative slope and a very small value. In this lower layer of the ionosphere (layers D and E), the atmospheric density is very high, and frequent collisions between ions and neutral particles dominate energy exchange. Therefore, the ion temperature is closely related to the neutral gas temperature, which is mainly influenced by solar radiation and local dynamical processes in the lower atmosphere, rather than directly by solar wind changes. In stark contrast, Figure (8b) shows a very strong and clear positive linear relationship between solar wind speed and ion temperature at an altitude of 500 km. The high correlation coefficient (R = 0.79) confirms that solar wind speed is a major factor in determining ion temperature at this altitude. The linear equation (Ti500 = 1164.6 + 0.8*SWS) shows a significant positive slope, meaning that an increase in solar wind speed leads to a corresponding increase in ion temperature. This strong relationship can be explained by the increasing influence of solar wind interactions with Earth's magnetosphere. At this altitude (F2 layer), the density of neutral particles has decreased significantly, reducing collisional cooling of ions. Consequently, ions become more susceptible to heating from the energy fluxes coming from the magnetosphere, which arise from magnetic reconnection processes, Birkeland currents, and the deposition of energetic particles associated with the increased solar wind speed. Figure 8c at 1000 km also shows a positive linear relationship between solar wind speed and ion temperature, with a correlation coefficient (R = 0.7) that is considered strong but slightly lower than that recorded at 500 km. The linear equation (Ti1000 = 2501.5 + 0.52*SWS) indicates that the ion temperature responds to increasing SWS, but with a lower slope compared to 500 km. At these higher altitudes, where the plasma is less dense, other factors such as thermal conduction along magnetic field lines, escape plasma flux, and outer magnetospheric dynamics may contribute to modulating the ion temperature. Although the solar wind remains an important factor, these processes may slightly reduce the strength of the direct correlation between SWS and Ti compared to the optimal altitude for direct influence at 500 km.



(a) 100 km

(b) 500 km

(c) 1000 km

Fig. (8) The effect of solar wind speed SWS on the Ion Temperature Ti in the ionosphere over Baghdad at different altitudes (a) 100 km, (b) 500km and (c) 1000 km

Table (3) provides strong evidence that the influence of solar wind speed on ion temperature in the ionosphere is strongly altitude-dependent. While the lower ionosphere (at 100 km) shows little response to solar wind changes due to the dominance of collisions with neutral particles, a dramatic shift occurs at about 150 km and above, where the solar wind becomes the decisive factor in determining ion temperature. This shift is attributed to the decreasing density of neutral gas, which enhances the coupling of the ionosphere to geomagnetic phenomena driven by the solar wind. The continuous increase in the slope of the relationship with altitude confirms that ions in the upper layers become more sensitive to changes in the solar wind due to their weaker coupling to the neutral layers and their increased exposure to energy fluxes from the magnetosphere. Although the correlation remains strong at high altitudes, the slight decrease in R values may indicate an increasing role for other mechanisms, such as ion thermal conduction or complex plasma interactions in the outer magnetosphere.

Table (3) Linear relationship parameters and correlation coefficient values for the independent parameter solar wind speed (SWS) and the dependent parameter ion temperature (Ti) for different altitudes for N=5114

Heights	Model	a	B	R	p
100	Linear	326.2	- 0.01	- 0.07	0.9
150	Linear	79.4	0.81	0.88	< 0.0001
300	Linear	613.2	0.91	0.82	< 0.0001
400	Linear	886.9	0.9	0.8	< 0.0001
500	Linear	1154.5	0.9	0.79	< 0.0001
600	Linear	1423.8	0.9	0.78	< 0.0001
700	Linear	1692.2	0.91	0.76	< 0.0001
800	Linear	1964.2	0.91	0.75	< 0.0001
900	Linear	2239.2	0.9	0.71	< 0.0001
1000	Linear	2501.5	0.92	0.7	< 0.0001

Figure (9) provides strong visual evidence that the ionospheric temperature response to solar wind speed changes is a strong function of altitude. While the lower layers of the ionosphere exhibit almost complete separation from the influence of the solar wind, the middle and upper layers become highly coupled, highlighting the complex and interconnected processes that govern ionospheric dynamics and temperature in the face of changing solar wind conditions.

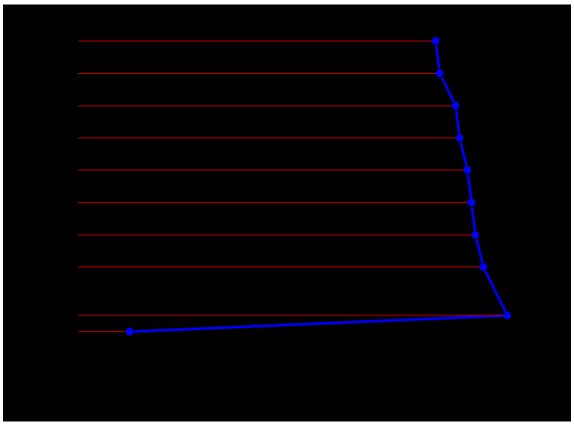


Fig. (9) The vertical variation of the correlation coefficient between the solar wind speed (SWS) and the ion temperature (Ti)

4. Conclusion

The results obtained in this paper reveal clear vertical changes in the electronic structure of the ionosphere over Baghdad city as follows. The electron density rises until it reaches a peak at approximately 300-400 km (the F2 layer). Thereafter, it gradually decreases with altitude. While the temperatures of electrons and ions increase with altitude, significant differences between them appear at intermediate altitudes. The results revealed a striking seasonal behavior of electron density at low altitudes: In 1996, the data showed that electron density varies seasonally, decreasing in the summer and increasing in the winter, spring, and autumn at low altitudes (100 km and 300 km). At 800 km, however, there is no clear seasonal pattern, but rather sharp fluctuations resulting from magnetic disturbances. The solar wind cycle has a long-term impact. Shows that solar wind speed follows a pattern consistent with the solar activity cycle (1996–2009), with fast winds being more common during periods of decline and minimum solar activity. There appears to be an effect of solar wind speed on electron density. The relationship between solar wind speed (SWS) and electron density (Ne) varies with altitude. It is weak at 100 km (lower layers) and very strong at 500 km (F2 layer), while it is very weak at 1,000 km (upper layer/plasma). This result indicates that the greatest influence of the solar wind is current in the middle layer of the ionosphere. Electron temperature (Te) is strongly affected by the solar wind at high altitudes. The effect is almost nonexistent at 100 km and very strong at 500 km. At 1000 km, the effect is still strong, but to a lesser degree. This result means that the solar wind contributes effectively to heating the electrons, especially in the upper layers of the ionosphere. The temperature of the Ti ions also increases with increasing solar wind speed, with the effect being negative and very weak at 100 km, strong at 500 km, and strong but to a lesser degree at 1000 km. This indicates that ions are also affected by the solar wind temperature, but to a lesser extent than electrons. These results were based mainly on the calculations of the IRI2020 model, and thus these results (while important) require similar studies in the same region to support or improve the accuracy of the results. Therefore, this work can be considered a first step on the road.

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