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Key Points:

- Persistence of the NWA effect has been approved at recent solar activity minimum
- Close correlation of NWA anomaly with MSNA and Weddell sea anomaly found
- Common physical mechanism for NWA, MSNA, and Weddell sea anomaly assumed

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The persistence of the NWA effect during the low solar activity period 2007–2009

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Abstract The ionospheric Nighttime Winter Anomaly (NWA) was first reported more than three decades ago based on total electron content (TEC) and vertical sounding data. The aim of this paper is to provide further evidence that the NWA effect is a persistent feature in the Northern Hemisphere at the American and in the Southern Hemisphere at the Asian longitude sector under low solar activity conditions. The analysis of ground-based GPS derived TEC and peak electron density data from radio occultation measurements on Formosat-3/COSMIC satellites confirms and further supports the findings published in earlier NWA papers. So it has been confirmed and further specified that the NWA appears at longitude sectors where the displacement between the geomagnetic and the geographic equator maximizes. Here NWA peaks at around 40°–50° geomagnetic midlatitude supporting the idea that wind-induced plasma uplifting in the conjugated summer hemisphere is the main driving force for the accumulation of ionospheric plasma in the topside ionosphere and plasmasphere. In parallel, the midsummer nighttime anomaly (MSNA) is caused at the local ionosphere. Simultaneously, interhemispheric coupling causes severe downward plasma fluxes in the conjugated winter hemisphere during night causing the NWA at low solar activity. With increasing solar activity, the downward plasma fluxes lose their impact due to the much stronger increasing background ionization that masks the NWA. It is assumed that MSNA and related special anomalies such as the Weddell Sea Anomaly and the Okhotsk Sea Anomaly are closely related to the NWA via enhanced wind-induced uplifting of the ionosphere.

1. Introduction

The Nighttime Winter Anomaly (NWA) effect was described for the first time by Jakowski et al. in a series of papers analyzing Faraday rotation observations and vertical sounding data at the American and Asian longitude sectors [*Jakowski et al.*, 1981, 1986, 1990; *Jakowski and Förster*, 1995]. The NWA effect consists of a higher mean ionization level in winter nights than in corresponding summer nights although the ionization is equal or even less at daytime in winter than in summer. It was found that the NWA occurs only under low solar activity conditions. Since the daytime winter anomaly effect [e.g., *Lee et al.*, 2011, and references therein] occurs mainly under high solar activity conditions in midlatitudes, both anomaly effects are totally decoupled originating from quite different processes in the thermosphere/ionosphere system. Whereas the daytime winter anomaly effect is primarily due to thermospheric-ionospheric processes, the NWA is assumed to be driven by ionosphere-plasmasphere coupling processes. Thus, to explain the NWA, interhemispheric coupling via the plasmasphere was assumed supported by the tilted geomagnetic field geometry showing strongest deviations of the geomagnetic from the geographic equator at the American and Asian longitude sectors. To further approve this hypothesis, Förster and Jakowski have performed simulation studies that support the suggested explanation very well [*Förster and Jakowski*, 1986, 1988]. This mechanism was also suggested to explain the strong occurrence of nighttime enhancements in particular at northern winter over Havana [*Jakowski et al.*, 1991]. *Rishbeth* [2007] has addressed these points, hemispherical asymmetry and nighttime ionization, to be targeted in theoretical modeling of the global thermosphere-ionosphere system. This paper completes the empirical background of earlier observations for better understanding the physics of the NWA including more sophisticated physics-based modeling in subsequent studies.

In the meantime, a few papers referred to these former studies confirming the existence of the NWA effect under low solar conditions at both longitude sectors. So *Meza et al.* [2012] and *Natali and Meza* [2013] found some indications of the NWA during 2008 at the American longitude sector, in the North-East of Africa, and in the South-West of Oceania. On the other hand, some other anomalies such as the Weddell Sea anomaly and the midsummer nighttime anomaly (MSNA) have been described in recent years [*Horvath and Essex*, 2003, *He et al.*, 2009,

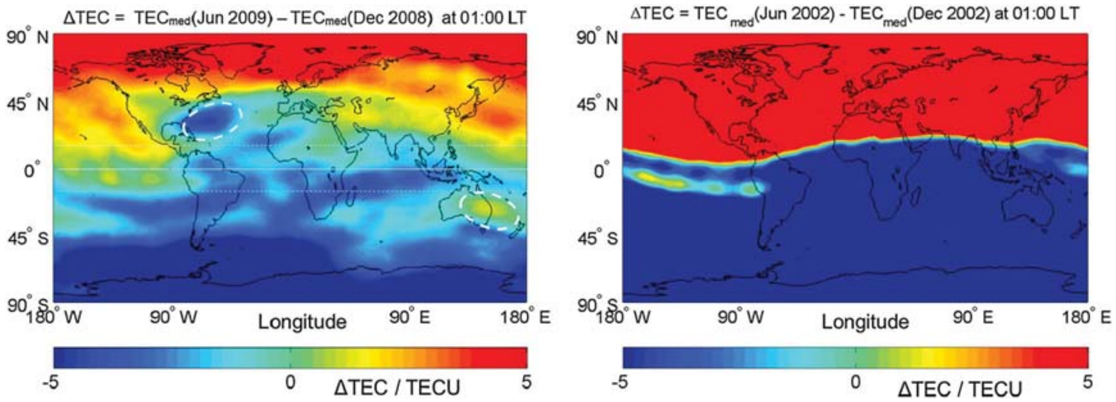

Figure 1. Differential TEC map of monthly medians in (left) June 2009 and December 2008 and of monthly medians in (right) June 2002 and December 2002.

Lin et al., 2010]. All these anomalies appear under low solar activity (LSA) conditions as the NWA, too. Although related publications did not refer to NWA, there seems to be a close relationship between these anomalies. We will discuss the relationships in more detail in section 3.

The long period of low solar activity between solar cycles 23 and 24 in the years 2007–2009 provided ideal conditions to check whether NWA reappears. Furthermore, compared with former studies, the experimental database has grown up essentially due to the global availability of dual-frequency measurements of Global Navigation Satellite Systems (GNSS), on ground [*Dow et al.*, 2009; *Hernandez-Pajares et al.*, 2009; *Jakowski et al.*, 2011b] and in space [*Rocken et al.*, 2000; *Jakowski*, 2005; *Schreiner et al.*, 2007]. Hence, there were ideal conditions to study the persistence of NWA using ground- and space-based dual-frequency measurements of the Global Positioning System (GPS) obtained in years 2007–2009. Whereas ground-based measurements allow estimating the total electron content (TEC) comparable with former Faraday rotation measurements at linearly polarized VHF signals from geostationary satellites, space-based radio occultation measurements provide vertical electron density profiles comparable with vertical sounding data also used in former studies.

2. Database

Instead of using TEC derived from Faraday rotation measurements at single stations in this study, we use global TEC data derived from dual-frequency GPS measurements. Nowadays, the GNSS technique provides a unique tool for high-resolution monitoring of the global ionosphere. Due to the dispersive nature of the ionosphere, the ionospheric signal delay or range error d_I can be deduced from differential phases of dual-frequency measurements [e.g., *Jakowski*, 1996]. In a first order approximation, TEC is directly proportional to the ionospheric range error d_I in GPS measurements along the related ray path between GPS satellite and ground station according to

$$d_I = \frac{K}{f^2}\int n_e \mathrm{d}s = \frac{K}{f^2}\mathrm{STEC} \qquad (1)$$

where $K = 40.3\ \mathrm{m^3\,s^{-2}}$ and the integral of the electron density n_e along the raypath s defines the slant total electron content (STEC). Due to this strong relationship between d_I and TEC, single-frequency navigation systems can be corrected by knowing STEC. This is the reason why vertical TEC (VTEC) is routinely estimated as a geometry-free reference for positioning and navigation since many years. For practical use, the provided VTEC data have to be converted to the specific raypath geometries valid for the GNSS customers.

It should be underlined that the free availability of dual-frequency GNSS measurements made in current national and international geodetic networks—in particular the International GNSS Service (IGS) network [*Dow et al.*, 2009; *Hernandez-Pajares et al.*, 2009]—supports essentially ionospheric and space weather research.

In this paper, we use TEC maps generated by the Center for Orbit Determination in Europe (CODE) at the Astronomical Institute of the University of Bern [*Hugentobler et al.*, 2000] (http://cmslive2.unibe.ch/unibe/philnat/aiub/content/e15/e59/e440/index_eng.html). We rely on these data because the same data set has been successfully used to determine the coefficients of the Neustrelitz TEC Model [*Jakowski et al.*, 2011a].

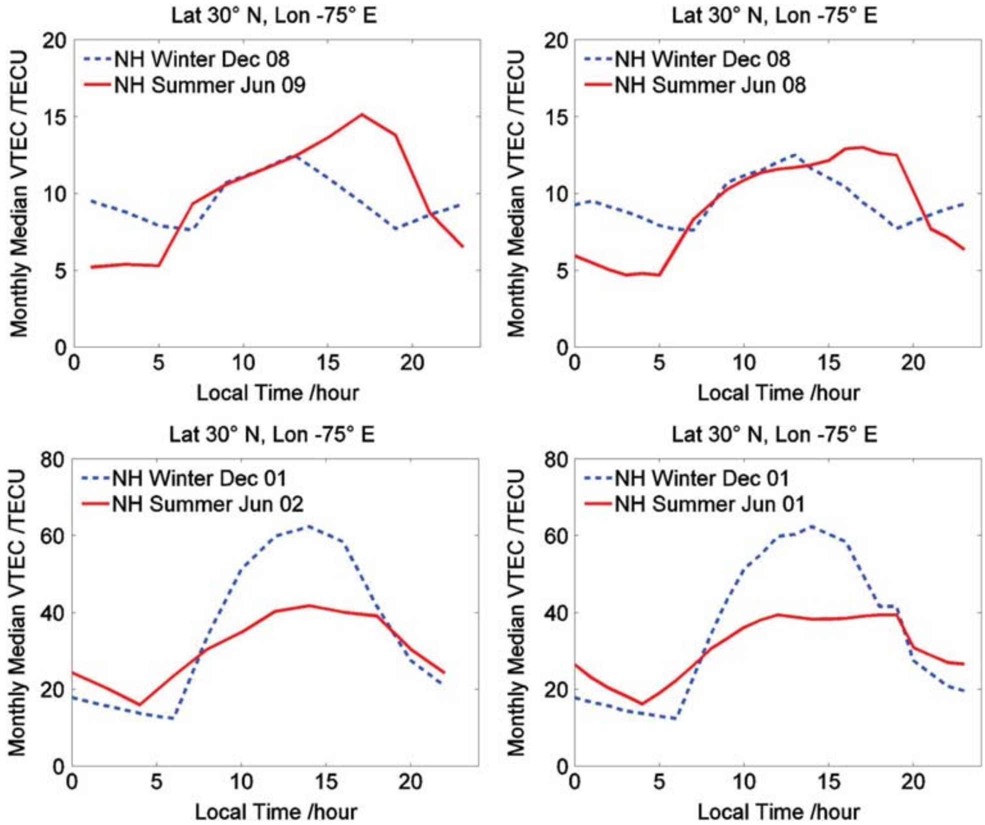

Figure 2. Diurnal variation of TEC showing the NWA effect under LSA conditions in (top row) 2008/2009 in comparison with equivalent figures related to HSA conditions in (bottom row) 2001/2002 where no NWA effect is observable.

Besides the just mentioned ground-based GPS data, we use also space-based GPS data that enable deriving vertical electron density profiles by GPS radio occultation measurements aboard a Low Earth Orbiting (LEO) satellite like CHAMP [*Reigber et al.*, 1996], Gravity Recovery and Climate Experiment (http://www.csr.utexas.edu/grace/), or satellites of the Formosat-3/COSMIC constellation (http://www.cosmic.ucar.edu/) [*Rocken et al.*, 2000]. Radio occultation observations of GNSS signals can effectively be used to derive vertical electron density profiles of the ionosphere [e.g., *Hajj and Romans*, 1998; *Jakowski et al.*, 2002; *Jakowski*, 2005]. The

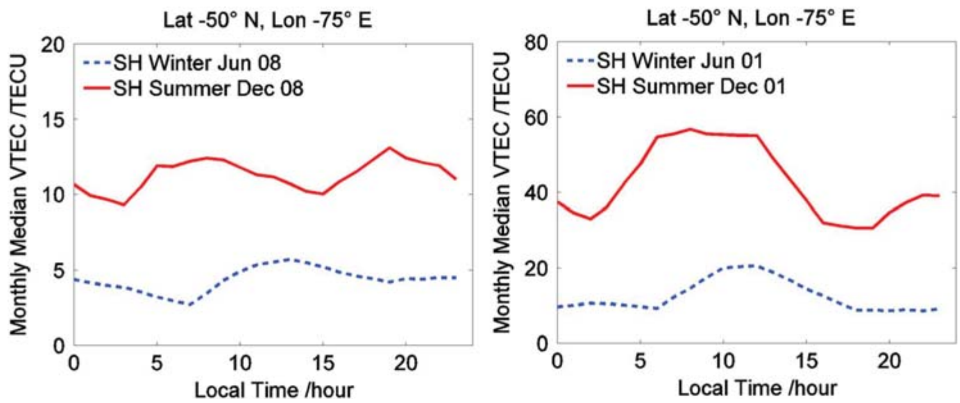

Figure 3. Diurnal variation of TEC at the conjugate region in the Southern Hemisphere under LSA conditions in (left) 2008 in comparison with the equivalent figure related to HSA conditions in (right) 2001.

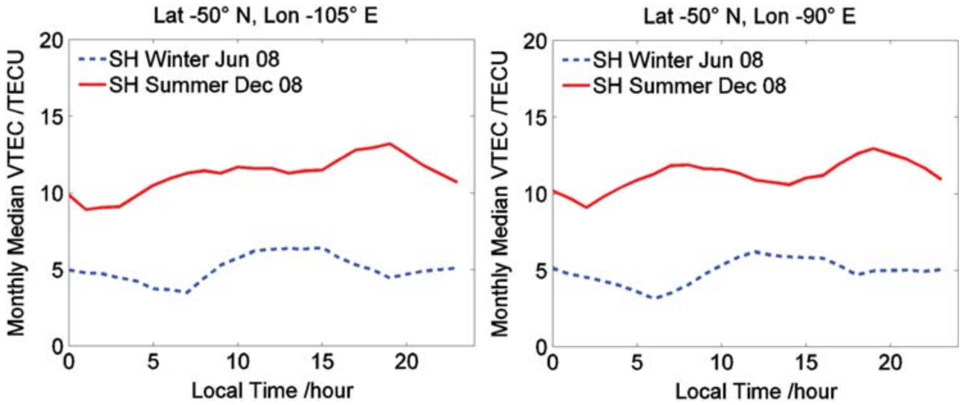

Figure 4. Weddell Sea Anomaly in the Southern Hemisphere at the American sector shown in the diurnal variation of TEC in summer (December 2008) as a function of local time.

profiles provide the peak electron density N_mF_2, the peak height h_mF_2, and valuable profile shape information such as the slab thickness τ or scale height H.

Since the multisatellite constellation COSMIC covers the LSA years 2007–2009 very well and furthermore provides more than 1000 electron density profiles per day, we have selected data sets of this mission for studying the persistence of the NWA effect during the LSA period between solar cycles 23 and 24. Northern winter months have been defined by the days 335–365, 1–31, and northern summer months have been defined by the days of the year 152–212. At the Southern Hemisphere, the seasons are defined in an opposite way.

3. The NWA Effect in the LSA Period 2007–2009

The long duration of low solar activity between solar cycles 23 and 24 provided optimal conditions to check the persistence of the NWA effect. To get a global view on the NWA locations, Figure 1 shows a differential TEC map obtained by subtracting TEC medians of December 2008 from monthly medians of June 2009. As it can be seen, the NWA effect is clearly visible (ΔTEC < 0) at the North American sector in the geographical area: $20° < \varphi < 45°$N; $50° < \lambda < 80°$W ($20° < \varphi < 55°$N; $50° < \lambda < 75°$W for Formosat/COSMIC data analysis). At the Asian longitude sector, we find the NWA effect (ΔTEC > 0) in the region $15° < \varphi < 40°$S; $135° < \lambda < 165°$E ($20° < \varphi < 50°$S; $135° < \lambda < 155°$E for Formosat/COSMIC data analysis). Both locations fit quite well with the measurement sites of earlier publications when NWA was described at the first time by using TEC from Faraday rotation measurements and vertical sounding data [*Jakowski et al.*, 1981, 1986].

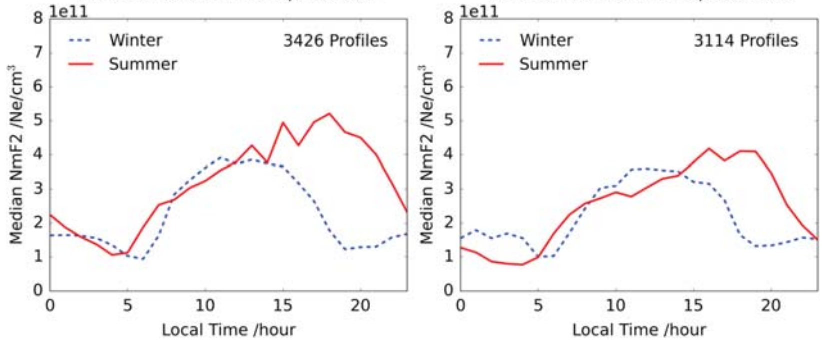

Figure 5. Persistence of the NWA in N_mF_2 at the North American hemisphere during LSA years 2007/2008 derived from IRO measurements on Formosat/COSMIC satellites.

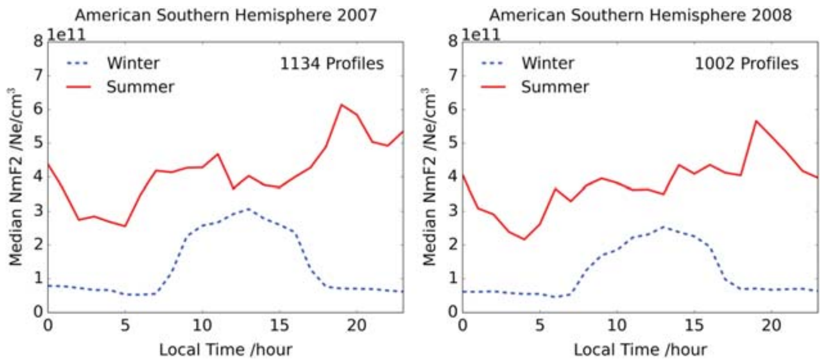

Figure 6. Diurnal variations of averaged N_mF_2 derived from IRO measurements at Formosat/COSMIC satellites at the American longitude sector in the LSA year 2008 showing the Weddell Sea Anomaly with highest ionization values in summer values of N_mF_2 in the evening hours during years of low solar activity 2007/2008.

As originally stated, NWA is a typical LSA effect that disappears under high solar activity (HSA) conditions. This statement is cross checked by computing a similar differential TEC map as shown in Figure 1 (left) but adapted to HSA years 2002 and 2001. The result is shown in Figure 1 (right) where no NWA effect is visible. The NWA is described at both longitude sectors in more detail in the subsequent chapters.

3.1. The American Sector

In agreement with earlier Faraday rotation measurements of TEC, the NWA is clearly visible in the Northern Hemisphere at the American sector also in TEC derived from GNSS measurements. The comparison of the

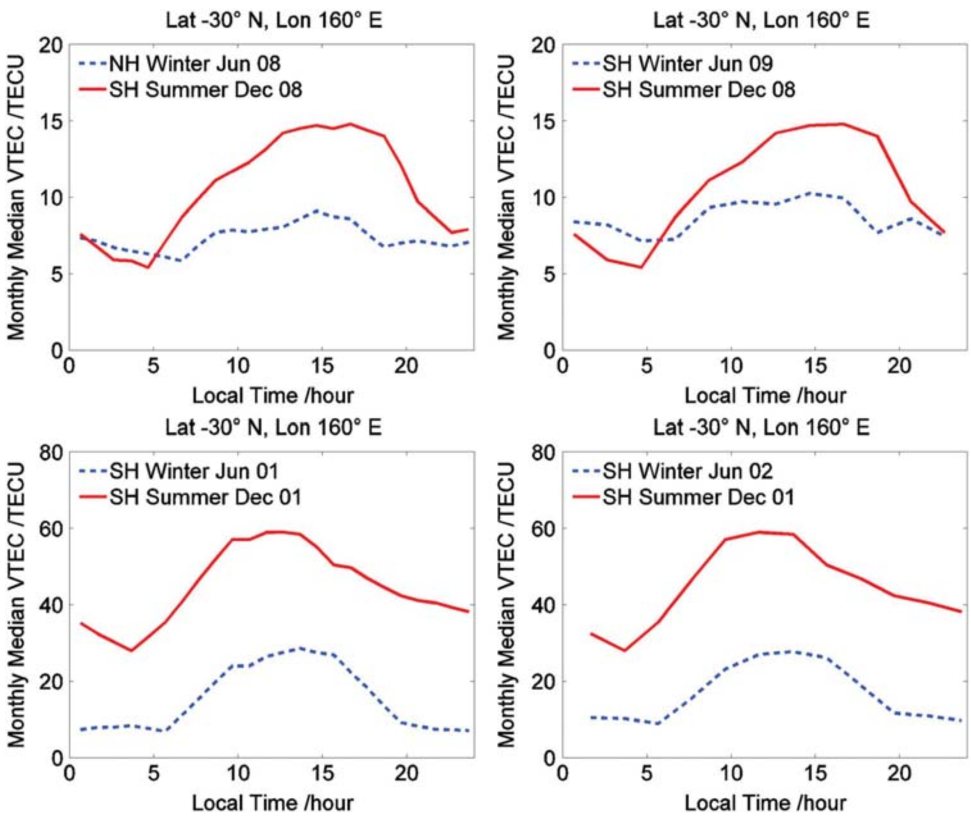

Figure 7. Diurnal variation of TEC showing the NWA effect in the Southern Hemisphere at the Asian sector under LSA conditions in (top row) 2008/2009 in comparison with equivalent figures related to HSA conditions in (bottom row) 2001/2002 where no NWA effect is observable.

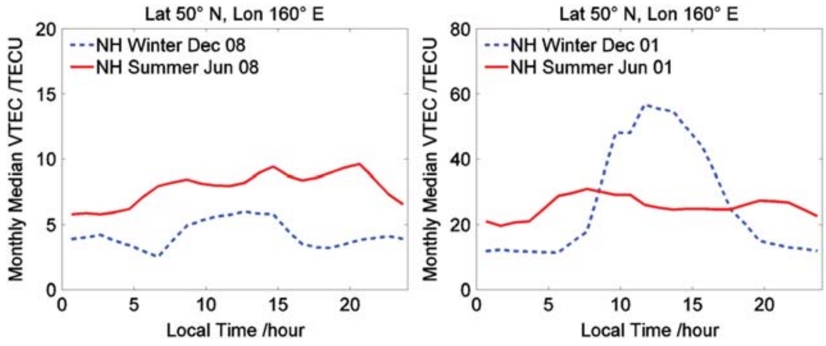

Figure 8. Counter-Weddell Sea Anomaly or OSA in the Northern Hemisphere at the Asian sector shown in the diurnal variation of TEC in summer (June 2008) in comparison with corresponding data in winter, i.e., in December (left) 2008. Comparison is also made with corresponding observations under HSA conditions in (right) 2001.

diurnal variation of monthly averages of TEC in December 2008 (winter) and June 2008/2009 (summer) at 30°N, 75°W shown in Figure 2 (upper panel) clearly indicates a much higher TEC level during night of about 8 to 9 total electron content units (TECU), 1 TECU = 10^{16} el m^{-2} in winter than in summer at around 5–6 TECU. The effect disappears at HSA conditions in 2001/2002 as shown in equivalent plots in Figure 2 (bottom row). This is remarkable because the daytime winter anomaly [e.g., *Lee et al.*, 2011] is well pronounced. So it is evident that day and nighttime winter anomaly are not coupled.

According to the hypothesis suggested by *Jakowski et al.* [1981, 1986], the NWA should not be visible at the conjugated hemisphere as confirmed by the graphics in Figure 3. It is assumed that the geophysical conditions in this region support an enhanced filling of the plasmasphere, e.g., due to strong ionization and appropriate dynamic forces. Thus, Figure 3 shows that monthly averages of TEC for December 2008 in the order of 10–12 TECU exceed TEC values in June by a factor of 2 during the entire day (left) for the selected location −50°N, 75°W. The TEC values under HSA conditions in 2001 (Figure 3, right) are much higher in general, in particular also higher in December than in June as indicated for 2008 too. However, there is a remarkable difference in the diurnal behavior of TEC during summer. Whereas TEC values in 2001 show a typical diurnal variation with maximum values around noon, related TEC values in 2008 reach their absolute maximum in the evening hours around 19:00 LT. This phenomenon is called the Midlatitude Summer Nighttime Anomaly (MSNA) [*Lin et al.*, 2010; *Thampi et al.*, 2011] and is well known as Weddell Sea Anomaly (WSA) in the Southern Hemisphere [*Horvath and Essex*, 2003; *He et al.*, 2009].

Indeed, when moving westward to 90°W and 105°W as shown in Figure 4, the MSNA effect becomes clearer indicating a close connection with the WSA as described in detail by *Horvath and Essex* [2003] and *He et al.* [2009]. Thus, it is concluded that there is probably a close connection between NWA and MSNA effects as will be discussed in section 4 in more detail.

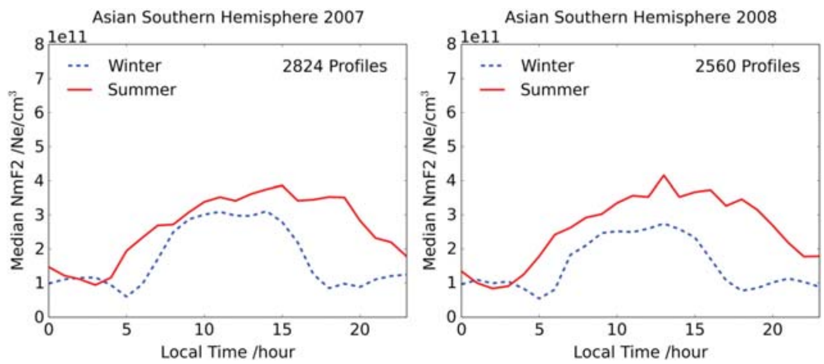

Figure 9. Persistence of the NWA effect in N_mF_2 in the Southern Hemisphere at the Asian sector during LSA years 2007/2008.

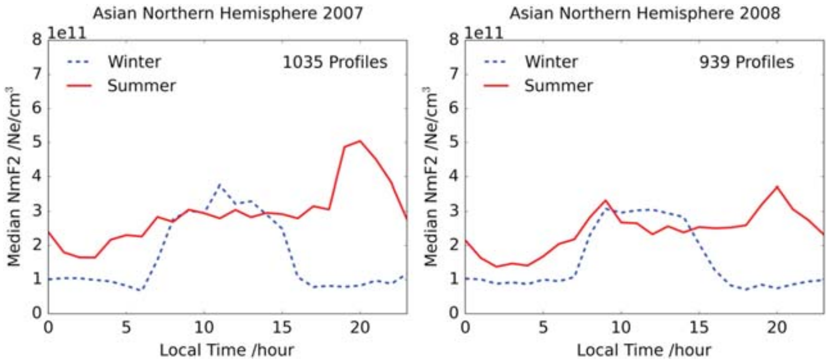

Figure 10. Diurnal variations of averaged N_mF_2 derived from IRO measurements at Formosat/COSMIC satellites at the Asian longitude sector in the LSA years 2007–2008 clearly showing the Okhotsk Sea Anomaly with highest ionization in the late evening hours in northern summer values.

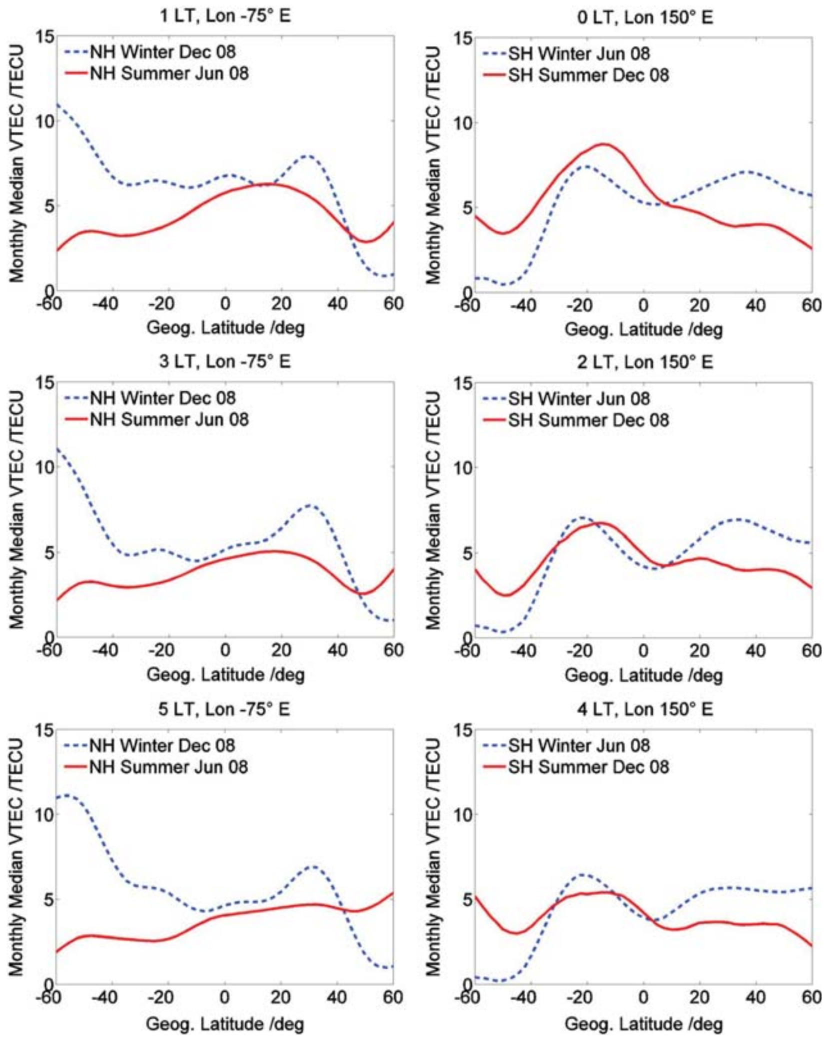

Figure 11. Latitudinal dependence of monthly TEC medians at different nighttime values at American (−75°E) and Asian (150°E) longitude sectors in December and June 2008.

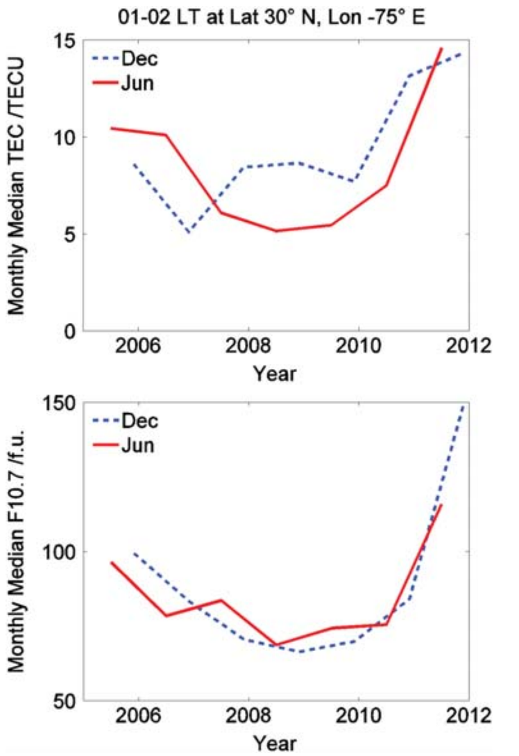

Figure 12. Dependency of NWA occurrence from solar activity level expressed by TEC medians in December and June from 2005 to 2011.

Because the NWA should be visible also in the peak electron density N_mF_2 as it has been shown in earlier studies by *Jakowski et al.* [1981, 1986, 1990] and *Jakowski and Förster* [1995], we subsequently confirm the NWA results by using N_mF_2 data derived from ionospheric radio occultation (IRO) data obtained from the Formosat/COSMIC satellite mission.

Since IRO measurements are not spatially and temporally fixed, certain time slots and areas, i.e., latitude and longitude ranges, must be defined to get representative data usable for the analysis. Due to the high variability of N_mF_2 in space and time, the obtained graphics are not always smooth although averaged. Here we use N_mF_2 averages of all IRO measurements collected within 1 h in the defined spatial window defined at the beginning of section 3 for COSMIC data analysis. The number of profiles used for averaging is given in the graphics. In analogy to the TEC data presented in Figure 2 (top row), also the peak electron density in Figure 5 shows the NWA at the North American sector during LSA years 2007 and 2008 in the selected geographic region (20° $< \phi <$ 45°N; 50° $< \lambda <$ 80°W) as indicated in Figure 1 by white colored ellipsoidal lines. The graphics look very similar as the corresponding TEC data shown in Figure 2 (top row). Besides, the NWA also the MSNA is well pronounced in N_mF_2 data. As expected, the MSNA is also nicely visible in N_mF_2 at the Southern Hemisphere in Figure 6 underlining the connection with the WSA. Furthermore, the summer values of N_mF_2 exceed the corresponding winter values by a factor of even more than 2 as observed for TEC (Figure 3).

3.2. The Asian Sector

Following the early papers by *Jakowski et al.* [1981, 1986], the NWA should also be visible at the Asian sector but there at the Southern Hemisphere due to the northward displacement of the geomagnetic equator. As indicated in Figure 1 the NWA region is centered at the east coast of Australia. So we have selected a location at 30°S, 160°E to have a view on the diurnal TEC behavior in December and June. At the Southern Hemisphere, we expect the NWA to occur in June 2008 and 2009 as confirmed in Figure 7. Compared with the corresponding location in the Northern Hemisphere at the American sector, we see a big difference in the daytime. There is practically no evening enhancement, and the daytime values of TEC in summer clearly exceed the wintertime values that is less pronounced at the American sector under HSA conditions. The more remarkable is the appearance of the NWA effect at LSA conditions (see Figure 7, top row). In agreement with the American sector, the NWA disappears at HSA conditions as seen in Figure 7 (bottom row). It is worth noting that here no daytime winter anomaly effect is present in contradiction to the Northern Hemisphere at the American sector. However, the daytime winter anomaly effect appears at the same longitude in the Northern Hemisphere over North-East Russia (Okhotsk Sea) as seen at HSA in Figure 9 (right). Furthermore, it is interesting to note that a well-pronounced MSNA effect is observed in northern summer (Figure 8, left), i.e., in southern winter when the NWA occurs. This observation can be considered as a kind of Counter-WSA or as we say here, Okhotsk Sea Anomaly (OSA).

A cross check of TEC observations with related peak electron density N_mF_2 measurements at the Asian sector confirms the results obtained by using TEC described earlier (Figures 9 and 10). Compared to the American sector, the NWA is less pronounced but clearly visible even as a Nighttime Enhancement (NE) effect whose physical origin is assumed to be closely related to NWA causing processes at the regions considered here [*Jakowski et al.*, 1991].

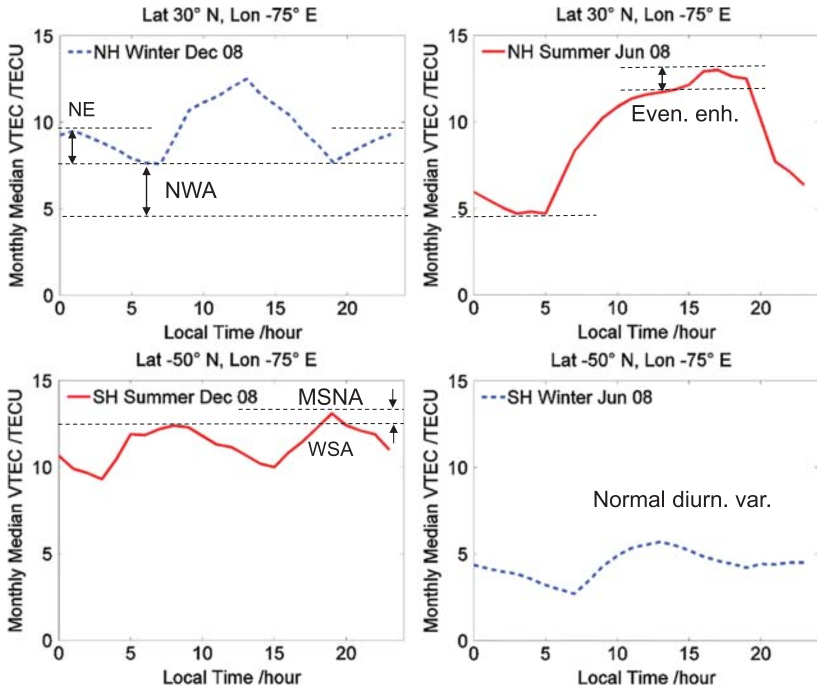

Figure 13. (top and bottom rows) Ionospheric anomaly effects related to the tilted geomagnetic field at the American longitude sector (75°W) under low solar activity conditions: NWA effect, higher nighttime ionization in winter than in summer in the Northern Hemisphere; MSNA effect, higher ionization in evening and night than at daytime around noon in summer; and NE effect, relative maximum of ionization during nighttime.

The availability of global TEC maps enables us to study the meridional and zonal behavior of the NWA effect easily. Thus, Figure 11 provides meridional cuts of the hourly averaged nighttime TEC level in December and June 2008, i.e., at LSA conditions at the American and Asian longitude sectors from 60°S to 60°N. As it can be seen, the NWA dominates at both sectors at geographic latitudes of about 10°–40°N/S. Due to the strong displacement of the geomagnetic equator at these sectors, these latitudes correspond with about 20°–50°N/S geomagnetic latitude. In agreement with the previous discussion, the NWA is stronger at the American sector compared with the Asian sector.

To study the dependency of the NWA on the solar activity level, Figure 12 shows monthly median TEC values representing the nighttime level around 00:00–02:00 LT of the ionospheric ionization in December (winter) and June (summer) at 30°N, 75°W over the years 2005–2011 around the solar activity minimum between solar cycles 23 and 24. As Figure 12 clearly demonstrates, the NWA occurs when $F_{10.7}$ falls below 80 solar flux units (sfu: 1 sfu = 10^{-22} W m^{-2} s^{-1}) and vanishes at a solar activity level that exceeds about 120 sfu. So the threshold values slightly differ for the decreasing and increasing phase of solar activity.

4. Discussion

As it is shown in the previous section, the TEC and N_mF_2 observations agree with earlier papers by *Jakowski et al.* [1981, 1986] and *Jakowski and Förster* [1995] describing the NWA effect first time, thus showing the persistence of the NWA under LSA conditions. To figure out some new findings, the subsequent discussion will focus on comparing our observations and modeling studies [*Förster and Jakowski*, 1986, 1988] with more recent observations obtained by other authors using new measurement techniques. Before doing this, the current understanding of the NWA effect as elaborated in the above mentioned papers shall be summarized briefly. The NWA signatures of the total electron content derived from Faraday rotation measurements and vertical sounding data at the American and Asian longitude sectors lead to the assumption that the higher ionization level in winter time compared with summer conditions is due to an enhanced interhemispheric plasma transport within geomagnetic plasma tubes connected to the conjugated summer hemisphere. It was underlined that the tilted geomagnetic field geometry showing strongest deviations of the geomagnetic from the geographic equator at the American and Asian longitude sectors plays a key role to support such a mechanism. Due to the resulting asymmetry in geomagnetic-geographic relationships, there exist optimal conditions for uplifting ionospheric plasma at those longitude sectors where moduli of the geographic latitudes exceed the geomagnetic ones essentially, e.g., by approximately 10°. Such conditions are fulfilled in the Southern Hemisphere at the American and in the Northern Hemisphere at the Asian longitude sector. Here equatorward blowing thermospheric winds maximize uplifting the ionospheric plasma just created by strong photoionization in summer at 45° geomagnetic inclination. This statement is underlined by the latitudinal range of the NWA effect. So Figure 11 indicates that the NWA peaks between about 20° and 30° geographic latitude. Taking into account the tilted geomagnetic field, this range corresponds with a geomagnetic latitude range of about 40°–50° at the conjugated hemispheres which is an optimal range for wind-induced plasma uplifting. To further approve these assumptions, *Förster and Jakowski* [1986, 1988] and *Jakowski and Förster* [1995] used a physical numerical model of the coupled system ionosphere-plasmasphere-ionosphere along a flux tube ($L = 1.5$) for simulation studies. Thus, it was shown that equatorward winds ($v \leq 200$ m/s) blowing from summer to the winter hemisphere cause a strong increase of the electron content of plasma tubes connecting both hemispheres accompanied by an increase of the equivalent slab thickness τ ($\tau = \mathrm{TEC}/N_mF_2$), the ionospheric F_2 layer height h_mF_2, and the topside plasma scale height H_p at both hemispheres. This result agrees with tube content estimates inferred from whistler measurements at the American longitude sector [*Park et al.*, 1978] and plasmasphere content enhancements derived from Beacon satellite (ATS-6) observations by *Davies et al.* [1976] at Boulder in December/January 1974/1975. More recently, a study by *Lee et al.* [2011] based on Jason-1 satellite altimetry-derived TEC data confirmed the increase of the plasmasphere content in December at the American longitude sector. Furthermore, the authors state that the plasma in the ionosphere does not keep flowing up to the plasmasphere although the ionospheric density continues to increase with increasing solar activity. This means that the downward fluxes causing the NWA do not grow in the same way as the background ionization increases, in other words, the interhemispheric plasma fluxes lose their impact on the ionization level during nighttime at HSA as observed. This agrees with theoretical studies by *Richards and Torr* [1985] that show that the upward proton flux from the ionosphere to the plasmasphere decreases with increasing solar activity. Under LSA conditions, on the other hand, when the regular ionization level is rather low in particular at night, strong downward plasma fluxes up to 2.5×10^9 electrons cm^{-2} s^{-1} [*Jakowski and Förster*, 1995] may cause a significant increase of the ionization level that exceeds the ionization level in summer thus causing the NWA. Downward fluxes in the order of 3–5 $\times 10^8$ electrons cm^{-2} s^{-1} may produce already nighttime enhancements in Faraday records obtained in Havana at North America at LSA in 1976. Consequently, the NWA mechanism was also suggested to explain the strong occurrence of nighttime enhancements in particular at northern winter over Havana [*Jakowski et al.*, 1991].

After summarizing the basic understanding of NWA which is consistent with the observations presented in section 3, it is worth discussing the relationship of NWA with other anomalies that have been discussed recently based on tremendous data sets provided by dual-frequency ground and space-based GNSS and satellite altimetry measurements. Thus, various anomalies of ionospheric ionization have been discussed in recent years by *Lin et al.* [2010], *Thampi et al.* [2011], *Meza et al.* [2012], and *Natali and Meza* [2013]. Daytime and nighttime anomaly studies by *Natali and Meza* [2013] and *Meza et al.* [2012] confirmed the occurrence of the daytime winter anomaly (WA) and the NWA in TEC maps from the IGS applying principal component analysis and wavelet transform tools. In our observations presented here the WA occurs only in the Northern Hemisphere under HSA conditions as it is shown in Figures 2 and 8. It is worth noting that NWA is not caused by the daytime winter anomaly. Even if the ionization level is much lower at daytime, NWA may occur as it is seen in Figures 7 and 9.

It is interesting to note that at LSA the diurnal summertime variation of TEC and N_mF_2 indicates a typical enhancement of the ionospheric ionization in evening hours around and after sunset. This phenomenon is observed at both hemispheres (cf. Figures 2–10). The evening enhancement of ionospheric ionization is closely related to the so-called Midlatitude Summer Nighttime Anomaly (MSNA) as studied by *Lin et al.* [2010] and *Thampi et al.* [2011]. Extreme MSNA show an absolute maximum after sunset, whereas the minimum can be found around noon when the regular daytime maximum is expected. In our data set, we find such a behavior typically in the Southern Hemisphere at the American sector (see Figures 3 and 4). This anomaly is well known as the Weddell Sea Anomaly (WSA) which appeared as a nighttime enhancement and a daytime depletion of TEC in the Southern Hemisphere summer as derived from TOPEX data sets by *Horvath and Essex* [2003] and *Horvath* [2006]. Theoretical modeling studies of the WSA by *Chen et al.* [2011] using the SAMI2 model have shown that an equatorward neutral wind is identified as the major cause of the WSA, while the downward flux from the plasmasphere provides an additional plasma source to enhance or maintain the density of the anomalous structure. According to *Horvath* [2006], the WSA region covers a large area extending from 60° to 160°W and peaking around 50°–60°S/90°–110°W.

Taking into account the just mentioned scenario to explain the WSA and the location of the WSA area, it can be concluded that the major physical mechanism of MSNA and WSA is identical with the physical mechanism causing the NWA. To verify the assumed close relationship of NWA and MSNA/WSA let us check whether similar relationships exist at the Asian longitude sector where NWA is observed at Southern Hemisphere winter. Indeed, a kind of Counter-WSA has been reported by *Lin et al.* [2010] for the peak electron density N_mF_2 in the Northern Hemisphere summer near the Northeast Asia region when studying MSNA on global scale. The authors state that the anomaly is a midlatitude feature of the summer ionosphere at longitudes where the magnetic equator locates poleward away from the geographic equator. These observations are in line with the presented results and former NWA studies which identified the same geomagnetic-geographic relationship as being typical for the region of enhanced plasma uplifting to cause the NWA at the Southern Hemisphere winter at the Asian sector. As shown in Figures 8 and 10, the diurnal variation of TEC and N_mF_2, respectively, shows a typical MSNA effect. It is worth mentioning that the evening enhancement of ionization in summer is still visible at HSA (Figure 8, right) in the Northern Hemisphere but is dominated by a prenoon maximum. In winter, the WA effect is only visible at HSA.

It is generally accepted that equatorward blowing neutral winds are the major driving force producing the MSNA effect [e.g., *Horvath and Essex*, 2003; *Horvath*, 2006; *He et al.*, 2009, *Thampi et al.*, 2011, *Chen et al.*, 2011]. These winds blowing equatorward in the afternoon-evening hours find optimal conditions for uplifting ionospheric plasma at geomagnetic midlatitudes. Hence, the plasma is stored in the topside ionosphere and plasmasphere where the loss is low. In the evening hours, the downward plasma flow exceeds the flow required to maintain the nighttime ionization essentially thus producing the ionization maximum in the night in the local ionosphere. To explain the NWA effect, it is additionally assumed that this high plasma pressure feeds also the conjugated nighttime hemisphere. As mentioned above, such a scenario has been numerically simulated by *Förster and Jakowski* [1986, 1988] and *Jakowski and Förster* [1995] in almost the same manner. Thus, it is evident that the basic processes causing NWA and MSNA are the same. Whereas MSNA considers only the local ionosphere, NWA takes into account also the conjugated hemisphere where interhemispheric plasma fluxes may cause a strong increase of the nighttime ionization compared with the low ionization background under LSA conditions. In addition to arguments provided in early NWA papers including this one supporting the scenario just described, further evidence is provided in more recent publications. Thus, *He et al.* [2009] show that the enhancement of N_mF_2 is associated with an enhancement of the peak electron density height h_mF_2 correlated with geomagnetic field lines.

Zonal winds can certainly modify the effectiveness of the wind-induced uplifting of plasma depending on the local declination of the geomagnetic field. Thus, considering the South Atlantic Anomaly of the geomagnetic field in the vicinity of the American longitude sector, differences in the observations made between both longitude sectors, e.g., the smaller NWA effect at the Asian sector might be explained (cf. Figures 2, 7, 5, 9, and 10). As pointed out by *Thampi et al.*, [2011] their model simulations indicate that zonal electric fields have only little contribution to plasma uplifting as locally needed for the formation of the MSNA and consequently via interhemispheric coupling for the NWA too.

When considering the differences in the observations made between both longitude sectors, it should be mentioned that nondipolar geomagnetic contributions to a permanently changing Earth's magnetic field should have significant consequences, in particular, in the topside ionosphere and plasmasphere. As pointed out by *Cnossen and Richmond* [2013], the secular variation of the geomagnetic field may cause significant changes in ionospheric key parameters such as h_mF_2 and f_oF_2, in particular, in the Atlantic region ionosphere. Thus, it appears worthwhile to include the concrete geomagnetic field configuration in future modeling studies concerning the NWA.

The summary of our discussion is illustrated in Figure 13 where different types of ionospheric anomalies discussed in this section are demonstrated on TEC observations at the American sector during low solar activity conditions in 2008. Figure 13 (top row) shows monthly medians of the diurnal variation of TEC in December (left column) and June (right column), whereas Figure 13 (bottom row) shows the corresponding TEC variation in the geomagnetic conjugated region at the Southern Hemisphere. Comparing the ionization level (TEC) at the Northern Hemisphere in winter and summer (Figure 13, top row), the diurnal minimum of TEC around 05:00 LT is higher in winter than in summer by about 3 TECU (NWA). Considering TEC in June, an evening enhancement of about 1–2 TECU is indicated. The related plasma uplifting is not strong enough to keep the ionization at a high level during night. Consequently, TEC is obviously not impacted at the conjugated Southern Hemisphere (Figure 13, bottom right). When considering summer conditions at the Southern Hemisphere in December (Figure 13, bottom left), the behavior of TEC differs considerably from related northern summer observations (Figure 13, top right). This is due to the MSNA and WSA which are well pronounced in these median plots. TEC varies at a high level at around 10–13 TECU and even increases in the afternoon at around 15:00 LT due to effective plasma uplifting reaching a maximum in TEC at around 20:00 LT. This high ionization level provides good conditions to feed the conjugated Northern Hemisphere via interhemispheric plasma fluxes causing a relative high ionization level including a nighttime enhancement (NE) around 01:00 LT (Figure 13, top left).

5. Conclusions

It has been shown that the NWA is a persistent feature in low solar activity years in the Northern Hemisphere at the American and in the Southern Hemisphere at the Asian longitude sector. The observations of TEC and the peak electron density N_mF_2 presented in this study fully confirm and further support the findings published in earlier NWA papers [*Jakowski et al.*, 1981, 1986, 1990; *Förster and Jakowski*, 1986, 1988; *Jakowski and Förster*, 1995].

Thus, in agreement with former studies, the NWA will appear when solar radio flux index falls below about 80 sfu and will terminate above around 120 sfu (cf. Figure 12). This asymmetry that obviously depends on the history of the thermosphere-ionosphere system remains unclear, i.e., its understanding requires further studies. NWA appears at longitude sectors where the displacement of geomagnetic and geographic equator has a maximum, more specific; NWA appears only at that hemisphere where the geomagnetic latitude exceeds the geographic latitude. NWA peaks around 40°–50° geomagnetic midlatitudes indicating that wind-induced plasma uplifting is the main driving force for the delayed storing of ionospheric plasma in the topside ionosphere and plasmasphere causing the MSNA. Simultaneously, interhemispheric coupling causes severe downward fluxes of plasma ($\approx 7 \times 10^8\,\text{cm}^{-2}\,\text{s}^{-1}$ at 1000 km height during sunset after *Jakowski and Förster* [1995]) in the conjugated winter hemisphere during night that generates the NWA at LSA. With increasing solar activity, the downward plasma fluxes, although still present, are not able to dominate the nighttime ionization level at nighttime, i.e., NWA is not visible at HSA conditions.

It has been shown for the first time that MSNA and related special anomalies such as the Weddell Sea Anomaly and the Okhotsk Sea Anomaly introduced in this paper are closely related to the NWA via enhanced wind-induced uplifting of the ionosphere causing high plasma pressure in the topside ionosphere and plasmasphere connecting both hemispheres along geomagnetic field lines.

The well-known daytime winter anomaly has a quite different nature from the NWA. The WA was visible in our data sets at both longitude sectors at high solar activity but only in the Northern Hemisphere.

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