Anomalies in the Ionospheric F2 layer - A brief review

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Abstract- Ionosphere, upper part of the Earth's atmosphere, is mainly divided into D, E, F1 and F2 layers. F2 layer is the most important layer as it persists through day and night while the other layers vanish at night. The ionospheric layers are expected to be solar controlled behavior. However, it was observed that F2 layer occasionally deviates in electron density and height from solar controlled behavior. These deviations are termed as F2-layer anomalies. These anomalies manifest across various spatial and temporal scales, influencing radio-wave propagation through the ionosphere. This study reviews the four F2-layer anomalies namely-Weddell Sea Anomaly (WSA) where midnight electron density is greater than noon time in mid-latitude in summer, annual anomaly where global average electron density is greater in December than in June, semiannual anomaly where electron density is larger in equinoxes than in solstices, and winter anomaly where electron density is larger in winter than in summer.

Keywords – Ionospheric variations, F2-layer anomalies, Seasonal variations, Annual variations

I. INTRODUCTION

Region between 60 km – 1000 km of the earth's atmosphere is filled with ions. This region is known as ionosphere. Ionosphere is mainly divided into D, E, F1 and F2 layers. D, E and F1 layers vanish at night, while F2 layer persists through day and night [1-2]. The main source of ions (plasma) in the ionosphere is the ions produced due to the photoionization of neutral molecules or atoms such as $O_2, N_2, He, CO_2, CO, Mg, CH_4$ etc. caused by extreme ultraviolet (EUV) and soft X-ray radiation from the sun [3]. Photoionization rate depends on the density of neutral molecules or atoms in the atmosphere and the intensity of the solar EUV radiation which varies with altitude and solar zenith angle. Ions are also formed due to charge exchange process, particle precipitation and collisional ionization of neutrals by energetic particles [4]. The ions distribute themselves according to their weight due to gravity, with the heaviest closest to the earth. The heavier ions such as O_2^+ and N_2^+ dominate at low altitudes below 200 km, and the lighter ions such as O^+ and H^+ dominate at higher altitudes [5].

Ions and free electrons also undergo dissociative and radiative recombination in which they may disappear or produce other types of ions. The rate of recombination is determined by neutral density and is consequently high at low altitudes due high neutral density and then decreasing with altitude as the neutral density falls. Transport mechanisms such as ambipolar diffusion, neutral winds and electrodynamic drifts carried away the electrons and ions. The electrons and ions move together with a slight charge separation under the influence of gravity and temperature gradients along the Earth's magnetic field causing ambipolar diffusion. The pressure gradients due to differential heating of the atmosphere at day and night side drive horizontal winds called thermospheric winds or neutral winds causes the ions to move along the magnetic field causing the upwelling or downwelling of plasma [6]. Poleward wind during daytime pushes the ions down while the equatorward wind during nighttime pushes the plasma upward [7]. The neutral wind effects are more near the poles and the electrodynamic drift effects are more at the equator [8].

The major charge carriers of F2 layer are dominated by O^+, H^+ and He^+ [9]. During day hot plasma moves up to higher altitudes, where it is effectively stored because of the slower rate of recombination at higher altitudes. At night when the plasma cools, it moves down again and maintains the F2 region against loss by recombination at lower altitudes [10]. A radio wave propagating through F2 layer is reflected back at a particular frequency called critical frequency of F2 layer (f_c2) and electron density corresponding to the critical frequency is called peak electron density. Radio wave above critical frequency penetrates through the ionosphere. The D, E and F1 layers normally obey the Chapman model, while F2 layer occasionally deviates from it. This behavior of F2 layer led to anomalies in the F2 layer.

II. F2 LAYER ANOMALIES

Unlike the other layers of the ionosphere, variations in the F2 layer occasionally deviate from solar controlled behavior leading to anomalies such as Weddell Sea Anomaly (WSA) where midnight electron density is greater than noon time in mid-latitude in summer, annual anomaly where global average electron density is greater in December than in June, semiannual anomaly where electron density is larger in equinoxes than in solstices, and winter anomaly where electron density is larger in winter than in summer. These phenomena were first detected in the 1930s and were well described by the end of the 1950s [11].

2.1. Weddell Sea Anomaly (WSA)

The F2 layer electron density and thus the critical frequency ($f_c 2$) is expected to fall to minimum after sunset as the ionization is caused by the photoionization in the neutral atmosphere. But electron density was reported to show daily peak at midnight than noon near Weddell Sea at Halley Bay (76°S, 27°W) of Antarctica during summer [12]. This unusual phenomenon was named as Weddell Sea Anomaly (WSA). Same phenomena were also later reported in Yakutskin of the Asian zone and Port Lockroy in the Antarctic zone [13]. Later it was found that the zone of the anomaly is much larger than the Weddell Sea.

The mechanism of the formation of WSA is fully not yet understood. Many mechanisms were proposed such as ionization by solar radiation and the neutral wind [14]; plasma transfer from the dayside by high-latitude convection [15]; declination, inclination, and divergence of magnetic field lines [16-17]; large difference between geographic and geomagnetic poles [18]; horizontal plasma flows in the region of the South Atlantic geomagnetic anomaly [19]; plasma inflow from the plasmasphere [20]; close relationship with the equatorial anomaly [20-21]; particle precipitation [22]; and electric fields [23-24].

Seasonal and solar variation studies reveal that the WSA occurs only during the southern summer hemisphere in periods of low solar activity but appears in all seasons except winter during periods of high solar activity [21]. A better understanding of the anomaly was achieved by various studies [25-27] such as using GPS occultation data from the Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC), which highlighted the influence of neutral winds and downward plasma diffusion from the plasmasphere. The WSA is apparently more pronounced at a minimum of solar activity than at an activity maximum.

2.2. Annual anomaly

Occurrence of higher global average of electron density value during the December solstice compared to the June solstice is referred to as annual anomaly or non-seasonal anomaly. This ionospheric annual anomaly was first observed and reported by Berkner and Wells [28]. According to Buonsanto's hypotheses [29], greater flux in December solstice results in more dissociation of O_2 than N_2 which increases O/O_2 ratio than O/N_2 ratio, influences production and loss coefficient of F2 layer causing annual anomaly. Liu et al. [30] investigated the annual anomaly in the topside ionosphere (~840 km) using Naval Research Laboratory Mass Spectrometer and Incoherent Scatter Radar Exosphere (NRLMSISE-00) model and showed that the changes in atomic oxygen concentration can partially explain the annual anomaly. Annual anomaly is reduced during daytime and enhanced during the post-sunset hours [31]. Studies revealed that varying Sun-Earth distance, offset between geographic and geomagnetic equator and the tilt of geo- magnetic dipole axis could be the main causes of the anomaly, and only a minor contribution from atmospheric tides of lower atmospheric origin [32]. Large offset between subsolar point and magnetic equator, effective upward/downward neutral wind due to geomagnetic field configuration were also some of the reasons for annual anomaly [33].

2.3. Winter anomaly

In accordance with Chapman theory, electron density is expected to be greater in summer than in winter. But it was observed that electron density in winter is more than during summer, and this anomaly is called winter anomaly (WA) [34-35]. This was first reported by Appleton and Naismith [36] with measurements over England. But the first articles analyzing observations in both hemispheres and documenting similar anomalous phenomena were published by Berkner et al. [34] and Berkner & Wells [37].

Using the data of 140 ionosondes of the years 1958 (low solar activity), 1964 (moderate solar activity) and 1969 (high solar activity) Torr M and Torr D [38] showed that North American sector is the region where electron density is greatest in winter under any solar activity level. Using the data of 98 ionosondes of the years 1957 – 2009, Pavlov & Pavlova [39] showed that occurrence probability of the winter anomaly is strongly related with geomagnetic latitude. Analyzing the COSMIC satellites data measured in 2007 (low solar activity) Lee et al. [40] investigated the height, local time, latitude, longitude, and hemispheric variations of the electron density. They concluded that winter anomaly was stronger in the northern hemisphere, and a more intense winter anomaly

occurred in the region closer to the magnetic pole [41]. The strong nighttime equatorward wind enhances electron density in the summer hemisphere, and as a result, the anomaly disappears at night [42]. Studies on ionospheric electron density profiles retrieved from radio occultation measurements of COSMIC (Constellation Observing System for Meteorology, Ionosphere and Climate) mission during the deep minimum of 2007 have supported the absence of winter anomaly during low solar activity in southern hemisphere [40]. It is to be noted that winter anomaly and annual anomaly are in phase in the northern hemisphere with maximum in December and minimum in June, while they are out of phase in southern hemisphere [43]. Recent studies reveal that the anomaly is most prominent in the mid-latitude regions of America and the Pacific during high solar activity, while the nighttime winter anomaly is limited to the African low-latitude region during low solar activity [44].

According to Rishbeth and Shetty [45], Rishbeth [46], Zou et al. [43] winter anomaly is caused by seasonal neutral composition changes of O/N_2 due to global thermospheric circulation with upwelling zone in the summer hemisphere and downwelling zone in the winter hemisphere, just equatorward of the auroral oval. Density ratio of O/N_2 is greater in winter than in summer. This model could not reproduce the enhancement of the winter anomaly with increasing solar activity, as well as stronger winter anomaly in the Northern Hemisphere than in the Southern Hemisphere. Burns et al. [47] showed that winter-to-summer electron density ratio is large at the solar maximum and small at the solar minimum. They analyzed the O/N_2 ratio measured by GUVI and concluded that this feature was mainly due to greater winter-to-summer differences of O/N_2 in solar maximum than in solar minimum, with a secondary from the effects of temperature on the recombination coefficient between O^+ and the molecular neutral gas. According to Qian et al. [48], summer-to-winter meridional wind (solar heating-induced) is interrupted by Equatorial Ionospheric Anomaly (EIA). This interruption is primarily due to plasma-neutral collisional heating, which maximizes near the EIA. The EIA-associated heating reduces the summer-to-winter pressure gradient in the summer hemisphere, but increases the pressure gradients in the winter hemisphere. As a result of this, summer-to-winter wind is suppressed in the summer hemisphere but accelerates again at mid-latitudes in the winter hemisphere after it passes through the EIA. The meridional wind then converges as equator-pole pressure gradients diminish at high latitudes and is countered by Joule heating in auroral regions, creating an opposing pressure gradient. This convergence and thus downwelling causes large values of O/N_2 at subauroral latitudes in the winter hemisphere. The EIA effect is stronger near the December solstice than near the June solstice. This December-June difference is attributed to the electron density larger near the December solstice than near the June solstice [49]. As a result, the meridional wind convergence and downwelling at subauroral latitudes in the winter hemisphere are stronger in December than in June.

2.4. Semiannual anomaly

The observed greater electron density in the equinoxes than in the solstices over the same Earth's surface point at the same universal time is known as semiannual anomaly. The first studies of the semiannual anomaly in electron density of F2 layer were carried out by Yonezawa and Yonezawa and Arima [50].

Burkard suggested that semiannual anomaly is due to anisotropic emission of solar EUV, so that the flux reaching the Earth varies with the Earth's heliographic latitude in such a way that it maximizes at the equinoxes, but he gave no evidence to support his idea. Zou et al. [51-53] stated that the mid-latitudinal semiannual anomaly of electron density might be caused by seasonal differences in the plasma drift along magnetic field lines due to corresponding changes in the neutral wind and by seasonal variations in the neutral composition and temperature. In the middle latitudes, the offset of the geomagnetic axis from earth spin axis is also considered as the cause of the semiannual variations of noontime electron density [54]. In the low latitudes, the semiannual variation of electrojet due to the diurnal tide variation is considered as the main reason of semiannual anomaly [55]. Investigation into ionosphere using Langmuir probe onboard the China Seismo-Electromagnetic Satellite (CSES) showed that semiannual variation is predominant at the magnetic equator and low magnetic latitudes, with two peaks occurring during the equinoxes [56].

III.CONCLUSION

Ionospheric F2-layer anomalies can occur on timescales ranging from minutes to seasonal cycles. Understanding their occurrence is essential since F2-layer disturbances strongly influence radio-wave propagation, satellite communication, and GPS/GNSS signal accuracy. Data from ionosondes, topside sounders, incoherent scatter radars, rockets and satellites were analyzed to understand the causes of these anomalies. Many different theoretical models of the ionosphere have been developed over the last several years. These models are essential for satellite design and data analysis, radio propagation studies and space weather concerns. Many empirical models have also been

modelled, one such important model is the International Reference Ionosphere (IRI), jointly developed by the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI), yet many mechanisms behind their onset and evolution remain unresolved.

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