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Climatological study of Nighttime Winter Anomaly by GRACE satellite and ground-based observations

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ABSTRACT

The Ionospheric Nighttime Winter Anomaly (or seasonal anomaly) is a persistent feature in the Northern Hemisphere for the American sector and the Southern Hemisphere for the Asian longitude sector under Low Solar Activity (LSA) conditions. During the Nighttime Winter Anomaly, the mean ionization level is higher in the winter nights compared to the summer nights. The aim of this paper is to investigate the occurrence of Nighttime Winter Anomaly during LSA periods utilizing measurements of vertical total electron content (VTEC) obtained through the International Global Navigation Satellite System (GNSS) Service (IGS) during the years 2009 and 2020 for several stations located in Asian and American sectors. The NWA phenomenon was also studied through the use of electron density measurements taken from the GRACE satellite in 2009. The Midlatitude Summer Nighttime Anomaly (MSNA) is visible on the GRACE satellite in the American Southern Hemisphere and the Okhotsk Sea Anomaly (OSA) with the highest ionization in the late evening hours in the northern summer values of the Asian sector.

1. Introduction

The Nighttime Winter Anomaly (NWA) refers to a phenomenon in the ionosphere that occurs during

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periods of Low Solar Activity (LSA) and at nighttime in specific mid-latitude longitude sectors. During the NWA, it has been observed that the mean ionization level is notably higher during winter nights when compared to summer nights. It occurs in the Northern Hemisphere within the American sector and the Southern Hemisphere within the Asian longitude sector. Several additional anomalies, for example, the Weddell Sea anomaly (WSA), the Mid-Summer Nighttime Anomaly (MSNA), the Okhotsk Sea Anomaly (OSA), and Mid-latitude Post-midnight Enhancement (MPE) have been documented [1-3], which also defines an anomaly in electron density. Interestingly, these anomalies manifest during LSA periods, much like the NWA. The MSNA has been observed in both the Northern and Southern Hemispheres during the local summer and is widely recognized as the Weddell Sea Anomaly (WSA) in the Southern Hemisphere [4-6]. The neutral wind effect in the geomagnetic frame is the most significant mechanism proposed for the development of MSNA [7]. A comparable ionospheric anomaly, known as the Okhotsk Sea Anomaly (OSA), is also seen close to the Okhotsk Sea in the northern hemisphere [8]. The investigation into the interhemispheric plasma transport process involved numerical modeling to examine the coupling of ionospheric and plasmaspheric regions along magnetic field lines [9], which is considered a significant mechanism contributing to the presence of NWA [10]. Furthermore, the reasons for nighttime enhancements encompass multiple mechanisms, such as the long-lasting sunlight at ionospheric altitudes during summer, ionospheric elevation due to neutral wind, and the inflow of downward plasma from both the topside ionosphere and the plasmasphere [11]. Over the past few years, the nighttime enhancements have been researched utilizing electron density profiles obtained from the COSMIC satellite to investigate nighttime NmF2 enhancements in the Northern and Southern Hemispheres, as demonstrated by studies conducted by Chen et al. [12]. Additionally, global ionospheric total electron content (TEC) maps, produced from ground-based Global Positioning System (GPS) receivers, have revealed that these enhancements are more prominent during periods of low solar activity, as reported by Jakowski et al. [13] In addition, the winter anomaly has been examined by analyzing NmF2 data gathered from ground ionosonde [14-16].

The objective of this paper is to investigate the presence of the Ionospheric Nighttime Winter Anomaly during periods of LSA. This investigation relies on VTEC data acquired from the IGS for the years 2009 and 2020, focusing on various stations located in both the Asian and American sectors. Additionally, the NWA phenomenon is examined using electron density measurements obtained from the GRACE satellite for the year 2009. Furthermore, this paper explores related anomalies, including the Midlatitude Summer Nighttime Anomaly (MSNA) observed in the American Southern Hemisphere and the Okhotsk Sea Anomaly (OSA) characterized by increased ionization during late evening hours in the northern summer within the Asian sector.

2. Data and method

To investigate the presence of NWA, we utilized electron density from the GRACE satellite, which covered 14 years between 2002 and 2015. On March 17, 2002, two satellites, GRACE-A and GRACE-B, were launched into a circular polar orbit as part of the Gravity Recovery and Climate Experiment (GRACE). They started their mission at an initial altitude of 490 km. These identical GRACE satellites moved in tandem, keeping a distance of around 200 km between them. The inclination angle of their orbital route was 89°. GPS and microwave ranging systems are used in these two satellites. When the gravitational field of Earth's surface's remains steady, they travel towards one another but they travel far away when the gravity field suddenly changes. GRACE is able to acquire extremely precise measurements of the Earth's gravitational field because of its operational mechanism.

The electron density utilized in this study was obtained through measurements from the GRACE K-band ranging system (KBR). The KBR instrument possesses the capability to precisely gauge changes in distance between the two GRACE satellites. Estimations of average electron densities were calculated based on the differential TEC derived from the changes in distance between these two satellites [17]. The density data for KBR employed in this research were processed by the German Research Centre for Geosciences (GFZ) in Potsdam, Germany, and retrieved from the GFZ archive (ftp://isdcftp.gfzpotsdam.de/grace/IONOSPHERE/KBR_Electron_Density/01 01/).

The International Geomagnetic Reference Field (IGRF) was utilized to transform geographic latitude into magnetic latitude. Besides the electron density obtained from the GRACE satellite, we utilized ground-based GPS data for LSA years 2009 and 2020 for a number of stations situated in the Asian and American sectors. Data is considered only from periods characterized by quiet geomagnetic conditions [18]. The database used to investigate the occurrence of Nighttime Winter Anomaly during LSA periods is obtained from the IGS website (http://www.igs.org). The dense ground-based GNSS TEC observations have found extensive use in the thorough investigation of ionospheric climate and weather horizontal structures. They provide high temporal resolutions (30 seconds) and spatial resolutions of less than 1 degree in both longitude and latitude.;19].

3. Results and Discussion

3,1 Detection of the NWA Signature

Between solar cycles 24 and 25, there was a prolonged period of low solar activity, which offered an ideal opportunity to verify the NWA effect.

3.1.1 GNSS Stations

Table 1: GNSS Stations in the Asian and American Sectors.

Station Name	Latitude	Longitude
BARH	44.39°N	68.22°W
GODS	39.03°N	77.38°W
DARW	12.8°S	131.1°E
KOUC	20.5°S	164.28°E

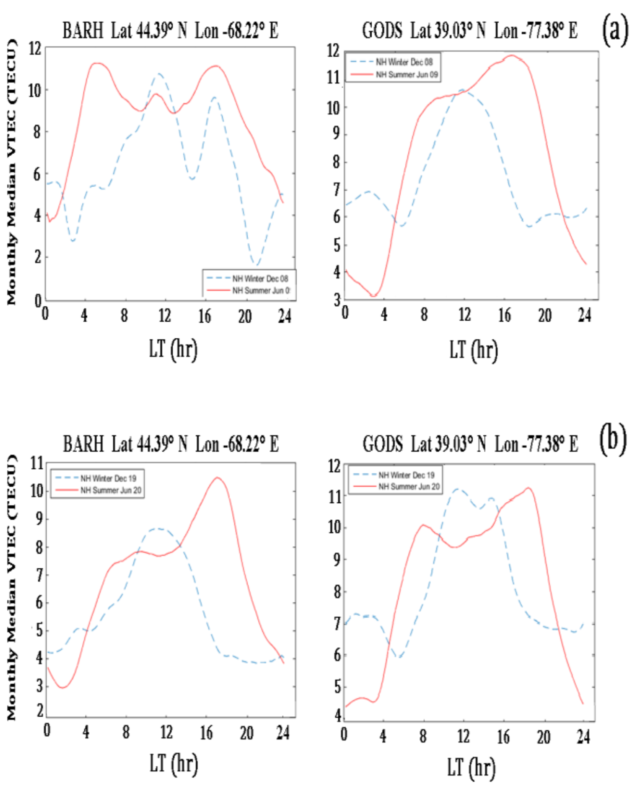

Figure 1. Local time variations of the Monthly median of VTEC for the American sector stations BARH and GODS during periods of LSA, in the years a)2008/2009 and b)2019/2020.

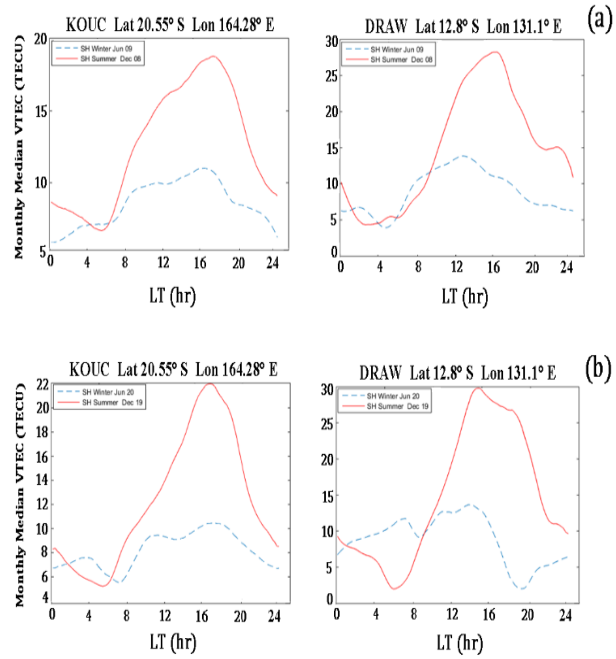

Figure 2. Local time variations of the Monthly median of VTEC for the Asian sector stations KOUC and DRAW during periods of LSA, in the years a)2008/2009 and b)2019/2020.

In Figures 1 and 2, Panel (a) illustrates the temporal variations in the monthly median of VTEC values for the American and Asian sectors for the winter months of December 2008 and the summer months of June 2009. Panel (b) presents a similar analysis, focusing on the winter months of December 2019 and the summer months of June 2020. These figures clearly illustrate that there is NWA for the LSA years 2009/2020, where the nighttime VTEC values during winter were higher than those observed during summer. By investigating the monthly values, we pointed out that the most preferable values, giving better results as mentioned by Farid HM et al. [20].

3.1.2 GRACE satellite

Figure 3 – Panel (a) illustrates the seasonal variations of the Ne median during the winter and summer months from GRACE satellite data, plotted against LT for the American sector during the LSA year 2009; the Northern American sector is defined by latitudes ranging from 20° to 50°N and longitudes spanning from 50° to 80°W. Panels (b and c) display the number of GRACE observations plotted against LT for the American sector during the winter, and summer months of 2009, respectively. It illustrates that the nighttime Ne values in winter exceeded those in summer, indicating the presence of NWA during the LSA year 2009 in the American sector based on GRACE data. Panel (a) in Figures (3 – 6) the dashed line indicates data gaps or missing information within the GRACE dataset.

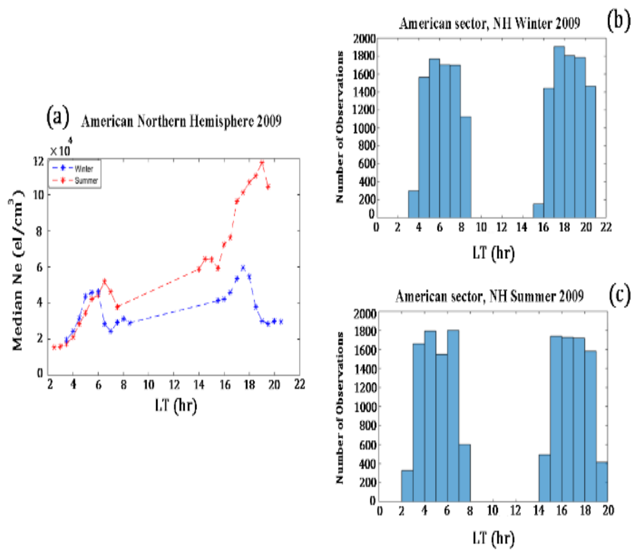

Figure 3. a) Seasonal variations of the Ne median in winter and summer months from GRACE satellite plotted against LT for the American sector during LSA year 2009. The histograms illustrate the number of GRACE observations plotted against LT in the American sector during b) the winter months of 2009 and c) the summer months of 2009.

Figure 4, on the other hand, examines the Asian sector using GRACE data during the same LSA year. In this case, Panel (a) illustrates the seasonal variations of the Ne median during the winter and summer months from GRACE satellite data, which is plotted against LT. The Southern Asian sector is defined by the region between latitudes 20° and 50°S and longitudes 135° and 165°E. This figure does not provide evidence of the existence of NWA. This absence of NWA can be attributed to the absence of nighttime data in the GRACE observations. Panels (b and c) display the number of GRACE observations against Local Time (LT) for the Asian sector during the winter and summer months of 2009, respectively.

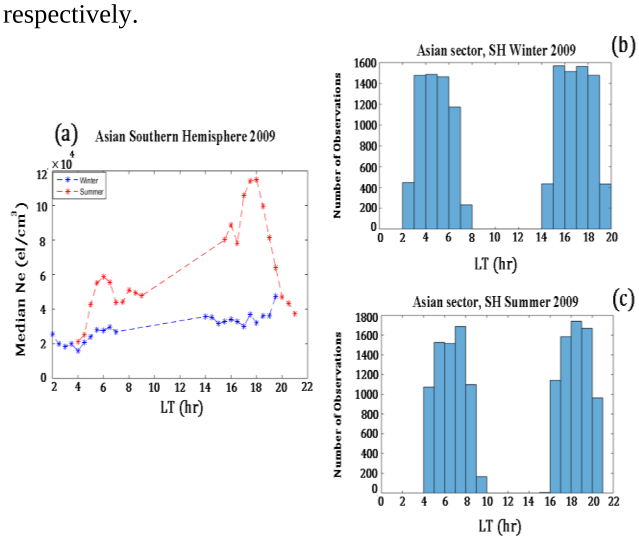

Figure 4. a) Seasonal variations of the Ne median in winter and summer months from GRACE satellite plotted against LT for the Asian sector during LSA year 2009. The histograms illustrate the number of GRACE observations Plotted against LT in the Asian sector during b) the winter months of 2009 and c) the summer months of 2009.

In Figure 5 (Panel a) displays the seasonal variations of the Ne median during the winter and summer months, derived from GRACE satellite data and plotted against LT. The Southern Hemisphere's American Sector is defined by latitudes ranging from 20° to 50°S and longitudes spanning from 50° to 80°W. It illustrates the Weddell Sea Anomaly (MSNA) in the Southern Hemisphere's American Sector during LSA year 2009. Panels (b and c) provide the number of GRACE observations against Local Time (LT) for the Southern Hemisphere's American Sector during the winter and summer months of 2009, respectively. This figure turns our attention to the Southern Hemisphere's American sector and noticeable differences in electron density (Ne) behavior. This behavior is primarily attributed to the presence of the MSNA and WSA patterns, which are prominently evident in the median plots. Ne is attributed to effective plasma uplift, with Ne reaching its maximum around 18:00 LT. This elevated ionization level offers favorable conditions for facilitating interhemispheric plasma fluxes, contributing to a relatively high ionization level.

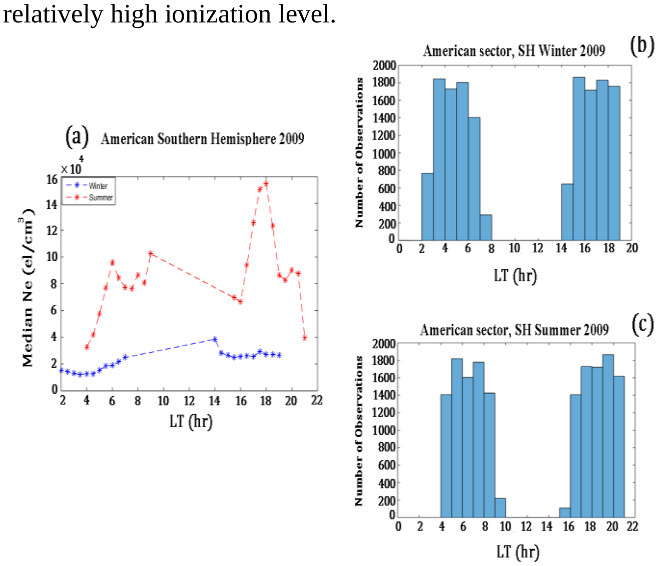

Figure 5. a) Seasonal Variations of Ne Median in Winter and Summer Months from GRACE Satellite, Illustrating the Weddell Sea Anomaly (MSNA) in the Southern Hemisphere's American Sector with respect to Local Time (LT) during LSA year 2009. The histograms illustrate the number of GRACE observations plotted against LT in the Southern Hemisphere's American Sector during b) the winter months of 2009 and c) the summer months of 2009.

Figure 6 (Panel a) displays the seasonal variations of the Ne median during the winter and summer months from GRACE satellite data, plotted against LT. The Northern Hemisphere's

Asian Sector is defined by latitudes ranging from 20° to 50°N and longitudes spanning from 135° to 165°E. It illustrates the Okhotsk Sea Anomaly (OSA) in the Northern Hemisphere's Asian Sector during LSA in 2009. Panels (b and c) provide the number of GRACE observations against Local Time (LT) for the Northern Hemisphere's Asian Sector during the winter and summer months of 2009, respectively. The OSA attribute exhibited peak ionization during the evening hours of the northern summer, as indicated by Ne values.

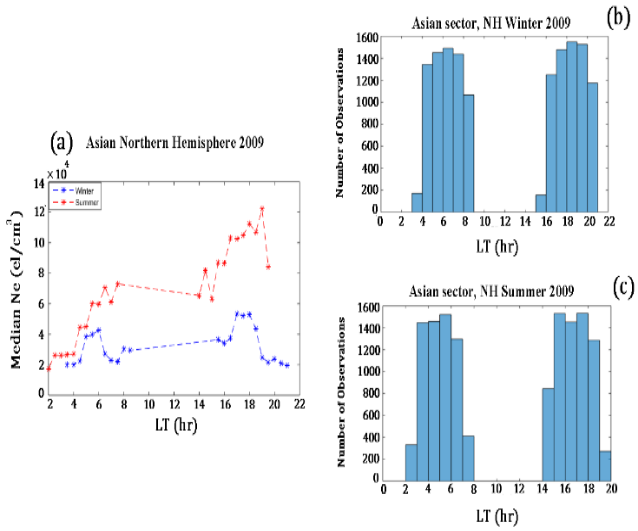

Figure 6. a) Seasonal Variations of Ne Median in Winter and Summer Months from GRACE Satellite, Illustrating the Okhotsk Sea Anomaly (OSA) in the Northern Hemisphere's Asian Sector with Respect to Local Time (LT) during LSA year 2009. The histograms illustrate the number of GRACE observations plotted against LT in the Asian sector during b) the winter months of 2009 and c) the summer months of 2009.

Conclusions

The study provides strong evidence of the Ionospheric Nighttime Winter Anomaly (NWA) during periods of LSA years, specifically in the American and Asian sectors. It confirms the phenomenon of increased ionization levels during winter nights compared to summer nights, which is characteristic of the NWA. The analysis was conducted using vertical total electron content (VTEC) measurements obtained from the IGS source for the years 2009 and 2020.

Furthermore, the study utilized electron density measurements from the GRACE satellite to examine the NWA effect in 2009. The results indicated that nighttime Ne values were higher in winter compared to summer, thereby affirming the existence of the NWA in the American sector. However, the Asian sector during the same year did not provide evidence of the NWA. The absence of NWA in this region was attributed to the lack of nighttime data in the GRACE observations. Following that, our inquiry pivoted towards the Southern Hemisphere's American sector, spotlighting the emergence of the Weddell Sea Anomaly (MSNA). This event has an impact on the patterns of electron density (Ne), particularly during the summer months when Ne levels reach their peak. Moreover, our scrutiny expanded to encompass the Northern Hemisphere's Asian Sector in the same year, where we uncovered the presence of the Okhotsk Sea Anomaly (OSA). This anomaly displayed its highest ionization levels during the evening hours of the northern summer, as evidenced by Ne values.

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