Journal of Atmospheric and Solar-Terrestrial Physics 140 (2016) 65–78

Contents lists available at ScienceDirect

Journal of Atmospheric and Solar-Terrestrial Physics

journal homepage: www.elsevier.com/locate/jastp

Research paper

Modeling and analysis of ionospheric evening anomalies with a physics-based data assimilation model

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ARTICLE INFO

Article history:
Received 16 July 2015
Received in revised form
12 January 2016
Accepted 9 February 2016
Available online 10 February 2016

Keywords:
Weddell Sea Anomaly
Ionospheric evening anomalies
Thermospheric neutral winds
Ionospheric modeling
Data assimilation
COSMIC

ABSTRACT

Anomalous evening enhancements of electron densities in the mid-latitude ionosphere take place during summer and are most prominent over the west of the Antarctic Peninsula (Weddell Sea Anomaly). Although the phenomenon has been known for several decades, its generation mechanism is still being debated and its modeling remains a challenge. In this paper, data assimilation models were used to understand the role of thermospheric winds in the anomalies, and to elucidate the physical mechanism behind them. COSMIC radio occultation data were used and a newly developed Thermospheric Wind Assimilation Model (TWAM) was employed to estimate the horizontal wind components. Next, the TWAM winds were used to drive the Ionosphere-Plasmasphere Model to simulate the anomalies. The model results show close quantitative agreement with the COSMIC measurements and indicate that while the geographic meridional wind alone can drive the electron density evening peak, the zonal wind further enhances the anomaly. Furthermore, for closer agreement with the COSMIC data, the zonal wind effect was found to be important. To understand the physical mechanism behind the anomalies, the plasma production, loss and transport processes were analyzed. It was found that due to the equatorward wind during the evening, the density maximum forms at higher altitudes where the density reduction due to recombination is slow. Furthermore, it was revealed that during the evening, the plasma loss due to transport weakens. As a consequence of the reduced rate of recombination and the weakened plasma loss due to transport, the relative role of solar production increases and the electron density enhancement occurs.

1. Introduction

During the early days of ionospheric research, the typical daily variation of the electron density was thought to follow a simple photochemical behavior, characterized by a noon-time maximum due to higher solar production rate and by a gradual decrease in density at night when plasma recombination becomes dominant. Interestingly, a seemingly unusual behavior of the F2-layer critical frequency (foF2) was reported at Halley Bay when the diurnal maximum of the density was observed near midnight in December (local summer) (Bellchambers and Piggott, 1958). Considering the abnormality of such behavior also at other magnetically upper-midlatitude stations close to the Antarctic Peninsula, this phenomenon was later called the Weddell Sea Anomaly (WSA) as its extent was believed to span from the Falkland Island to the southern shore of the Weddell Sea reaching Halley Bay (Penndorf, 1965). However, in spite of the longevity of the topic, the research on the morphology and possible causes of the WSA still continues (Ren et al., 2012; Chen et al., 2013; Slominska et al., 2014; Klimenko et al., 2015). In addition, the modeling of the phenomena remains a challenge (Burns et al., 2008; Jee et al., 2009), and therefore, its investigation is important for a better understanding of the underlying processes in the ionosphere and for elucidating and improving current shortcomings of global ionospheric models.

Since the discovery of the WSA, similar anomalies, but with relatively smaller noon–evening density differences, have been known to exist over certain northern hemisphere mid-latitude stations during local summer (Eyfrig, 1963; Evans, 1965; Kohl et al., 1968; Eccles et al., 1971; Eccles and Burge, 1973). For example, Papagiannis and Mullaney (1971) investigated the global distribution of the ionospheric evening anomaly using F2-layer

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http://dx.doi.org/10.1016/j.jastp.2016.02.009
1364-6826/

critical frequency obtained by harmonic analysis of worldwide ionosonde data. Their results show three regions during northern summer over north-east America, western Europe, and eastern Siberia where evening anomalies are strongest, as well as the WSA during southern summer.

In spite of the apparent similarities between the WSA and the evening anomalies in the northern hemisphere, their analysis often was separate. Several mechanisms were proposed to explain the WSA. Bellchambers and Piggott (1958) first attributed the near midnight maximum of the electron density in summer, which is now known to be part of the WSA, to the dynamics of the ionosphere and not to the role of recombination processes; Rastogi (1960) interpreted the density pattern over the WSA more with a midday depression and suggested the daytime minimum was due to the lack of horizontal transport of ionization from the equator along the magnetic field lines and excluded the role of vertical drifts of the ionization. Hill (1960) suggested horizontal winds with vertical shear as a possible cause of the anomalous behavior of the electron density. Penndorf (1965) (noted the necessity of F2-layer peak height analysis) related the WSA to the South Atlantic (SA) magnetic anomaly and suggested excess ionization above the F region over the SA anomaly could be drifted downwards and then, through horizontal drifts, brought into the Weddell Sea area. Dudeney and Piggott (1978) underlining the role of magnetic declination over the anomaly area, considered solar illumination superimposed with the upward drift due to thermospheric winds to be responsible for the formation of the WSA (a similar idea of explaining the evening density enhancement in general, was earlier developed by Eccles et al. (1971)). They noted that their modeling result showed an additional morning enhancement in foF2, which was, however, not observed. They pointed out that this could be due to their inaccurate winds, or more likely due to some extra physical process missing from the simulation.

Other studies were more global. Eyfrig (1963) noticed that the daily electron density maximum was shifted towards the evening hours over stations with westerly magnetic declination in the northern hemisphere and with easterly magnetic declination in the southern hemisphere. Using numerical modeling, Kohl et al. (1968) and Eccles et al. (1971) showed thermospheric neutral winds can be responsible for the observed evening enhancements of electron densities at certain southern and northern mid-latitude sites. Kohl et al. (1969) explained the magnetic declination effect in the ionosphere (Eyfrig, 1963) by the dependence of the phase and amplitude of the wind-induced vertical drifts on the declination angle. More recently, Zhang et al. (2011) found that total electron content (TEC) over the continental US displays a clear longitudinal variation with evening TEC being substantially higher on the US east coast than on the west coast, and a minimum of variability at the longitudes of zero magnetic declination. They suggested that these differences were caused by the so-called declination-zonal wind mechanism. Zhang et al. (2012) further examined the results using neutral wind and electron density data from the co-located Millstone Hill Fabry-Perot Interferometer (FPI) and Incoherent Scatter Radar (ISR), respectively and found that the zonal wind climatology was consistent with the east–west electron density differences. It was also noted that the zonal-wind declination effect was a favoring factor for WSA-like variations, but not a dominant one to cause the WSA. Rishbeth (1967, 1968) showed neutral winds can produce a secondary maximum in the summertime NmF2 during the evening. Evans (1965) studied the evening increase of the electron density above Millstone Hill by using incoherent scatter radar data. He found that the density above the peak starts to decrease a few hours earlier than the peak density, which reaches its maximum in the evening, accompanied by a rapid fall in electron temperature. The role of this thermal contraction was later rejected by Eccles and Burge (1973) who performed model calculations and concluded that the evening enhancement of the electron density is a consequence of thermospheric winds. Papagiannis and Mullaney (1971) also found that the anomalies were more pronounced during local summer over areas with westerly magnetic field declination angles in the northern hemisphere and easterly declination angles in the summer hemisphere, as well as in regions where there was a poleward divergence of the magnetic meridians. By studying neutral wind patterns, it was suggested that wind plays a very important role in the geographic variations of the anomaly.

The interest in the WSA was renewed as new advances of ionospheric measurement technology, and especially satellite observations over the oceans, made it possible to obtain a global image of the extent of the WSA. This provided a unique opportunity to extensively study the phenomenon. For example, Horvath and Essex (2003) used TEC measurements from the TOPEX satellite during the 1998 and 1999 solar maximum and revealed the anomaly situated over the Bellinghausen Sea and not over the Weddell Sea. According to the TEC analysis by Horvath (2006), the anomalous region was found over a large area (~22 million km^2) peaking at 50°S–60°S/90°W–110°W. Jee et al. (2009) used 13 years of TOPEX TEC data to study the seasonal and solar activity variations of WSA for geomagnetically quiet periods. Their study shows that for low solar flux, the WSA occurs only for southern summer months; however, for high solar activity periods, it also occurs during the equinoxes, but is still most prominent during the December solstice. Karpachev et al. (2011) studied the anomaly using intercosmos-19 satellite data of foF2 for solar activity maximum and CHAMP satellite data for low solar activity. The anomaly was found to be more pronounced at solar activity minimum, but its main characteristics were almost independent of solar activity level.

The advent of the new observations also sparked new studies about the generation mechanisms of the WSA. Burns et al. (2008) studied the WSA using FORMOSAT-3/COSMIC radio occultation (RO) data and questioned the role of neutral winds and neutral composition in its generation. They suggested the plasmaspheric flux was at least partly responsible for the anomaly. Horvath (2006) and Jee et al. (2009) noted the importance of the combined action of the meridional and zonal winds for the plasma vertical motion that varies by inclination and declination of the Earth's magnetic field, and suggested it as a factor for the plasma density increase at night. Karpachev et al. (2011) analyzed the longitudinal variation of F2-layer peak parameters at the WSA latitudes and by comparing them to the zonal variation of calculated vertical drift velocities, which were based on experimental NmF2 and hmF2 values, concluded the anomaly is mainly caused by neutral winds. They also noted that solar radiation considerably contributes to the formation of the anomaly, while the estimated contribution of neutral composition and temperature is insignificant. The role of other mechanisms was questioned. Luan and Dou (2013) examined the longitudinal variations of nighttime NmF2 from COSMIC and equivalent winds derived from COSMIC NmF2 and hmF2 values using the so-called servo model. They found the larger electron densities in the WSA region to be generally consistent with the larger upward plasma drifts due to the winds, and noted, besides the importance of zonal wind-declination effects, the significance of geographic meridional and the magnetic inclination.

In addition to the studies of the WSA, the radio occultation measurements of electron density from the COSMIC satellites have also been used to investigate the evening anomalies at other locations (He et al., 2009; Lin et al., 2009, 2010; Lomidze and Scherliess, 2010; Burns et al., 2011). Using COSMIC RO data Lin et al. (2010) also revealed a less pronounced WSA-like structure in the northern hemisphere near northeast Asia, Europe/Africa and Central Pacific longitudes around June solstice. They linked both