Modeling and Analysis of Ionospheric Evening Anomalies with a Physics-Based Data Assimilation Model

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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.

Keywords: Weddell Sea Anomaly; Ionospheric Evening Anomalies; Thermospheric Neutral Winds; Ionospheric Modeling; Data Assimilation; COSMIC.

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 (f_oF_2) 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 critical frequency obtained by harmonic analysis of worldwide ionosonde data. Their results show three regions during

64 northern summer over north-east America, western Europe, and eastern Siberia where evening
65 anomalies are strongest, as well as the WSA during southern summer.

66 In spite of the apparent similarities between the WSA and the evening anomalies in the
67 northern hemisphere, their analysis often was separate. Several mechanisms were proposed to
68 explain the WSA. Bellchambers and Piggott (1958) first attributed the near midnight maximum
69 of the electron density in summer, which is now known to be part of the WSA, to the dynamics
70 of the ionosphere and not to the role of recombination processes; Rastogi (1960) interpreted the
71 density pattern over the WSA more with a midday depression and suggested the daytime
72 minimum was due to the lack of horizontal transport of ionization from the equator along the
73 magnetic field lines and excluded the role of vertical drifts of the ionization. Hill (1960)
74 suggested horizontal winds with vertical shear as a possible cause of the anomalous behavior of
75 the electron density. Penndorf (1965) (noted the necessity of F2-layer peak height analysis)
76 related the WSA to the South Atlantic (SA) magnetic anomaly and suggested excess ionization
77 above the F region over the SA anomaly could be drifted downwards and then, through
78 horizontal drifts, brought into the Weddell Sea area. Dudeney and Piggott (1978) underlining the
79 role of magnetic declination over the anomaly area, considered solar illumination superimposed
80 with the upward drift due to thermospheric winds to be responsible for the formation of the WSA
81 (a similar idea of explaining the evening density enhancement in general, was earlier developed
82 by Eccles et al. (1971)). They noted that their modeling result showed an additional morning
83 enhancement in foF2, which was, however, not observed. They pointed out that this could be due
84 to their inaccurate winds, or more likely due to some extra physical process missing from the
85 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 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 anomalies to a similar mechanism, noting they are located at areas where the offsets of the geomagnetic and the geographic equators are large, and proposed the possible role of upward/poleward transport of ionization from the poleward edge of EIA in the generation of the anomalies. Similarly, Burns et al. (2011) proposed the equatorial anomaly to be the source of the WSA where upward and poleward drifts, due to conjugate electric fields, transport the ionization. They applied a similar mechanism to the northern anomaly and considered the neutral winds to be an unlikely cause of the anomalies.

Besides the search for the drivers of the anomaly, which are still being debated, the modeling of the phenomenon is another challenge. The WSA was, for example, not found in the outputs of the Thermospheric General Circulation Models (TGCM's) and the Coupled Magnetosphere Thermosphere Ionosphere (CMIT) models (Burns et al., 2008; Jee et al., 2009). Lomidze and Scherliess (2010, 2011) used an ionospheric data assimilation model to study the WSA and evening anomalies, and similar to previous studies, suggested the thermospheric neutral winds to be the main drivers of the anomaly. Chen et al. (2011) studied the WSA using SAMI2 and investigated the role of neutral winds that were specified from the HWM93 model. They found the thermospheric equatorward wind is a critical driver of the WSA, and the plasmaspheric flux, although not the critical driver, only provides the plasma source at later times after the anomaly is already formed. While SAMI2 did reproduce the eveningtime density enhancement over the right location, Chen et al. (2011) did not compare the modeled results with observations making it difficult to speculate how well the model (driven by HWM93) was capable to fully reproduce the anomaly. Chen et al. (2013) used the SAMI3 model driven by HWM93 and TIEGCM neutral winds to study the northern and southern evening anomalies. The WSA was reproduced in both cases; however, no quantitative comparison of the results with

observations was made. It was also found that the used winds could not properly account for the location of evening density enhancement in the northern hemisphere.

Thampi et al. (2011) presented the SUPIM model simulations for the northern anomaly using HWM93 and MU radar winds. They found that electric fields and zonal winds have an insignificant contribution to the anomaly. They also reported that using the local MU radar winds along the magnetic meridian, which differ from their corresponding HWM93 model values, the model results were qualitatively closer to the COSMIC RO derived densities. However, it remains unclear how well the variation of the peak height of the F2 layer was reproduced by the SUPIM model. Ren et al. (2012) performed simulations with the TIME3D-IGGCAS ionosphere model driven by HWM93 empirical winds and studied the role of meridional and zonal winds, separately. They concluded that the anomalies are mainly driven by meridional winds, and found that zonal wind effects are also important for the WSA, but negligible for the northern hemispheric anomalies. The authors did not provide comparisons of the modeled NmF2 and hmF2 with observations; however, their magnitudes and patterns of the local time variations over the WSA seem to be very different from actual measurements (to be shown below).

It is apparent that the wind mechanism (combined with solar photoionization) is the most widely accepted mechanism for the formation of the evening anomalies, which is supported by phenomenological explanations and/or numerical simulations (Kohl et al., 1968, 1969; Eccles et al., 1971; Papagiannis and Mullaney, 1971; Eccles and Burge, 1973; Dudeney and Piggott, 1978; Horvath and Essex, 2003; He et al., 2009; Jee et al., 2009; Liu et al., 2010; Chen et al., 2011, 2013; Karpachev et al., 2011; de Larquier et al., 2011; Thampi et al., 2011; Ren et al., 2012). Yet, they fail to validate key ionospheric parameters (NmF2 and hmF2) simultaneously and/or

rely on simplified or empirical wind models, which are known to be less accurate over data sparse regions (Titheridge, 1995; Makela et al., 2012).

In the current paper, in order to understand the causes of the Weddell Sea Anomaly and the Northern hemispheric mid-latitude evening Anomaly (NA for short, one over Eastern Siberia/Kamchatka Peninsula), and to elucidate the role of the neutral wind and its meridional and zonal components in their generation we used a physics-based data assimilation approach. First, electron density measurements from FORMOSAT-3/COSMIC satellites were used to create global seasonal maps of ionospheric NmF2 and hmF2. The COSMIC maps were assimilated into the Utah State University Global Assimilation of Ionospheric Measurements Full-Physics (GAIM-FP) model to obtain global magnetic meridional winds consistent with the observed ionospheric morphology. Next, the obtained magnetic meridional wind data from GAIM-FP were assimilated into a newly developed Thermospheric Wind Assimilation Model (TWAM) that gives the geographic zonal and meridional wind components over low and mid-latitudes. Finally, the TWAM winds were used to drive the Ionosphere-Plasmasphere Model (IPM) in order to analyze the various physical processes, which play a role in the generation of the anomaly, and to understand, in detail, the relative role of the zonal and meridional winds.

2. Data and Models

2.1. COSMIC Data

The values of NmF2 and hmF2 were obtained from GPS radio occultation measurements from the Constellation Observing System for Meteorology Ionosphere and Climate/Formosa Satellite 3 (COSMIC/Formosat 3). The constellation consisting of six microsatellites in a circular orbit at about 800 km altitude and has been providing about 1,000 - 2,500 electron

density profiles per day globally (Rocken et al., 2000; Anthes et al., 2008), which are retrieved from slant total electron content measurements using an Abel inversion technique (Hajj and Romans, 1999; Schreiner et al., 1999). The data of electron density profiles used in this study were obtained from the COSMIC Data Analysis and Archive Center (<http://www.cosmic.ucar.edu>).

The values of NmF2 and hmF2 were extracted from the individual electron density profiles, and to obtain the seasonal global maps, the data were combined from 2007 to 2009 and binned into seasons consisting of December solstice (December 21 ± 27 days for the years 2007 and 2008) and June solstice (June 21 ± 27 days for 2008 and 2009). To obtain quiet time data, points were excluded for observations with a previous 24-hour average $A_p \geq 16$ and/or a corresponding 3-hour $a_p \geq 16$. The total number of ROs selected was $\sim 154,700$ for December and $\sim 137,500$ for June, respectively. The average solar and geophysical conditions for the selected periods were $F_{10.7} = 73$, $A_p = 5$ for December, and $F_{10.7} = 67$, $A_p = 4$ for June. The days that best represent the climatological average conditions of the selected seasons, based on their average solar declination, are DOY 006 (January 6th) for December solstice and DOY 189 (July 8th) for June solstice. The retrieved NmF2 and hmF2 were used to produce average global maps of these parameters in 30-minute intervals of universal time. For the binning we used a longitude $\times$ latitude grid of $7.5^\circ \times 2.5^\circ$, which is the current default output grid of the IPM and GAIM-FP models, and applied a $15^\circ \times 5^\circ$ sliding window to smooth the data and filter out noise. For more details about the COSMIC data and the applied data analysis the reader is referred to Lomidze et al., (2015).

2.2. Ionospheric Models

The GAIM-FP (Global Assimilation of Ionospheric Measurements Full Physics) is a data assimilation model that uses a physics-based ionosphere-plasmasphere model (IPM) and an ensemble Kalman filter technique to incorporate the main physical processes in the ionospheric directly into the data assimilation scheme (Schunk et al., 2004; Scherliess et al., 2004, 2009). The model can assimilate different types of data from different sources and provide specifications of the 3-D electron density distributions from 90 km to 30,000 km at low and mid-latitudes. The model can also provide an estimation of the ionospheric drivers (electric field, magnetic meridional wind, and neutral composition) that is consistent with the data and the model. In its current version, the data assimilation model excludes regions poleward of $\sim \pm 60^\circ$ geomagnetic latitudes.

In the IPM model (Schunk et al., 2003), the plasma transport equations are numerically solved along magnetic field lines for individual convecting flux tubes of plasma, and the 3-D nature of the model is obtained by following a large number of plasma flux tubes. The 3-D distribution is obtained by mapping the results on a geographic grid. The IPM is a state-of-the-art physics model that takes account of photoionization, chemical reactions, neutral dynamics, ionosphere-plasmasphere interactions, and cross-field plasma drift due to electric fields. The IPM also uses the International Geomagnetic Reference Field (IGRF), which includes realistic declination and inclination angles.

The Kalman filter (Kalman, 1960) combines the data from an observing system with the information obtained from the system model and their corresponding statistical description of uncertainties. It performs a recursive least squares inversion of the observations (NmF2 and hmF2 for our case) for the model variables using a dynamical model (IPM) as a constraint. As a result, an improved estimate of the model variables (electron density, magnetic meridional wind)

is obtained in a statistical sense. The estimation of the ionospheric drivers is an integral part of our ensemble Kalman filter and is achieved by using the internal physics-based model sensitivities to the various driving forces. In this procedure, the ionospheric data are used to adjust the plasma densities and its drivers so that a consistency between the observations (within their errors) and the physical model is achieved. As a result, the assimilation procedure produces the optimal model-data combination of the ionosphere-plasmasphere system with its self-consistent drivers (for details see Scherliess et al. (2009, 2011)).

In the current study, the climatology mode of GAIM-FP is used, which assimilates global seasonal maps of NmF2 and hmF2 using the geophysical conditions corresponding to the average conditions of the seasonal maps, and provides the low- and mid-latitude magnetic meridional wind, and the low-latitude vertical $\mathbf{E} \times \mathbf{B}$ drift (Lomidze et al., 2015). The global neutral composition is specified by MSISE-90 (Hedin, 1991).

2.3. Thermospheric Wind Assimilation Model

The physics-based 3-D Thermospheric Wind Assimilation Model (TWAM) uses ‘magnetic’ meridional wind data from GAIM-FP and combines it with the equation of motion for the neutral gas in the thermosphere to obtain the climatology of the ‘geographic’ zonal and meridional wind components (Lomidze, 2015; Lomidze and Scherliess, 2015). It is based on an implicit Kalman filter technique (Skliar and Ramirez, 1997) and solves for horizontal wind velocities in the 110-600 km range. The GAIM-FP ‘magnetic’ meridional wind data, which constrain the wind solution on a global grid, is assimilated at the altitude of hmF2. TWAM uses inputs from MSISE-90 and Scherliess-Fejer empirical drift model (Scherliess and Fejer, 1999; Scherliess et al., 2001), however, the pressure gradient forces are internally calculated by the model as a state parameter in the Kalman filter data assimilation process. The global 3-D

electron density distribution and ion diffusion velocity, which contribute to the ion drag term in the neutral momentum equation, are obtained from GAIM-FP. The results from the TWAM model have been validated by comparing the individual wind components with measurements from interferometers over stations that have long-term wind observations. More details about the TWAM model are given in Lomidze and Scherliess (2015).

3. Evening Anomalies and Neutral Winds

3.1. Evening Anomalies from COSMIC Data

The first step in our study is to investigate the evening anomalies using COSMIC radio occultation data. The utilized UT maps of global distribution of NmF2 and hmF2 were recast to represent their distribution for a constant local time (i.e. LT maps). Fig. 1 and 2 show global maps of NmF2 and hmF2 for noon (11:00-13:00 LT) and evening (20:00-22:00 LT) hours during December and June solstices, respectively. The black solid line indicates the location of the magnetic equator. The COSMIC RO data provides a good global coverage and successfully captures many well-known characteristics of the ionosphere. At low latitudes, these include the equatorial ionospheric anomalies, the seasonal asymmetry in hmF2, and the longitudinal variations in NmF2 and hmF2. At mid-latitudes, certain features are masked by the choice of our color scale; however, larger (smaller) noontime NmF2 (hmF2) values compared to values during evening hours are evident for most locations. The places that clearly do not fit to this general pattern are a large area over west of the Antarctic Peninsula during December and a relatively smaller area centered over the Kamchatka Peninsula during June. These anomalies are the Weddell Sea Anomaly and the Northern Anomaly, which have considerably larger NmF2 during

evening than during noon. They also are clearly distinct from their neighboring locations to the east and west (especially the WSA). Note, during June solstice, the evening NmF2 values over Europe are also close to those of the NA, but their noontime values are relatively larger than the noontime NmF2 values over the NA. The hmF2 values over the WSA exhibit a large depression during noon (Fig. 1), clearly making the region distinct, but a similar pattern over the NA is not seen in Fig. 2. Note the relatively high values of hmF2 during the evening over the WSA compared to its eastward and westward neighbors, which are seen not only during December, but also during June. Furthermore, the high evening values of hmF2 over the NA during June and December are clearly a distinct feature.

In order to obtain the global spatial extent and estimate the magnitude of the evening anomalies, we calculated global (normalized) differences between the evening and noon values of NmF2, which are presented in Fig. 3. The data are shown only over the places where the difference was positive (i.e., for $NmF2_{\text{evening}} > NmF2_{\text{noon}}$). The WSA occupies an area that is almost twice as large as the NA. The density anomaly is also stronger over the WSA with a difference between the evening and noon values over its center exceeding 100%, compared to ~40% for the NA. During the June solstice, a relatively weak (~15%) evening anomaly is also present over western Europe/north Atlantic. Note, the magnitude and global extent of the evening anomalies would be modified if we had taken different time intervals for evening and/or noon.

3.2. Modeling of Evening Anomalies and Effects of Neutral Wind

3.2.1. Modeling with HWM93 and TWAM winds

The modeling of the evening anomalies was performed using two different setups for the IPM model. In its default setup, the IPM uses winds from the HWM93 empirical model (IPM-HWM93). In the modified setup, the HWM93 winds can be replaced by the horizontal wind values from our 3-D thermospheric wind assimilation model (IPM-TWAM). Fig. 4 presents comparisons of LT variations of NmF2 and hmF2 from COSMIC radio occultation data to their corresponding model simulations over the specific locations of the WSA (53.75°S , 93.75°W , $\text{MLAT}=41.23^{\circ}\text{S}$, $D=+26.2^{\circ}$, $I=-55.3^{\circ}$) (left panels) and of the NA (53.75°N , 146.25°E , $\text{MLAT}=47.43^{\circ}\text{N}$, $D=-9.8^{\circ}$, $I=+67.0^{\circ}$) (right panels) during December solstice and June solstice, respectively. The COSMIC data are presented with their corresponding $1-\sigma$ standard deviations. Note there is an about five-hour gap in the morning data over the WSA. According to the COSMIC data, the general patterns of NmF2 and hmF2 variations are very similar over the two anomalies; however, the NmF2 over the WSA is about 50% higher. The values of hmF2 are about the same during the day, but are about 22 km higher during the night over the WSA. The electron densities over both anomalies start to gradually increase from the early morning hours. In the same time hmF2 descends rapidly first, reaching a minimum around 10:00 - 11:00 LT, soon after which it starts to rise. Interestingly, it is only after 18:00 LT when NmF2 also starts a sharp increase and attains a daily maximum around 20:00 - 21:00 LT. After that, the density starts to rapidly fall to a daily minimum around 2:00 - 3:00 LT.

During both seasons, the IPM-TWAM results are in close agreement (within errors) with the COSMIC data, in contrast to the IPM-HWM93 results, that indicates the TWAM winds correctly reproduce the observed evening anomalies. Note that because production, loss, and transport processes in the ionosphere depend on altitude, and neutral and electron densities, it is important to be able to closely reproduce the observed F2 layer variation before attempting to

analyze the role of these different physical processes. IPM-HWM93 generally overestimates both NmF2 and hmF2. Over the WSA the IPM-HWM93 displays large discrepancies in both NmF2 and hmF2 (except for a few hours around midnight). The largest difference in hmF2 occurs during the morning hours when it reaches ~ 80 km, together with relative differences in NmF2 of about 80%. Over the NA, NmF2 from both IPM-HWM93 and IPM-TWAM agree well (within 1σ) with the COSMIC data, but for most of the day, NmF2 from IPM-HWM93 is about 10 - 40% larger than the IPM-TWAM values. On the contrary, the late morning hmF2 from IPM-HWM93 is largely overestimated (by ~ 50 km) compared to the COSMIC values, whereas IPM-TWAM only overestimates hmF2 by about 20 km. It is interesting to note that even though the NmF2 from IPM-HWM93 does not agree with the COSMIC data over the WSA, the evening values of NmF2 are larger than their noontime values, indicating the HWM93 winds qualitatively represent the anomaly in terms of NmF2, but fail to quantitatively describe it.

As noted before, the differences between the two IPM simulations are due to the different thermospheric winds, since the rest of model inputs are kept identical. Fig. 5 shows the meridional and zonal winds from HWM93 and TWAM for the same locations for which NmF2 and hmF2 were shown in Fig. 4. The TWAM winds are similar in general shape to HWM93 winds, but are different in their magnitudes, phases, and reversal times. The TWAM meridional wind over the WSA (upper left panel of Fig. 5) becomes poleward earlier and reverses back later than the corresponding HWM93 wind, which remains poleward for only a few hours. Also, on average the TWAM meridional wind is less equatorward than the HWM93 wind. The reversal times are about the same for the TWAM meridional winds over the WSA and the NA, whereas the HWM93 wind over the NA has a minimum around noon, but never turns poleward. Similar to the WSA, the TWAM meridional wind over the NA is also less equatorward than the HWM93

values. The zonal winds are generally westward from midnight until about 15:00 LT and eastward during the evening. A difference of about 2 to 3 hours between the HWM93 and the TWAM zonal wind reversal times can be seen. Also note the HWM93 zonal wind has a strong semi-diurnal amplitude and its magnitude oscillates around the TWAM zonal wind values.

3.2.2. The Effects of Zonal and Meridional Winds

In order to establish the relative role of the zonal and meridional wind components on the evening anomalies, we have performed three additional model simulations using the IPM with (1) zero wind field, (2) TWAM geographic meridional winds set to zero and (3) TWAM geographic zonal winds set to zero. For all of these simulations all other model parameters were kept unchanged. Fig. 6 compares the local time variation of NmF2 and hmF2 obtained from these simulations with our previously shown results using the full TWAM winds (blue dots).

In our first simulation (black stars) i.e., the zero wind case, the ionosphere is driven by photochemistry and plasma diffusion, and, as a result, the daily electron density maximum occurs around 15:00 LT for both WSA and NA cases. A secondary peak, around 20:00 LT, is apparent for the NA case, but less pronounced over the WSA. Our analysis revealed that this small peak during the evening is due to plasma photoproduction, which slightly dominates over the plasma loss due to recombination and transport processes.

Our second simulation (red crosses in Fig. 6) shows that the effect of the zonal wind is to reduce NmF2 around noon and to increase it during the evening. Corresponding effects in hmF2 are a noontime decrease and an evening time rise with the larger effect during noon. The effect of the zonal wind is found to be much stronger for the WSA where it also produces noticeably larger density values during the evening than during noon. However, for this case (zonal wind

only) the NmF2 and hmF2 over both anomaly regions show variations that do not agree with the observations and their values are vastly different from the COSMIC data (see Fig.4). This is especially pronounced during the late evening and night when the zonal winds are not able to inhibit the downward plasma diffusion to maintain the observed high NmF2 and hmF2 values.

Finally, the simulation results with only geographic meridional winds (green diamonds) indicate that, similar to the zonal winds, the meridional winds produce a noontime reduction of the density and an enhancement in the evening densities.. As before, the density values are larger during the evening over the WSA but this time also become well pronounced over the NA location. The main differences between the zero-meridional and zero-zonal cases are that for the latter NmF2 and hmF2 are significantly larger during the evening and night and at the same time closer to the COSMIC observations. As expected, the relative contribution of the meridional wind compared to the zonal one is larger over the NA because of the small magnetic field declination angle over this location.

By comparing the zero-wind and full-wind cases in Fig.6 it becomes apparent that the effect of the neutral wind on the density during the daytime is almost as large as the effect on the density during the late evening. Consequently, the WSA can be viewed not only as a nighttime electron density enhancement but also as a daytime density depletion. This large reduction in NmF2 during the day together with the large enhancement of electron density during the evening leads to the large relative difference in the daytime to nighttime NmF2 at the WSA. However, for the NA the electron density enhancement during the evening is larger compared to the daytime depletion and as a result the relative differences in the day to night NmF2 values are not as pronounced as over the WSA.

Overall, we can conclude that for the WSA, both zonal and meridional winds can individually produce evening density enhancements. However, the meridional wind produces NmF2 and hmF2 variations and magnitudes in the model results that are in good agreement with the observations. The zonal wind is needed to bring both NmF2 and hmF2 in close agreement with the corresponding COSMIC data. For the NA, the effect of the zonal wind is minor and the variations and values of NmF2 and hmF2 are principally determined by the geographic meridional wind.

3.3. Comparison of Parameters over WSA and Outside WSA

In order to better understand the role of the various physical processes responsible for the density enhancement over the anomalies, it is helpful to compare and contrast the behavior of the ionospheric and the thermospheric parameters over the anomaly region and outside of the anomaly region. Since the WSA and NA displayed very similar variation of NmF2 and hmF2, here we focus on the WSA only. For the site outside of the WSA (the off-WSA, thereafter) we chose location at (53.75°S, 11.25°E, MLAT=53.06°S), thus it has the same geographic latitude as the WSA site. The magnetic field declination and inclination are $D=-26.5^\circ$ and $I=-60.8^\circ$, respectively. While the inclination angles are about the same, the declination angle at the off-WSA is similar in magnitude to the WSA, but has opposite sign (westerly magnetic declination).

Fig. 7 shows the variation of NmF2, hmF2, and the meridional and zonal winds over the WSA (blue dots) and the off-WSA (red stars). Different from the WSA, NmF2 over the off-WSA has a daily maximum around noon, and does not exhibit the anomalous behavior. The densities at the two locations are about the same during noon, but it is about two to four times larger at the WSA during the night. The hmF2 at the off-WSA is higher at noon and lower during

the evening. During the early morning, the hmF2 values at the two sites are similar, but the early morning NmF2 values at the WSA are much larger than the values at the off-WSA.

The winds have a strong influence on the variation of ionospheric plasma. The field-aligned ion drifts (positive upward/equatorward) that are induced by horizontal winds are given by

$$v_{i,\parallel,wind} = (v \cdot \cos D \pm u \cdot \sin D) \cos I, \quad (1)$$

where u and v are eastward and equatorward winds, respectively. The positive and negative signs correspond to the southern and northern hemispheres, respectively. As Fig. 7 shows, the winds are indeed different over the two sites. Both (WSA and off-WSA) meridional winds are poleward during day, but the wind is stronger over the WSA. During the evening, the meridional wind over the WSA turns equatorward about one hour earlier, increases more rapidly and attains higher values. The zonal winds are also different during the course of the day. However, since the WSA has easterly declination and the off-WSA has westerly declination, the zonal winds have opposite effect on the plasma motion over the two locations. The zonal winds on both sites further enhance the differences in plasma motions caused by differences in the meridional wind. Our analysis (similar to Fig. 6) of the relative role of meridional and zonal winds over the off-WSA site (not shown) indeed indicates the competing effects of the zonal and meridional wind, which are most pronounced around noon but also noticeable at late evening. Here, the daytime zonal wind leads to an increase in hmF2 and NmF2, whereas the meridional wind leads to a decrease in their values.. As a result, the total wind (i.e. both components together) only slightly modifies NmF2 when compared to the zero-wind case. Furthermore, none of the wind components individually produce a density anomaly over the off-WSA. This is in sharp contrast

to the WSA, where both zonal and meridional winds reduce hmF2 and NmF2 during the day and increase them during the evening.

3.3.1. Comparison between Plasma Motions

We have shown above that over the selected two sites the TWAM neutral winds are different (Fig. 7). To better understand the effect of these winds on the plasma motion, it is helpful to compare the field-aligned ion velocities obtained from our model runs over the two sites. Note, that besides the wind-induced part of field-aligned motion, plasma diffusion is also present, and it is the total ion drift

$$v_{i,\parallel} = v_{i,\parallel,wind} + v_{i,\parallel,diff} \quad (2)$$

that determines the net motion of the plasma along the geomagnetic field line. Here

$$v_{i,\parallel,diff} = -D_a \sin |I| \left[\frac{1}{n_i} \frac{\partial n_i}{\partial z} + \frac{1}{T_p} \frac{\partial T_p}{\partial z} + \frac{1}{H_p} \right] \quad (3)$$

is the ion diffusion velocity along the geomagnetic field (positive upward/equatorward) (Schunk and Walker, 1970; Banks and Kockarts, 1973). $D_a = 2kT_p/m_i v_{in}$ is the ambipolar diffusion coefficient, $T_p = (T_e + T_i)/2$ is the plasma temperature and $H_p = 2kT_p/m_i g$ is the plasma scale height. Since O^+ is the major ion species in the F region and $n_i \approx n_e$, we specifically focus on its motion.

The top row of Fig. 8 shows the local time versus height variation of the field-aligned velocity of the O^+ ions ($v_{i,\parallel}$) over the WSA (right panel) and over the off-WSA (middle panel) obtained from our IPM model results using the full TWAM winds. The differences between these two velocities are shown in Fig. 8 in the top right panel and the white lines seen in Fig. 8

indicate the height of the density maximum, hmF2. The largest differences in the total ion velocities appear during noon with stronger downward plasma flow over the WSA than over the off-WSA, and during evening when the plasma flow is upward/less downward at the WSA. Note that for both locations hmF2 starts to increase during the evening even though the plasma velocity is downwards. This should be due to the increasing relative role of recombination compared to production during the evening. However because the net plasma flow is less downward/upward over the WSA during the evening, the density peak forms at higher altitudes. The time when hmF2 over the WSA starts to rise sharply (~15:30 LT) also corresponds to the period when the magnitude of the downward flow starts to rapidly reduce, and the time of the largest evening difference between the WSA and the off-WSA field-aligned flows corresponds to the period when NmF2 attains its maximum over the WSA.

Furthermore, additional important difference between the two locations that needs to be pointed out is that, over the WSA the evening time downward velocity of the ions at the altitude of hmF2 reduces and even reverses into an upward flow for a short period around 19:00 LT. In contrast, over the off-WSA at corresponding hmF2, the total ion drift is always downward during the entire evening hours with values around -20 m/s.

Similar to the top row of Fig. 8, the separate motion of ions due to the winds ($v_{i,\parallel,wind}$) (middle row) and due to the diffusion ($v_{i,\parallel,diff}$) (bottom row) are also shown in Fig. 8. The differences in the wind-induced drifts are due to the different neutral winds over these two locations (values at 250 km are shown in Fig. 7.) During the day a stronger downward wind-induced flow is found over the WSA compared to the off-WSA, while during the evening, at around 16:30 LT, the difference becomes positive resulting from a stronger upward component

of the ion velocity due to the winds over the WSA. Note that there is no significant altitude variation of the wind-induced ion drifts above about 300 km.

Fig. 8 also shows that the ion diffusion velocities (bottom row) are significantly different over the two sites. This can be understood when realizing that, among other parameters, the diffusion velocities depend on the plasma densities and their gradients (Eq. (3), which are vastly different over the two sites (Fig. 7). Fig. 8 shows that over both sites the diffusion velocities are always downward at the altitude of hmF2, with largest values at night. In the topside ionosphere the diffusion velocities are upward during the day and downward during the night. The difference in the ion diffusion velocities over the two sites ($\Delta v_{i\parallel, diff}$) indicates that during the day the plasma motion due to diffusion is more upward over the WSA compared to the off-WSA (or less downward when $v_{i\parallel, diff} < 0$), however during the evening the picture reverses and the downward diffusion becomes stronger over the WSA.

Thus, over the WSA there is a larger upward component of the flow due to the wind and a larger downward component due to the plasma diffusion. However since $\Delta v_{i\parallel} (= \Delta v_{i\parallel, wind} + \Delta v_{i\parallel, diff}) > 0$ during the evening, the net effect of the wind-induced drift and the diffusion is the larger net upward ion flow over the WSA that is not the case for the off-WSA location.

3.3.2. Comparison between Plasma Transport, Production and Loss

To understand the mechanism of the electron density increase over the WSA during the evening, we compare the plasma production, loss, and transport processes over the WSA and off-WSA, which determine the change of plasma density through the continuity equation

$$\frac{\partial n_i}{\partial t} = -\nabla \cdot (n_i \mathbf{v}_i) + P - L. \quad (2)$$

Here n_i is the ion/electron density, and P and $L = n_i L'$ are plasma production and loss rates, respectively (Schunk and Nagy, 2009). The time evolution of the Transport ($= -\nabla \cdot (n_i \mathbf{v}_i)$), P , and L terms are available from our IPM simulations. Since our study primarily focuses on the variation of F region peak parameters, in the following we compare the variation of the individual terms of continuity equation at the altitude of hmF2. Note that at hmF2 the altitude gradient of the wind velocity is small (Fig. 8), and because at the density peak $\nabla_z \cdot n_i = 0$, the largest contribution to the transport term at hmF2 is due to $n_i \nabla_{\parallel} \cdot \mathbf{v}_{i,diff}$. This indicates that at hmF2 the transport term does not directly depend on the wind velocity, but instead strongly depends on the plasma density and its gradients. Note, however, that these parameters themselves have a strong dependence on the neutral winds.

Fig. 9a-e shows the total rate of plasma density change, density change due to P , $-L$, $P-L$ and Transport processes at the altitude corresponding to hmF2. Green dashed boxes in the panels highlight the evening time intervals ($\sim 18:00 - 23:00$ LT) when important differences between the various processes over the two sites take place. The $\partial n_i / \partial t$ displays a very distinct behavior at these times over the two sites (Fig. 9a) with large positive values over the WSA, but almost always negative values over the off-WSA. In order to understand the causes of these differences in $\partial n_i / \partial t$, four possible scenarios that could lead to this behavior were considered: (1) Large photoproduction over the WSA, (2) weak chemical loss over the WSA, (3) slow plasma loss due to transport over the WSA, and (4) a combination of these three scenarios. In the following, we address these possibilities. Fig. 9b shows that plasma production over the WSA is, in fact, slower

than the production over the off-WSA. This can be understood from the high hmF2 over the WSA. Fig. 9c shows that plasma loss due to recombination is slower over the WSA. Even though the electron density is larger over the WSA (contributing to enhanced chemical loss), the slower chemical loss rate over the WSA should be due to higher hmF2. It is also clear from Fig. 9b and Fig. 9c that the difference between the absolute values of production terms is smaller than that between recombination terms. This makes $(P-L)_{\text{WSA}} > (P-L)_{\text{off-WSA}}$ during the evening as seen in Fig. 9d. Therefore, the large $P-L$ over the WSA is due to weak loss due to recombination.

The effect of plasma transport in the electron density evening time increase is very important. However, its quantitative contribution to the net change of density has not been reported. Fig. 9e shows the comparisons of the rates of plasma density change due to transport terms. As it can be seen, the ionization is constantly lost due to the plasma transport processes throughout the day over both sites. Moreover, it can also be noticed that plasma loss due to transport is weaker over the WSA ($|Transport|_{\text{WSA}} < |Transport|_{\text{off-WSA}}$) between about 18:45 - 20:45 LT, further increasing the relative role of solar production in the density increase. Finally, to establish the relative role of chemistry and transport processes in the observed differences in $\partial n_i / \partial t$ in Fig. 9a, Fig. 9f compares the differences between the similar terms of the two locations. It becomes apparent from this comparison that for most of the evening the contribution from larger $P-L$ dominates; however during about a two-hour period centered on 19:45 LT, the role of the reduced transport is of equal importance. This makes the transport term (through its reduced amplitude) nearly as important in the evening time density enhancement as the increase in the net balance between chemical production and loss rates.

4. Discussion and Summary

In the present paper, we used COSMIC GPS radio occultation data, and a physics-based data assimilation approach to investigate the mid-latitude evening anomalies. The COSMIC data clearly showed a well-developed WSA during December solstice and the NA during June solstice. First, by combining COSMIC NmF2 and hmF2 data with an ionospheric data assimilation model (GAIM-FP), and next by using GAIM-FP data as input into our novel thermospheric wind assimilation model (TWAM), we estimated the global 3-D thermospheric wind field, which when used in the IPM model, was able to closely reproduce the observed NmF2 and hmF2 over the anomalies. We showed that the empirical HWM93 wind model does not provide an accurate description of the F2-layer parameters over the evening anomaly sites. Based on TWAM wind results, we estimated the role of the zonal component of the wind and found it is the meridional wind that mainly drives the anomalies. The apparent similarities between the WSA and NA were noted and the generation mechanism behind the anomalies was studied in detail for the WSA case. The analysis of plasma production, loss, and transport from the model has revealed that the density enhancement during the evening hours occurs at times when plasma solar production is still higher than its chemical loss; but, different from the site outside the WSA, the condition for the density increase is realized by a relatively weak plasma loss due to the recombination and transport processes.

This paper aimed to address the two main challenges regarding the electron density evening anomalies: The ability to properly model them with an ionospheric model, and to understand the physical mechanisms responsible for their generation. The previous studies that attempted to model the evening anomalies also considered the thermospheric winds to be the main drivers of the observed phenomenon (Kohl et al., 1968; Eccles et al., 1971; Dudeney and

Piggott, 1978; Chen et al., 2011, 2013; Thampi et al., 2011; Ren et al., 2012). In those studies, various ionospheric models were used, driven by different wind models to assess the model ability to reproduce the observed density enhancements. These studies either only produced the general anomaly pattern or the agreement of modeled electron densities with the observed NmF2 values, which, however, were often only qualitative. Even though these approaches demonstrate the winds can cause density increases in the evening, without a simultaneous analysis of hmF2, it is difficult to consider the anomaly properly modeled. The possibility that the modeled hmF2 is vastly different from its observed values exists if NmF2 values agree only qualitatively. This was, for example, clearly demonstrated when we performed IPM simulations with HWM93 winds (Fig. 4). In this simulation the morphology of the evening enhancement was qualitatively modeled (i.e., evening densities were larger than those during noon), but the height of the layer was largely different from the observations. It is, however, important to properly model the height of the layer to investigate the physical mechanisms behind the anomalies because production and loss processes, for example, exhibit a strong altitude dependence.

In contrast to the use of the HWM93 winds, the use of TWAM winds in IPM significantly improves the agreement with the COSMIC data, both qualitatively and quantitatively, for both NmF2 and hmF2. The obtained agreement between the data and model values (Fig. 4) together with the results of the wind effects on NmF2 and hmF2 (Fig. 6) demonstrate that the thermospheric neutral wind, in agreement with previous studies, is the main driver (if not sole) of the mid-latitude evening anomalies. The agreement was obtained by the change of neutral wind values only and the new wind values, which are obtained from GAIM-FP and TWAM data assimilation models, differ in phase and magnitudes with corresponding HWM93 winds (Fig. 5). The fact the empirical winds are less reliable over the data sparse

regions is well known (Titheridge, 1995; Makela et al., 2012). Note, Thampi et al. (2011) also reported that the use of MU radar winds instead of HWM93 improved their model ability to reproduce the observed features of evening anomaly.

We studied the effect of the zonal and meridional winds on the generation of anomalies. The declination is easterly over the WSA and westerly over the NA. The zonal wind is known to be westward during morning/noon and westward for evening/night (Titheridge, 1995; Emmert, 2001; Emmert et al., 2003). Therefore, according to Eq. (1) the zonal wind over the anomalies enhances the downward diffusion of plasma during noon and opposes it during evening. In that sense, it further enhances the similar effect of the geographic meridional wind on the plasma field-aligned motion, reducing the noontime densities and enhancing them during the evening (see Fig. 5 and Fig. 6). This idea about the magnetic field declination-zonal wind effect on the summertime evening density enhancements was previously discussed by Kohl et al. (1969) and Eccles et al. (1971), and more recently by Zhang et al., (2011, 2012). Eccles et al. (1971) emphasized the importance of the phase of the wind variation together with the longer summertime solar production for the density increase during the evening and also noted that the most pronounced effects of the winds were expected to be observed in the South American and European/Japanese regions because of the displacement between the magnetic and geographic poles. These regions have easterly declinations in the northern hemisphere and westerly in the southern hemisphere and coincide with the anomaly regions in Fig. 3. The declination-zonal wind effects were suggested as a possible mechanism for the evening anomalies by Jee et al. (2009) and Liu et al. (2010), however Zhang et al., (2012) pointed out that even though these effects are favoring for the WSA-like variations, they cannot be a dominant to cause the WSA.

We found that, indeed, the zonal wind contributes to the development of electron density evening anomalies, and for the WSA it can produce larger values during the evening than during noon. However, the geographic meridional winds play the dominant role to produce the observed variations and values of NmF2 and hmF2 over the anomalies. Our results indicate that the zonal wind effect is very small for the NA, but much larger over the WSA compared to the NA. The inclusion of the zonal wind is also important to improve the agreement between the COSMIC and the model data for both NmF2 and hmF2. Our result about the dominant role of the geographic meridional wind is in agreement with modeling studies by Chen et al. (2011), Thampi et al. (2011), and Ren et al. (2012) who used HWM93 winds and concluded the equatorward wind is the main driver of the anomalies. However, different from Ren et al. (2012) our simulations with TWAM winds showed that over the WSA the effect of the zonal wind on the daytime electron density is comparable to that of the meridional wind. Furthermore, at the WSA both zonal and meridional wind components cause a daytime reduction in the electron density that is comparable in magnitude to the evening enhancement.

We investigated to what degree the neutral composition can be responsible for the differences in NmF2 and hmF2 over the two locations. For this purpose we performed an additional IPM simulation with TWAM winds where the only change was that instead of default mode of MSISE-90 model, which includes longitudinal variability, longitudinally averaged MSISE-90 neutral atmospheric parameters were used. Our results indicated that the obtained evening enhancement of the electron density over the WSA is not a consequence of longitudinal variations in the MSISE-90 neutral atmosphere. Therefore, in agreement with Burns et al. (2008) and Karpachev et al. (2011), we also consider it unlikely for the neutral composition and temperature to be the causes of the WSA.

Burns et al., (2008) suggested the possibility of the WSA generation by downward plasmaspheric flux. The IPM model accounts for plasmaspheric refiling during the day and maintenance of the ionosphere at night. Our results (Fig. 8) show that even though the evening time plasma flow due to diffusion is downward over the WSA, the net plasma flow, due to large upward wind-induced velocities, is upward at the altitude of the density peak and above, and does not reverse until about 21:00 LT. This evening upward flow of plasma over the WSA does not support the idea of a WSA generation by downward plasmaspheric flux. Moreover, the density change due to transport is always negative (Fig. 9) regardless of the direction of the flow. The obtained result of upward plasma flow over the WSA is in agreement with the suggestion by Karpachev et al. (2011) and simulation results by Chen et al. (2011).

The studies that relate the mid-latitude evening anomalies to the neutral winds (e.g. see Rishbeth, 1967, 1968; Dudeney and Piggot, 1978; Eccles et al., 1971; Horvath and Essex, 2003; He et al., 2009; Thampi et al., 2011) suggest the possibility of the following scenario. The upward drift of plasma due to the neutral winds pushes plasma to higher altitudes where the recombination is very slow, and if this happens before photoionization ceases, NmF2 could increase. Our results certainly show the reduced recombination over the WSA; however, as it is discussed below, the slow recombination is not the only process responsible for the density enhancement.

The analysis of production, recombination, and transport processes at the altitude corresponding to hmF2 (Fig. 9) revealed that during the evening, due to high hmF2 over the WSA, plasma production was slower than it was over the off-WSA where hmF2 is lower. As for recombination, the larger NmF2 over the WSA contributes to the enhanced loss, but reduced concentration of molecular species at high hmF2 slows the recombination. The net effect of the

two was found to be a reduced rate of chemical loss over the WSA. Furthermore, this reduction in the recombination rate was found to be larger than the reduction in the production rate, making the net change due to chemistry more effective in increasing the electron density during the evening over the WSA. However, in our analysis we found that plasma loss due to transport was stronger over the off-WSA than over the WSA, resulting in a negative total rate of density change (no anomaly) over the off-WSA and a positive total rate of change (anomaly) over the WSA during the evening. More importantly, it was shown that the contribution of the reduced rate of plasma loss by transport to the density enhancement is comparable to the effect of the increased rate of plasma production due to changed chemistry.

In the presented IPM simulations, vertical $\mathbf{E} \times \mathbf{B}$ drifts were not considered over the mid-latitudes because of a lack of electric field observations over these regions. This limitation means that any transport of low-latitude plasma by electric fields to the mid-latitudes was not considered. Lin et al. (2010) and Burns et al. (2011) proposed the upward/poleward transport of ionization from the poleward edges of the equatorial ionization anomalies might be the source of the evening anomalies. In our work, we were able to model the anomalies without this effect. A conclusion that $\mathbf{E} \times \mathbf{B}$ drifts play an insignificant role in the generation of anomalies was given by Chen et al. (2011) and Thampi et al. (2011).

It needs, however, to be noted that the TWAM assimilates magnetic meridional winds from GAIM-FP, which themselves are effective winds at mid-latitudes, and therefore, include possible contributions due to electric fields (Lomidze et al., 2015). Yet, any contribution from a drift velocity perpendicular to the magnetic field, $v_{\perp}^{E \times B}$, to the magnetic meridional wind is equal to $v_{\perp}^{E \times B} / \sin I$. The difference between the magnetic meridional winds over the two sites (WSA-off WSA, calculated from results on Figure 5) is up to -80 m/s during noon and up to +70 m/s

during evening. The vertical drift velocity corresponding to this values would be 59 - 68 m/s (for an average $I = 58^\circ$). These values are found to be unrealistically high for typical quiet-time mid-latitude drifts, which are often less than 20 m/s (Scherliess et al., 2001), and therefore, even if they differ in phase over the two sites, cannot be the reason for the needed differences in the effective magnetic meridional winds.

The presented work showed that data assimilation models can be a useful tool for obtaining information about physical drivers in the ionosphere (i.e., neutral winds). This is especially important over places where ground- and space-based measurements of thermospheric winds are not available or difficult to obtain. Without accurate winds it becomes difficult to properly model the ionospheric electron density that, in turn, complicates the investigation of the various phenomena. The winds estimated by our data assimilation models enabled us to obtain close quantitative agreement with the observations of NmF2 and hmF2, simultaneously. The model winds also enabled us to separately estimate the role of the zonal wind in the anomaly generation. Finally, the analysis of various plasma density variation rates over the WSA revealed that during the evening the electron density increases due to solar illumination and it becomes more effective because of smaller loss due to the recombination and also due to weaker loss due to the transport.

In the following, we summarize the main findings of this work.

(1) The thermospheric neutral winds obtained from the GAIM-FP and TWAM models closely reproduce both NmF2 and hmF2 over the evening anomaly sites (the WSA in December and the NA in June) when used in the IPM model.

(2) The geographic meridional wind is the main driver of the anomalies in both hemispheres, and by itself can produce electron density variations that are close to the observations. The generation mechanisms of the mid-latitude evening anomalies in the two hemispheres during local summer are identical.

(3) The geographic zonal wind has a minor role for the northern hemispheric anomaly. However, at the WSA location, the zonal wind considerably enhances the anomaly and is important to provide a better agreement with the COSMIC data.

(4) Due to a strong equatorward wind over the WSA during the evening, the field-aligned plasma flow is small or even upward at the time when the electron density attains its maximum.

(5) The electron density evening enhancement over the WSA is due to solar photoionization, which is not balanced by loss due to chemical and transport processes.

(6) Transport processes were found to play a critical role in the generation of the evening anomalies.

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Fig. 1. Global maps of COSMIC NmF2 and hmF2 for noon (11:00-13:00 LT) and evening (20:00-22:00 LT) during December solstice in a geographic coordinate system.

Fig. 2. Same as Fig. 1, but for June solstice.

Fig. 3. Difference (in percentage) between evening and noon peak electron densities during December and June solstices. To highlight the global extent of the evening anomalies, only values for which $NmF2_{evening} > NmF2_{noon}$ are shown. Used is a geographic coordinate system.

Fig. 4. Local time variations of NmF2 (top panels) and hmF2 (bottom panels) over WSA (53.75°S, 93.75°W) during December solstice (left panels) and over NA (53.75°N, 146.25°E) during June solstice (right panels). Shown are COSMIC data (black circles) with corresponding one sigma standard deviations, and IPM simulation results with the HWM93 (magenta crosses) and TWAM (blue dots) neutral winds.

Fig. 5. Local time variations of meridional (top) and zonal (bottom) winds over the WSA during December solstice (left) and over NA during June solstice (right). Winds are from the HWM93 model (magenta) and the TWAM model (blue).

Fig. 6. Model results showing the effect of neutral wind components on local time variations of (top) NmF2 and (bottom) hmF2 over (left) the WSA during December solstice and (right) over NA during June solstice. Simulations are obtained from the IPM model with full TWAM winds (blue dots), zero winds (black stars), only TWAM zonal winds (red crosses) and only TWAM meridional winds (green diamonds).

Fig. 7. Local time variations of F2-layer peak parameters (left panels) and neutral wind components (right panels) at 250 km altitude over the WSA (53.75°S, 93.75°W) (blue dots) and the off-WSA (53.75°S, 11.25°E) (red stars). Results correspond to IPM model simulations with TWAM winds and the December solstice conditions. Note, the values of NmF2 and hmF2 for the WSA are the same as those shown in Fig. 6 for the IPM (TWAM) case.

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935 **Fig. 8.** Local time vs. height variations of field-aligned velocity of O^+ ions over the (left column)
 936 WSA, (middle column) off-WSA, and (right column) difference between the velocities over
 937 these two locations. The values are shown for (top row) total ion drift, (middle row) wind-
 938 induced ion drifts, and (bottom row) diffusion-induced ions drifts during December solstice. The
 939 white lines indicate the location of hmF2 for the corresponding location.

Fig. 9. Local time variations of (a) total rate of change of plasma density ($\partial n_i / \partial t$), (b) plasma production (P), (c) negative loss ($-L$), (d) $P-L$ and (e) Transport over the WSA (blue dots) and off-WSA (red stars) at the altitude of hmF2. Also shown are (f) local time variations of differences between similar terms ($P-L_{\text{WSA}} - P-L_{\text{off-WSA}}$ (magenta circles) and $|T_{\text{off-WSA}}| - |T_{\text{WSA}}|$ (black stars)).