The summer evening anomaly and conjugate effects

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[1] The Constellation Observing System for Meteorology, Ionosphere, and Climate (COSMIC) GPS occultation data have been analyzed in this study to provide a better understanding of the Weddell Sea Anomaly (WSA) and to place it in the wider context of a general phenomenon that occurs near dusk in summer, which we are calling the summer evening anomaly to better capture its global nature. The terminator and the magnetically conjugate points for the terminator in the other hemisphere have been plotted on top of global maps of COSMIC NmF_2 and hmF_2 for 2 months either side of the December and June solstices for 2006–2008. These plots show that there are distinct enhancements of NmF_2 and increases in hmF_2 as soon as the conjugate footprint of the field line on the winter terminator is seen at middle latitudes in the summer hemisphere. This effect is most pronounced where the WSA is formed, but it also occurs across the South Pacific Ocean in the southern summer and across much of the North Atlantic Ocean, Siberia, and Kamchatka during the northern summer. An hmF_2 increase occurs between the two terminators even at locations where there is no increase in NmF_2. A similar, but reversed, effect occurs in hmF_2 near dawn. This behavior appears to be most consistent with upward and poleward ion drifts in the evening, but neutral wind and downward precipitation may make important contributions to this effect.

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1. Introduction

[2] The Weddell Sea Anomaly (WSA) was discovered 50 years ago during the International Geophysical Year [*Bellchambers and Piggott*, 1958]. It is characterized by the unusual condition that NmF_2 is larger at night over the Weddell Sea than it is in the daytime, but only in summer. A number of attempts were made to explain the WSA in terms of high-latitude phenomena [e.g., *Penndorf*, 1965; *Dudeney and Piggott*, 1977], which was natural considering that the Weddell Sea is found at a latitude of about 60°S. However, none of these explanations could properly explain why this enhancement of electron densities occurs at night in this location and not elsewhere and at other times.

[3] These early studies were restricted because the only data that were available were measurements from ground ionosonde stations in Antarctica around the Weddell Sea. Consequently, no further progress was made in understanding the WSA, which also appeared to only be a local phenomenon near Antarctica. Interest in this phenomenon, therefore, slowly died.

[4] Attention to the WSA has been rekindled since *Horvath and Essex* [2003] and *Horvath* [2006] used data from the TOPEX (topography experiment for ocean circulation) satellite to study it and found that it actually extended over the South Pacific at the time of its formation near dusk in local solar time. *Horvath and Essex* [2003] did note that the Weddell Sea is quite near the southern equatorial anomaly but did not pursue that line of enquiry further. *Horvath* [2006] also looked at output from the Coupled Thermosphere Ionosphere and Plasmasphere model (CTIP) [*Fuller-Rowell et al.*, 1996] and found no evidence of the WSA. There is also no evidence of the WSA in the National Center for Atmospheric Research-Thermosphere-Ionosphere-Electrodynamics General Circulation Model (NCAR-TIEGCM). This inability to model the phenomenon suggests that some physics or chemistry is missing from both models.

[5] *Burns et al.* [2008a] used NmF_2 and hmF_2 data from the COSMIC satellites binned in local time to study the WSA. They suggested that the WSA was a continuation of the southern, summer equatorial anomaly that had been displaced southward. Hence, they associated the WSA with low-latitude phenomena, rather than high-latitude ones. They also showed that there was a much greater increase in hmF_2 in the region of the WSA than there was elsewhere near dusk. Although this height increase was regarded as

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significant, the importance of its exact nature was not recognized by them. They also discussed possible mechanisms that might form the WSA. None of them were found to be adequate, but they did suggest that precipitation from the plasmasphere may be involved.

[6] Two other recent papers have dealt with elements of the WSA that are important to the ideas developed in this paper. *Lin et al.* [2009] indicated that there was evidence of similar behavior in the Northern Hemisphere around the June solstice. *Jee et al.* [2009] studied the solar cycle variation of the Weddell Sea anomaly and suggested that the phenomenon was part of some larger-scale behavior in the ionosphere.

[7] All of these pieces of information have helped to develop our understanding of the processes that may cause the WSA. In this paper, we describe what we believe actually causes the WSA and other, more general behavior. The treatment here is phenomenological rather than mathematical.

[8] Before the causes of the WSA anomaly and other related phenomena can be considered, some background materials must be presented. The COSMIC data and its analysis are described in the section 2. The results are given in section 3, and the discussion of these results and the conclusions drawn from them are found in sections 4 and 5, respectively.

2. The Data

[9] Six satellites, which are together called COSMIC, were launched on 15 April 2006 [*Kumar*, 2006]. The instrument that interests us here is the GPS radio occultation receiver. It is used to make the atmosphere and ionosphere measurements through phase shifts of radio signals. The phase advance is used to compute the amount of signal bending that occurs as the impact parameter varies [*Rocken et al.*, 2000]. This bending is then used to compute vertical profiles of refractivity. The refractivity is directly proportional to ionospheric electron densities when impact parameters are above 80 km [*Lei et al.*, 2007]. The Abel inversion technique is then applied to retrieve electron density profiles from the total electron content along these ray paths [*Hajj and Romans*, 1998; *Schreiner et al.*, 1999].

[10] The COSMIC satellites were launched from the same rocket and initially followed the same orbit track at 512 km. The satellites were then sequentially raised to orbits at 800 km. The time delay for this increase in elevation was designed to spread the orbital planes, so the individual satellites are now 30° apart. The COSMIC satellites now provide approximately 24 h of local time coverage globally and about 1500–2000 vertical electron density profiles per day. Consequently, local time, universal time, longitude, and latitude coverage is mostly complete and thus provide a suitable data set for this study. Each inversion produces a vertical profile of electron density that is reliable from 200 km to above the F_2 peak. This is true for the early lower orbits as well as the later ones, so all of these data are used here.

[11] The data used in this study were retrieved from the COSMIC (http://www.cosmic.ucar.edu) observations over the following southern summer periods: 15 October 2006 to 15 February 2007; and 15 October 2006 to 15 February 2008. The northern summer periods used were 15 April 2007 to 15 August 2007 and 15 April 2008 to 26 July 2008. Abel inverted data [*Lei et al.*, 2007] were used in this study to obtain values for NmF_2 and hmF_2. The data were sorted into latitude and longitude bins for each universal time (UT) hour using a uniform horizontal grid with a resolution of 15° in geographic longitude and 5° in geographic latitude. This led to relatively small amount of data in each bin. Consequently, medians were used to calculate values in each bin rather than means. This had the added advantage of eliminating data from relatively rare events, like geomagnetic storms.

[12] The data are presented on cylindrical equidistant maps of the Earth (e.g., see Figure 1a). Three lines are drawn on top of the contours. The solid line with shading is the terminator at the ground. The ground terminator was chosen, because, although the Sun sets in visible light some hours later, EUV radiation cannot pass through the lower atmosphere, so EUV sunset occurs at 100 km at nearly the same time as sunset on the ground. The dash-dotted line is the magnetic conjugate of the terminator in the other hemisphere calculated using apex coordinates [*Richmond*, 1995]. This represents the footprint of the other end of flux tubes associated with the terminator in the opposite hemisphere.

[13] Studies of the data show that the solstice terminator was an appropriate line to use in almost every case, even though the data coverage included a wide range of months around the solstice. The terminator moves very little for quite a long time near the solstice, and the use of medians tends to result in the selection of days close to the solstice rather than more distant days. The third, dotted line represents the magnetic equator.

3. Results

[14] The problem with plotting TEC or NmF_2 in local time coordinates as *Burns et al.* [2008a] explicitly did and *Horvath* [2006] implicitly did is that it does not isolate the progression of the local behavior of the evolution of the WSA near South America. To isolate this progression of behavior, individual features of the data need to be determined more effectively. This determination of the individual features of the data was obtained here by plotting NmF_2 and hmF_2 in longitude and latitude bins for each UT (see section 2). Two examples of the results of this plotting are given in Figure 1. Figure 1a gives NmF_2 for 0000 UT, just as the Sun is setting over the eastern Pacific and southern South America. The color scale in Figure 1, like those in Figures 2 and 4 shown in this paper, has a maximum value of 8×10^5 cm^{-3}. Electron densities greater than this value are saturated at it. This saturation is used to accentuate effects in the middle latitudes near dusk, where the summer evening anomalies (SEAs) are occurring. The main feature of interest in this paper is the enhancement of electron densities near dusk over much of the globe in summer. This enhanced NmF_2 occurs in a narrow band of local times. The onset of the enhancements (in local time) is strongly related to the time when the magnetic conjugate points associated with the northern (winter) sunset pass overhead. In other words, the enhancements commence as soon as the northern (winter) footprint of the flux tube is in darkness. These enhanced electron densities decrease rap-

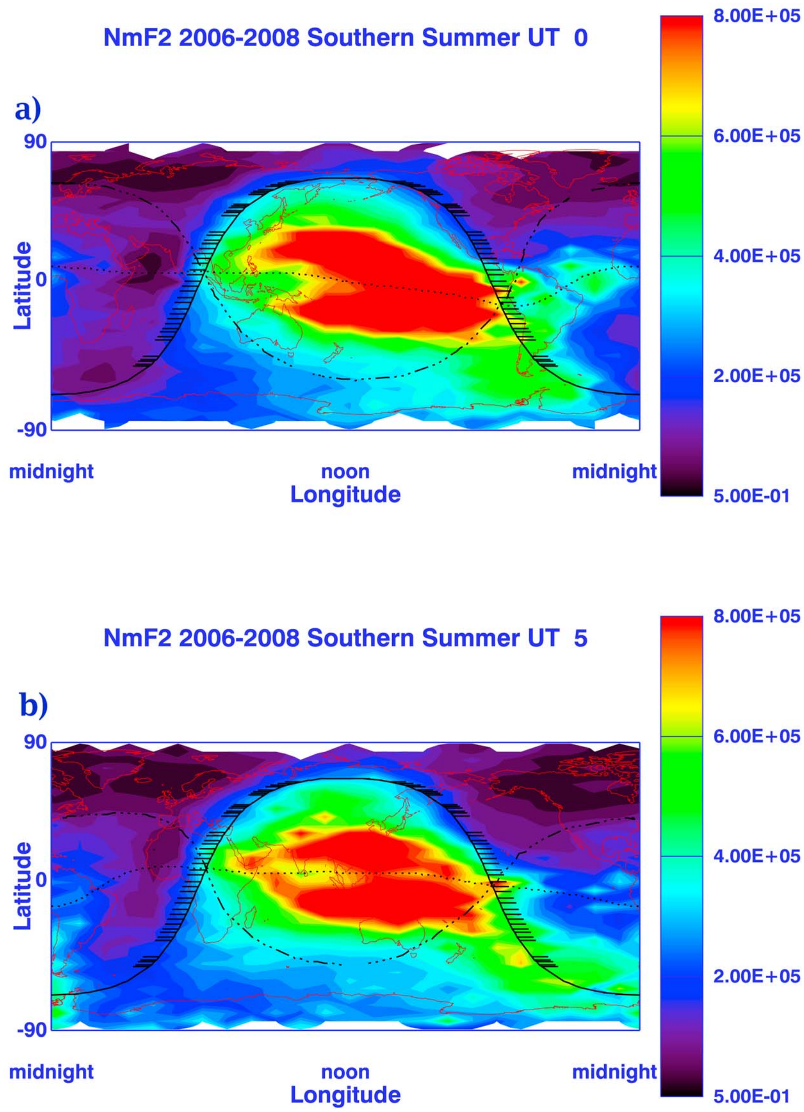


Figure 1. Global plots of NmF_2 for two universal times: (a) 0000 UT and (b) 0500 UT. Figures 1a and 1b are median plots of NmF_2 for the periods from 15 October to 15 February 2006–2007 and 2007–2008. The color scale is saturated at 8×10^5/cc electrons. The hatched line represents the terminator, the dashed line represents the magnetic conjugate locations of the terminator in the other hemisphere (footprints of the flux tube running through the terminator in the opposite hemisphere), and the dotted line represents the magnetic equator.

idly in the middle latitudes after sunset in the Southern (summer) Hemisphere. Another feature of the enhancement is that it commences at successively higher latitudes at later local times between conjugate sunset and actual sunset.

[15] Figure 1b is the same as Figure 1a but for 0500 UT. Again the occurrence of the initial signs of the enhancement in the Southern (summer) Hemisphere is related to sunset at the magnetically conjugate points in the winter hemisphere. However, in this case, the electron density enhancements associated with the southern equatorial anomaly occur at much lower geographic latitudes than they did in Figure 1a. Note also that the southern equatorial anomaly (the continuation of the daytime anomaly crests) does not appear after dark at the latitudes at which it appeared during the daytime. This is in contrast to the behavior shown later in Figure 2, where the southern equatorial anomaly is seen to continue for some hours after dark. This lack of continuity of the equatorial anomaly after dark was also not apparent in Figure 1a but did appear at all of the intervening UTs between those of Figures 1a and 1b.

[16] Another feature of Figure 1 is the very slow build up of electron density after sunrise in the southern (summer) middles latitudes compared with that which occurs in the winter hemisphere. Much of this slow build up could be associated with the different neutral composition in the two hemispheres but increases of NmF_2 in the southern summer hemisphere are rapid once sunrise occurs at the magnetically conjugate points, suggesting that it is related to this sunrise rather than to neutral composition.

[17] In contrast to Figures 1a and 1b, Figure 2 is an NmF_2 map for a case (2000 UT) where there is little or no apparent presunset enhancement of electron densities poleward of the

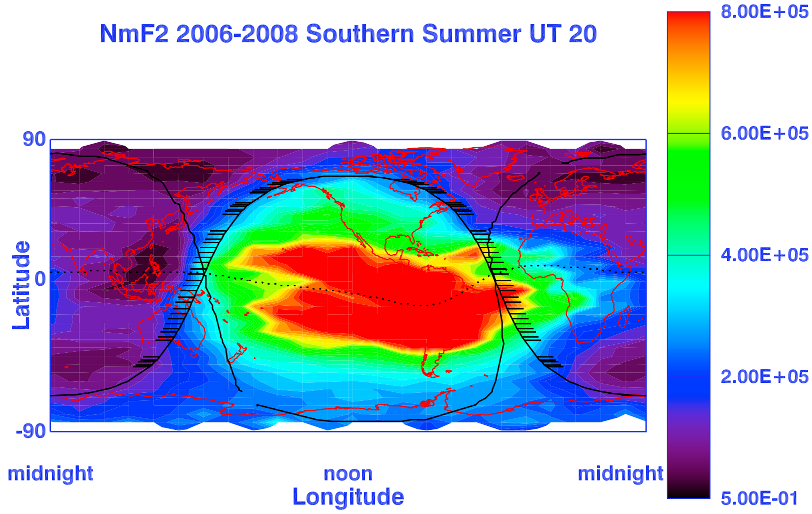


Figure 2. Global plot of NmF_2 for 2000 UT. This is a median plot of NmF_2 for the periods from 15 October to 15 February 2006–2007 and 2007–2008. The color scale is saturated at 8×10^5/cc electrons.

southern equatorial anomaly. Several factors are in play in Figure 2 compared with Figures 1a and 1b. First, the southern equatorial anomaly occurs at low latitudes near sunset. This has two effects: conjugate sunset is fairly close in local time to actual sunset and the anomaly is far from the high geographic latitudes, where there is prolonged illumination. Second, the magnetic equator has a strong northward tilt from west to east in this location. This too affects the observed changes in NmF_2: it results in normal sunset and conjugate sunset being even closer in local time.

[18] *Burns et al.* [2008a] showed that it is not just NmF_2 that changes in the region where the WSA is formed, hmF_2 also increases greatly in this region. Figure 3 shows hmF_2 for the same UT (0000 UT) that was shown in Figure 1a. Although the 15° longitudinal resolution smears things out a little, there is a large increase in hmF_2 associated with the conjugate terminator in the Southern (summer) Hemisphere in the Weddell Sea Anomaly region. There is no such increase in hmF_2 before dark in the Northern (winter) Hemisphere. However, there is a rapid increase in hmF_2 in this hemisphere between dusk and the time that the conjugate terminator indicates that the Sun has set in the summer hemisphere.

[19] One of the issues that has prevented a greater understanding of the causes of the WSA is that it appears as a local phenomenon. However, *Lin et al.* [2009] showed that there were signs that something similar to the conditions leading to the formation of the WSA appeared in the Northern Hemisphere near the June solstice, suggesting that the WSA is a special case of the more widespread phenomena that we call SEAs. This work is extended here using the analysis techniques that were described earlier. Figure 4 contains two plots of NmF_2 at different UTs in the northern (around the June solstice) summer. Figure 4a shows NmF_2

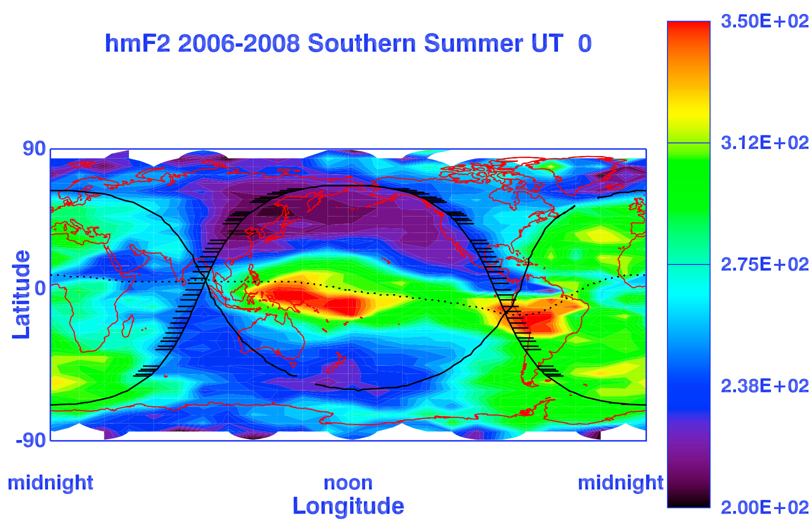
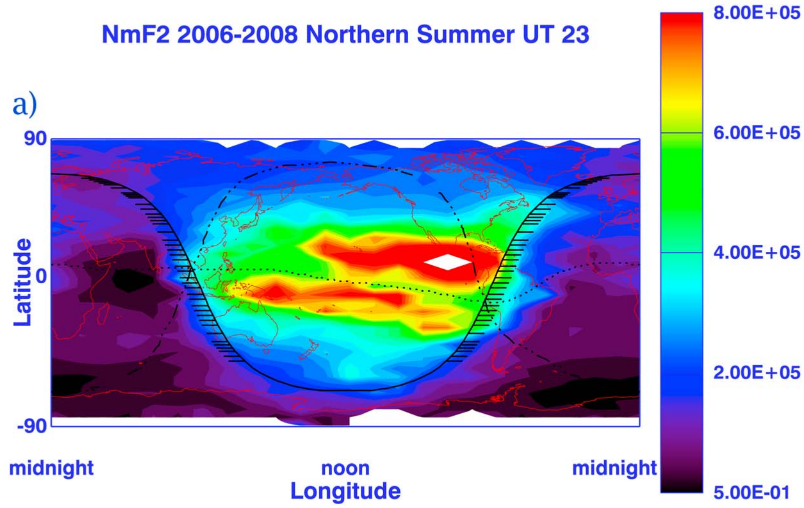


Figure 3. Global plot of hmF_2 for 0000 UT. This is a median plot of hmF_2 for the periods from 15 October to 15 February 2006–2007 and 2007–2008.



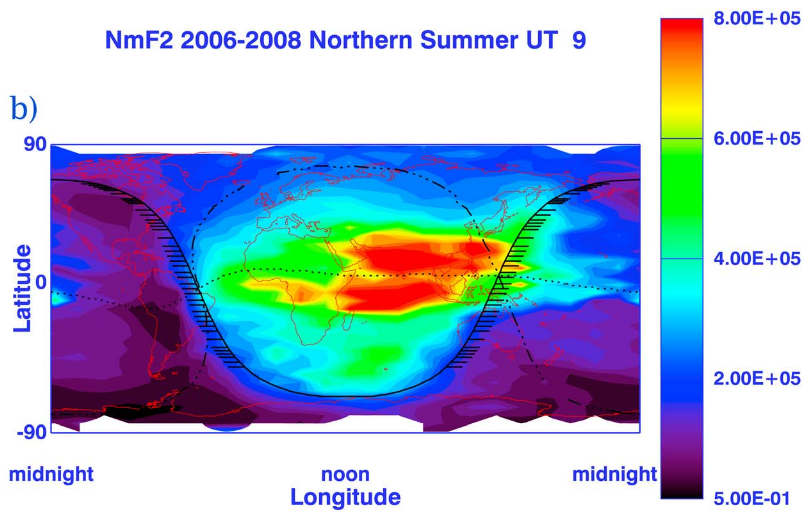


Figure 4. Global plots of NmF_2 for two universal times: (a) 2300 UT and (b) 0900 UT. Figures 4a and 4b are median plots of NmF_2 for the periods from 15 May to 15 August 2007 and 2008. The color scale is saturated at 8×10^5/cc electrons.

at 2300 UT, when dusk occurs over the North Atlantic off the coast of North America. There is an enhancement of NmF_2 at middle latitudes prior to dusk, just as there was in the southern summer. The local time of the commencement of this enhancement is again closely associated with the conjugate terminator. As this enhancement bends northward with later local time in a way that is much sharper than the bending with later local time of the magnetic equator over eastern North America, it cannot be simply the result of the bending of the magnetic equator at this location. Note that, even though the geometry of the magnetic equator creates a significant separation between the conjugate terminator and the actual one at this local time at higher latitudes, the relatively low geographic latitude of the northern edge of the northern equatorial anomaly means that the separation between the two terminators on the northern boundary of the northern equatorial anomalies is relatively small.

[20] Figure 4b gives NmF_2 at another UT (0900 UT) where a predusk enhancement occurs. Dusk occurs here in the Pacific just east of Japan. The enhancements of electron density are not large over Japan, but they extend to southern Kamchatka, where the largest daily values of NmF_2 occur just prior to dusk. The magnetic equator is largely parallel to the geographic equator in this region. However, the magnetic equator is sufficiently far north to permit a significant temporal separation between the conjugate and the regular terminator on the northern edge of the northern equatorial anomaly in this region. As in other cases where this middle latitude enhancement is seen, it starts where the conjugate terminator crosses the boundary between the low electron densities in the middle latitudes and the high electron densities in the northern equatorial anomaly (as the contours change from green to blue). There are other UTs during the northern summer where no such enhancement occurs (not

shown here). These are associated with regions where the magnetic equator is south of the geographic equator and/or the angle which the magnetic equator subtends to the geographic equator is such that the conjugate and actual terminators occur close together in longitude and consequently where the longitudinal separation between sunset and the conjugate terminator is relatively small on the northward edge of the northern equatorial anomaly.

4. Discussion

[21] Understanding the WSA has been difficult in part because it was first observed over Antarctica. The natural assumption was that, as it was a high geographic latitude phenomenon, it was also a high geomagnetic latitude phenomenon. Therefore, all of the original explanations of this phenomenon involved processes that were in some way associated with the high latitude convection pattern. The first suggestion that something different might be occurring came when *Horvath and Essex* [2003] noted that the southern equatorial anomaly was close to the region where the WSA occurred, but they did not pursue this idea further. Later, *Burns et al.* [2008a] found that there appeared to be continuity between the WSA and the southern equatorial anomaly over the Pacific. *Lin et al.* [2009] pointed out that there were indications that something similar was occurring in the Northern Hemisphere during the northern summer and that the formation of these effects was similar to the formation of the WSA. This similarity has lead us to label both effects SEAs.

[22] In this paper, we have presented a number of pieces of evidence connecting the WSA to a more widespread phenomenon: a middle latitude, summertime eastward (increasing local time) gradient of NmF_2 before sunset that occurs when the longitudinal difference between the local and conjugate terminators is large (SEAs). The height of the F_2 peak also increases between the two terminators. Although the processes causing the WSA and the SEAs appear to be the same, their final form is different; the SEAs do not have the defining characteristic of the WSA, peak electron densities at midnight. This linkage leads to two questions: can we use this evidence to infer the causes of this phenomenon, and can we provide an explanation of why the changes in the WSA are so much more noticeable (for example the midnight maximum that occurs in the WSA) than in the SEAs? Before these questions can be answered, the various threads of evidence must be compared and an overall pattern of behavior must be described.

[23] Perhaps the most salient features to come out of the results presented here are the narrow local time (or longitude) band (its width is a few hours in local time at its greatest extent), in which the middle latitude enhancements occur at a given universal time and the direct relationship between the start of this band and the location of the conjugate terminator. A critical aspect of the importance of this band of enhancements is the separation in either geographic longitude or local solar time between the conjugate terminator and the actual terminator in the middle latitudes. This is greatest over the South Pacific where the WSA is formed. The poleward extent of the enhancement is determined by the separation of the conjugate and real terminators and the geographical latitude of the poleward edge of the summer equatorial anomalies as indicated by the abrupt change in color between low-latitude electron densities and middle latitude ones. Two factors determine the separation of these two terminators: where the latitude of this boundary is high the separation is relatively large, as there are large changes in the length of daylight hours with season at middle latitudes; and the separation is also large in places where the lines of constant magnetic longitude are oriented so the summer end of the flux tube is significantly westward of the winter end. Both conditions are only met simultaneously over the eastern South Pacific Ocean off the coast of South America.

[24] There is evidence that there are similar, but weaker, dusk enhancements of middle latitude electron density off the east coast of America and off the east coast of Japan during the northern summer (SEAs). In the former case, the lines of constant magnetic longitude have a sharp latitudinal gradient that is conducive to a large local time separation between the conjugate and the real terminators, even though the summer equatorial anomaly occurs at relatively low latitudes. In the latter case and, in fact, over much of Siberia, the magnetic equator is significantly north of the geographic equator, so there is separation between the conjugate and real terminators as the local sunset in summer is considerably later than conjugate sunset in local solar time at the northern edge of the northern equatorial anomaly. The NmF_2 enhancements that were observed just before, and persisted after sunset, probably explain the difficulties that *Burns et al.* [2008b] had in reconciling May ionosonde observations over Siberia in the immediate post dusk period with their model output, as no such enhancements are produced by the National Center for Atmospheric Research-thermosphere-ionosphere-electrodynamics general circulation model (NCAR-TIEGCM).

[25] Significant changes in hmF_2 are related to this difference in electron density that occurs between the conjugate and real terminators. In the summer evening, the F_2 peak begins to rise after conjugate sunset rather than after the actual sunset. No presunset rise of the F_2 peak occurs in the winter hemisphere. Also, the beginning of the rise always occurs in conjunction with the conjugate terminator. That is, in winter the local time of the beginning of this height rise is the same as the local time of the location of the conjugate terminator; thus, it occurs at earlier local times at higher latitudes. Also, when the conjugate terminator is close to the real terminator, the height rise begins near the real terminator and occurs only between the conjugate terminator and the actual terminator. In the morning, the height of the F_2 peak decreases in the summer hemisphere from sunrise until the conjugate terminator occurs (e.g., see Figure 3). A decrease also occurs in winter from the time that the conjugate terminator is seen until real dawn. In winter, minimum heights of the F_2 peak usually occur at dawn, whereas they occur when the conjugate terminator passes overhead in summer. This is true for all universal times, but hmF_2 is shown for only one UT in this paper.

[26] Another feature to note is the continuity of the summer equatorial anomaly after dark in Figure 2, but not in Figure 1b (Figure 1a is an anomaly because the longitude of this plot is such that the remains of the equatorial anomaly that occurred over South America). This lack of a summer equatorial anomaly at night occurs all across the Pacific (not

shown) in the southern summer and is coincident with areas where there are middle latitude enhancements. It also occurs in the Northern Hemisphere during the northern summer, at longitudes where there are middle latitude electron density enhancements (see Figure 4a).

[27] Changes in hmF_2 and NmF_2 do not occur in the same way. Height increases are found at all latitudes in summer after the conjugate terminator has passed overhead in the late afternoon, but NmF_2 increases occur at progressively higher latitudes at later local times. The first such NmF_2 enhancements are seen at the local time when the conjugate terminator crosses the poleward edge of the equatorial anomaly in the summer hemisphere. The local solar time at which these enhancements occur then is progressively later as the latitude gets higher.

[28] Given these observations, is there a possible explanation that can encompass all of this behavior? The data presented here allow most of the mechanisms presented by *Burns et al.* [2008a] to be questioned. Burns et al. discussed how temperature and neutral composition changes were not the probable cause of the WSA. They also suggested that neutral wind effects were not likely, that electric field effects had difficulties as there was no known source of the field and that the drift speeds that were required seemed too great, and finally they suggested that downward transport from the magnetosphere was possible.

[29] The results presented in this paper indicate that neutral wind effects and downward precipitation are unlikely to be the primary sources of the WSA. In both cases the mechanism predicts that the NmF_2 increases should follow the hmF_2 increases in a regular way and not have a particular latitude dependence. Neutral winds require the height rise of the F_2 peak to then result in decreased recombination. This decreased recombination will, in turn lead to enhanced electron densities. Therefore, the height rise of the F_2 peak should be directly related to the increase of electron densities. The start of the increase in the height of the F_2 peak begins at conjugate sunset in the summer (which occurs at earlier local times, and thus more westward longitudes, with increasing latitude), whereas electron densities increase at later local times (more eastward longitudes) times as latitudes get higher. This is not consistent with a simple relationship between increasing F_2 height and increasing electron densities. Also, there is no reason why wind increases would be associated with the occurrence of the conjugate terminator, yet this association is immediately apparent in the data presented here. For a precipitation theory there are increased contributions from the downward diffusion of ions. This will lead to increased electron densities and a higher F_2 peak. However, the height rises and the electron density increases will occur in the same locations and times, something that is not seen in the observations presented here. This does not, however, rule out the possibility that the processes do not make contributions to the overall changes. For these reasons the possible effects of electric fields need to be further examined.

[30] The critical factor in producing the SEAs and the WSA appears to be that they only occur when a flux tube is illuminated in one hemisphere and in darkness in the other. In this case one end of the flux tube is in the highly conductive E region, where the neutral winds cause a strong dynamo effect [e.g., *Richmond et al.*, 1992] and the other end is in the poorly conducting F_2 region where horizontal currents are weak. If it assumed that the E region dynamo electric field is a polarization one in this situation, then there should be a strong upward and poleward drift in the evening when the polarization electric field is eastward and a downward and equatorward one in the hours near dawn when the polarization electric field is westward. Both theory and observations [*Behnke and Hagfors*, 1974; *Behnke et al.*, 1985; *Burnside et al.*, 1983; *Buonsanto et al.*, 1993; *Takami et al.*, 1996; *Fejer*, 1991, 1993] have indicated that downward drifts possessing these characteristics occur in the morning when one end of the flux tube is illuminated and the other is in darkness. The current NCAR-TIEGCM and CTIPe assume that the conductivity is halved in this situation, rather than imposing the full electrodynamic solution in which a polarization electric field is connected to a very weakly conducting F region in the other hemisphere. The analysis of *Carlson and Walker* [1972] shows this simplification misses the polarization physics of the conductivity gradient driving plasma transport upwards (downwards) at conjugate dusk (dawn).

[31] A recent study by Pacheco et al. (manuscript in preparation) used ROCSAT drift data to study vertical drifts in the low-latitude and low-middle-latitude regions. They found pronounced downward drifts (of the order of 20–50 m/s) near dawn and upward drifts of similar magnitude near dusk.

[32] *Takami et al.* [1996] stated that "the history of conjugate effects proceeded from the Ph.D. work of R. Behnke on F region vector drifts at Arecibo." *Behnke and Hagfors* [1974] noted that conjugate sunrise had a very noticeable effect on the drift velocities. *Behnke et al.* [1985] expanded these ideas and discussed how there was evidence for Northern Hemisphere electrodynamics at Arecibo being controlled by the conjugate hemisphere, both following conjugate sunrise in one case and during a 2 h nighttime interval in another. They conjectured that, "a southern hemisphere 'battery' had lower internal resistance than the local F layer dynamo and hence controlled the electric field." Other investigators have also discussed this effect including *Burnside et al.* [1983], *Buonsanto et al.* [1993], and *Takami et al.* [1996]. *Fejer* [1991, 1993] also included discussion of it in two summary papers.

[33] There have been at least two theoretical efforts to model the electric fields that occur when one hemisphere is sunlit and the other is in darkness. *Carlson and Walker* [1972] examined the situation near dawn when one hemisphere was in darkness and the other was sunlit. Among other results, they found that when there is a polarization field in the westward direction on the dayside (as there is near dawn), there was a downward drift in both hemispheres, just as we infer from the observations presented here. *Burnside et al.* [1983] expanded this work to investigate the case when the conjugate footprint of the flux tube occurred in the F region. This work is of less relevance to the results described here, but Burnside et al. did also demonstrate that the F region neutral winds measured by a Fabry-Perot Interferometer moved separately from the ion drifts measured by the Arecibo Incoherent Scatter Radar, suggesting that the electric field was being driven by something other than the neutral wind dynamo.

[34] One concern about the idea that conjugate electric fields drive the WSA is the distance that the ions associated with the equatorial anomaly would have to be transported to produce it. However, if the ions traveling to the tip of South America are originally associated with the poleward edge of the equatorial anomaly, these ions need only travel about 1000 km or 10° of latitude. Rough, back of the envelope calculations can be made, assuming that the time difference between conjugate sunset and the actual sunset is about 4 h (it actually gets longer at higher latitudes) that suggest a poleward speed of about 250 km/h or about 70 m/s is needed to advect ions from the equatorial boundary of the southern equatorial anomaly to the area of the WSA. Such speeds are higher than have been observed but not that much higher than those observed by Pacheco et al. A contributing factor may be that ions, which are lifted up by $E \times B$ drift will move down field lines as a result of ambipolar diffusion. This will add to the poleward effect of the $E \times B$ drifts and may be sufficient to explain the observed displacement and the observation that the vertical displacement of the F_2 peak is much smaller than the horizontal displacement that has been discussed here. Clearly, these concepts need further quantitative investigation.

[35] The upward movement of the F_2 peak after conjugate or actual sunset (whichever occurs at the earliest local time) is the most important factor that controls the height of the F_2 peak in the evening. Similarly, the height of the F_2 peak declines rapidly after conjugate or actual sunrise (whichever occurs at the earliest local time). This is the dominant factor controlling the height of the F_2 peak at dawn. One consequence of this downward motion at dawn is that plasma densities build up slowly after dawn in the summer hemisphere and only increase rapidly after conjugate sunrise. This lack of buildup of electron density in the summer hemisphere presumably occurs because the plasma is being pushed down to altitudes where recombination is rapid. *Lin et al.* [2009] showed that a SEA-like phenomenon could be produced by adjusting neutral winds and electron precipitation. However, their work was not constrained by the observations of the connections with the conjugate terminator that have been presented there, nor were they constrained by the unusual changes in the height of the F_2 peak. They also do not explain the behavior of the ionosphere near dawn.

5. Conclusions

[36] COSMIC GPS occultation data have been used to study predusk changes in NmF_2 and hmF_2. The data were binned in longitude and latitude bins for each UT, so that changes at specific locations could be followed through time. The magnetic equator, the terminator and the magnetically conjugate line corresponding to the terminator were plotted over the contoured data to place these data in context. The following conclusions were drawn from this study:

[37] The Weddell Sea Anomaly is built up in the southern summer in a restricted band that is constrained by the magnetic conjugate footprint of the terminator in the winter hemisphere and the actual terminator.

[38] Other such bands of enhanced electron density (SEAs) occur poleward of the northern equatorial anomaly during the northern summer. They too are constrained by the conjugate terminator and the actual terminator.

[39] The Weddell Sea Anomaly is strong for two reasons. First, the equatorial anomaly, which appears to be the source of the WSA, occurs at relatively high latitudes over the western South Pacific. This results in a wider separation in both local time and longitude between the conjugate terminator and the actual one in this region. Second, the footprint of the illuminated (summer) end of the field line is considerably westward of the footprint of the dark end (winter) of the field line. These two effects increase the distance in longitude and local time between the conjugate terminator and the actual one, allowing upward and poleward drifts to occur for a number of hours of local solar time.

[40] This combination of a relatively high latitude of the poleward boundary of the equatorial oval and the summer footprint of the field line being far west of the winter one only occurs off the west coast of South America. Therefore, this is the only location in which the full Weddell Sea type of anomaly can occur.

[41] Because hmF_2 increases occur over a wider range of locations between the conjugate and real terminators than NmF_2 does, processes that can only enhance electron densities coincidentally with increasing height, like the effects of equatorward neutral winds are unlikely to be sources for the WSA and SEAs.

[42] A downward movement of the F_2 peak also occurs between the conjugate and actual terminators at dawn.

[43] These various morphological features may be caused by upward and poleward drifts in the evening and downward and equatorward drifts in the morning although other processes may also be occurring.

[44] The changes in altitude described above are very important sources of diurnal variations in the height of the F_2 peak at middle latitudes.

[45] The downward motion of the F_2 peak between actual dawn and conjugate dawn in summer prevents the buildup of electron densities at middle latitudes in this season until after conjugate sunrise.

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